Chapter 3

Tevatron

In our study, we have analyzed the data which was collected using the DØ detector at the Tevatron $p\bar{p}$ collider located at Fermi National Accelerator Laboratory during (1992-1996). The Fermilab Tevatron collides protons and antiprotons at a center-of-mass energy ($\sqrt{s}$) of 1.8 TeV. Until the LHC at CERN, where $\sqrt{s} = 14$ TeV is built, this is the largest center-of-mass energy available. The Tevatron is among the more recent machines in a long line of accelerators which have contributed tremendously to the development of particle physics [19, 20].

The production of top quark pairs requires a large center-of-mass energy and therefore a colliding beam experiment is necessary and the detection of top quark pairs requires a detector capable of identifying and measuring the energies of electrons, muons, jets and neutrinos. The preference of proton beams over electron beams for this purpose comes from consideration of the synchrotron radiation emitted by an accelerating charged particle. The energy dissipated by synchrotron radiation decreases as the fourth power of the mass of the accelerated particle and hence it is far easier to accelerate proton beams to the needed energy. The drawback is that protons themselves are complex objects comprised of quarks and gluons, which complicates the analysis of the collisions and results in only some fraction of the total proton energy being delivered to any particular collision.

One way of implementing a colliding beam experiment is to collide beam of a particles with beams of its antiparticles. As the antiparticle shares all the characteristics of the particle but has opposite electric charge, the two beams will circulate in opposite directions in the same ring of magnets. Because of this, there is no need to reconstruct a separate accelerating apparatus for each beam.

3.1 Principles of Operation

The Tevatron is a complex device and actually a total of seven acceleration devices are used to produce the colliding proton and antiproton beams as shown in Figure 3.1. The Tevatron has a long circumference of 3.7 miles which reduces the energy loss due to radiation. The Tevatron consists of the following different parts
as briefly explained below (details can be found in \cite{21, 22}):

- **Cockroft-Walton Accelerator**
  The beam's birth place, a Cockroft-Walton electrostatic accelerator is the preaccelerator. The process begins with a pressurized bottle of hydrogen gas. Hydrogen gas is used as a source of protons. The proton beam initially starts with 18 keV $\text{H}^-$ ions, which are accelerated to 750 keV by a Cockroft-Walton electrostatic generator. The Fermilab preaccelerator operates in a pulsed mode with a frequency of 15 Hz.

- **Linac**
  The $\text{H}^-$ ions from Cockroft-Walton generator are injected into the Linac. It is 150 m long. This device induces an oscillating electric field between a series of electrodes thus raising the energy of the ions to 200 MeV. At this stage, the $\text{H}^-$ ions are passed through a carbon foil which strips the two electrons from the ion to create a beam of protons $\text{H}^+$.

- **Booster-Synchrotron Ring**
  The protons are then steered into the Booster Synchrotron Ring (151 m diameter). It is a cyclic machine which confines the protons to a closed orbit using bending magnets. On each pass around the ring, the particle's energy is increased by acceleration in a synchronized radio-frequency (RF) cavity. As the momentum increases, the magnetic field in the bending magnets must be increased if the particles are to remain in the ring (since $p = qB\rho$, $p$ is the particle momenta, $q$ is the particle charge, $B$ is the magnetic field and $\rho$ is the radius of curvature). Thus for a given ring the maximum particle energy is limited by the maximum strength of the magnets and on exiting the booster the protons have an energy of 8 GeV. As the energy of the protons increases in this ring, the magnetic field is increased accordingly to keep the protons in the ring.

- **Main Ring (MR)**
  MR is a 400 GeV proton synchrotron with a radius of 1000 m. This ring is composed of about 1000 conventional (Cu - coiled) magnets. MR is employed to further accelerate protons upto 120 GeV and proton beam strikes a nickel target to produce antiprotons. The protons circulate around the 3.7 miles long MR in bunches containing $2 \times 10^{12}$ protons each. Six bunches circulate around the MR simultaneously. The bunch crossing time $\tau$ for any part on the ring is
  \[
  \tau \sim \frac{\text{Circumference}}{cN_{\text{bunch}}} = 3.5 \, \mu\text{s} \quad (3.1)
  \]
  The Target Hall in which $2 \times 10^7$ antiprotons are produced by extracting proton bunches onto a nickle/copper target. Then a magnetic lens is used to form and inject the antiprotons into the debuncher in which a coherent
beam is formed. This process is known as “stochastic cooling” process and it reduces the transverse movement of the antiprotons. This process continues until about $4 \times 10^{11}$ antiprotons are stored. The antiprotons are then injected into the MR where they are accelerated to 150 GeV and then transferred to the Tevatron ring. In the Tevatron, antiprotons circulate in the opposite direction to the protons. Both protons and antiprotons are accelerated to acquire an energy of 900 GeV before they collide at DØ i.e. the center-of-mass energy of $p\bar{p}$ collisions is 1.8 TeV. At present, the center-of-mass energy of $p\bar{p}$ collisions in DØ upgrade for Run II is 2.0 TeV.

The instantaneous luminosity is given by

$$L_{\text{inst}} = \frac{N_p N_\bar{p}}{\tau S} \sim 5 \times 10^{30} \text{ sec}^{-1} \text{ cm}^{-2} = 0.5 \text{ nb}^{-1}/\text{sec} \quad (3.2)$$

where $N_p$ and $N_\bar{p}$ are the number of protons and antiprotons per bunch respectively and $S$ is the geometrical area of the interaction. The integrated luminosity, $L$, is defined as

$$L = \int L_{\text{inst}} dt \quad (3.3)$$

The cross-section $\sigma$ for a process is given by

$$\sigma = \frac{N}{L} \quad (3.4)$$

where $N$ is the number of events produced by the process.
Figure 3.1: Schematic diagram of Tevatron collider at Fermilab.

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