

Chapter 2

Experimental Apparatus

2.1 The Accelerator Chain

Figure 2.1 shows a schematic of the Tevatron and other components of the accelerator chain. Reference [1] provides an excellent introduction to the Tevatron and injector accelerator chain.

The Tevatron is a superconducting synchrotron, proton anti-proton collider, with a circumference of roughly 6 km. Up to 1995 (Run I), the Tevatron collided at a centre of mass energy of $\sqrt{s} = 1.8$ TeV, with a design luminosity, $\mathcal{L}^{\text{inst}}$, of $10^{30} \text{ cm}^{-2} \text{ s}^{-1}$. For a bunch crossing frequency of f , luminosity is defined as

$$\mathcal{L}^{\text{inst}} = \frac{f N_p N_{\bar{p}}}{4\pi\sigma_p\sigma_{\bar{p}}},$$

where $N_p(N_{\bar{p}})$ and $\sigma_p(\sigma_{\bar{p}})$ are the number of particles per bunch and the transverse width of the proton (antiproton) beam respectively. Significant upgrades were made to the Tevatron and to the experiments before the start Run II (in 2001). The centre of mass energy was increased to $\sqrt{s} = 1.96$ TeV and, thanks to the addition of the main injector and recycler, the design luminosity was increased to $200 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$. In fact, luminosities have now exceeded $400 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$. Details of the Run II accelerator upgrade can be found in Ref. [2].

2.1.1 The Initial Accelerator Chain

The accelerator chain starts with a humble bottle of hydrogen gas. A 750 kV Cockcroft-Walton generator ionises the H_2 molecules into H^+ ions. These ions are then accelerated through a 150 m linac up to an energy of 400 MeV. At this point, a thin carbon foil strips the H^+ ions of their electrons, and the resulting protons proceed into the

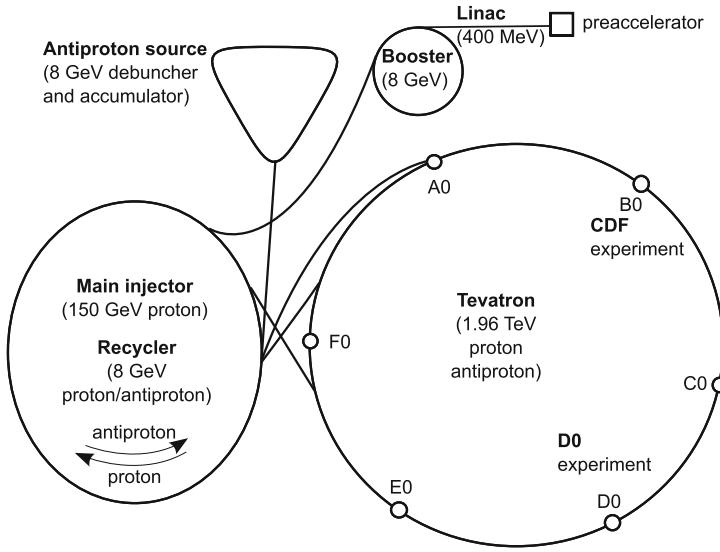


Fig. 2.1 Schematic diagram of the Tevatron and accelerator supply chain

booster ring. The booster is a circular synchrotron which accelerates the protons up to 8 GeV.

2.1.2 The Main Injector and Antiproton Source

Protons are extracted at 8 GeV from the booster into the main injector, which accelerates them to 150 GeV, ready for injection into the Tevatron. Antiprotons, $\bar{p}$ s, are produced by bombarding a Ni target with 120 GeV protons from the main injector, every 1.5 s. The angular spread of the produced particles is reduced through a lithium lens. A pulsed magnet mass-charge spectrometer selects the small fraction ($\sim 10^{-5}$) of desired $\bar{p}$ s from the large number of particles produced in the p -Ni collisions.

At this point, the $\bar{p}$ s have a very large spread in energy, but a relatively small spread in time. The debuncher is a triangular accelerator, which effectively has an energy dependent phase. Higher energy $\bar{p}$ s travel further around the debuncher, and thus see a different phase of the accelerating RF cavity, compared to lower energy $\bar{p}$ s. Thus, the $\bar{p}$ s are gradually “debunched”, meaning that the temporal spread is increased whilst the energy spread is decreased. After ~ 1.5 s, the pulse of $\bar{p}$ s is moved to the accumulator, making space for the next incoming pulse. The accumulator “stacks” $\bar{p}$ s from the debuncher over a period of a few hours. During this time, the energy spread and transverse size of the beam are reduced using the method of stochastic cooling [3]. The $\bar{p}$ s are periodically transferred from the accumulator to the recycler, which sits on top of the main injector, and also uses the stochastic cooling method.

The $\bar{p}$ s are injected into the main injector which ramps their energy up to 150 GeV ready for injection into the Tevatron.

2.1.3 The Tevatron

Protons and antiprotons are transferred from the main injector to the Tevatron at 150 GeV. The Tevatron is a superconducting synchrotron accelerator which increases the beam energies to 980 GeV. Particles at the edges of the beam are removed by collimators. All magnets within the Tevatron lattice are cooled by liquid helium. Dipole magnets operate at 4.2 T, and maintain the circular orbit. There are 36 proton and 36 antiproton bunches, which cross every 396 ns. The D0 detector was originally designed for the much larger 3.6 μ s bunch spacing of Run I. Whilst allowing a significant increase in instantaneous luminosity, the shorter Run II bunch spacing required significant upgrades to the trigger and readout system, and still causes challenges in calorimetry as we shall see in Chap. 4. Close to the CDF and D0 detectors, superconducting “low beta” quadrupole magnets focus the beams towards a narrow collision region at the detector centres. Periods of beam collisions are referred to as “stores”, typically lasting around 10 h. The transition time in between stores is roughly 1–2 h.

2.2 The D0 Detector

Figure 2.2 shows the layout of the D0 detector. A detailed description of the detector can be found in Ref. [4]. D0 uses a right hand cylindrical coordinate system, where the z axis is along the proton direction, the y axis is upward, and the x axis points to the centre of the accelerator. The azimuthal and polar angles are denoted as ϕ and θ respectively. A vector pointing towards the centre of the accelerator defines $\phi = 0$, and ϕ increases anti-clockwise, such that $\phi = \pi/4$ points upwards. The pseudorapidity, η , is defined as $\eta = -\ln[\tan(\theta/2)]$. The region of small $|\eta|$ ($|\eta| < 1$, say) is typically referred to as “central”, and the region of larger $|\eta|$ as “forward”. In many situations it is more appropriate to use the detector pseudorapidity, η_{det} , which is defined by a line connecting the passage of a particle in a particular detector subsystem and the centre of the detector.

The following sections describe in more detail the specific detector subsystems which are used extensively in this work. Particular mention is made to regions in ϕ which are poorly instrumented: the central calorimeter module boundaries, and the muon system octant boundaries. The reduced lepton identification efficiencies in these regions requires careful treatment in the measurement of the Drell-Yan ϕ_η^* distribution described in Chap. 6.

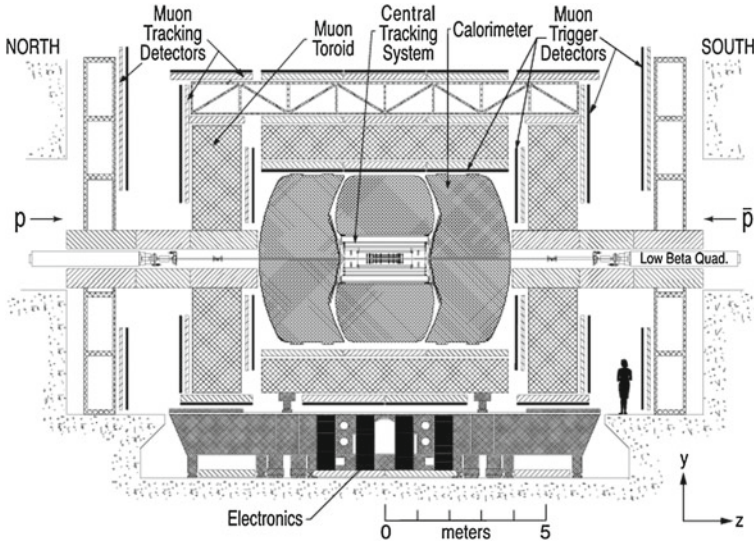


Fig. 2.2 Cross section through the D0 detector, viewed from the centre of the collider ($r - z$ plane). The major sub detector systems are labelled (from Ref. [4])

2.2.1 Inner Tracker

Figure 2.3 shows the layout of the inner tracker region of the detector. The two main components are the silicon microstrip tracker (SMT) and the central fibre tracker (CFT). The beam pipe is made from beryllium, with an outer diameter of 38.1 mm, length of 2.37 m, and thickness of 0.508 mm.

Figure 2.4 shows the layout of the SMT. A detailed description of the SMT can be found in Ref. [5]. The central region in z is covered by 6 barrels, interspersed with 6 so-called F-disks. The forward and backward regions each have a set of three F-disks and additional so-called H-disks. This (disk/barrel) design ensures that tracks generally meet a perpendicular surface, given a luminous region with a roughly a 25 cm wide Gaussian profile along the z axis.

It was decided to upgrade the SMT after Run IIa of the Tevatron ($\int \mathcal{L} dt \approx 1 \text{ fb}^{-1}$). The closest layer to the beam pipe (layer-1) was projected to suffer serious performance degradation due to radiation damage. A more “radiation hard” layer, the so-called layer-0, was inserted very close to the beam line, adding an additional tracking point, and maintaining vertexing capability whilst the layer-1 performance inevitably degrades. Details of the layer-0 upgrade can be found in Ref. [6].

Figure 2.5 shows a view of the CFT in the $r - \phi$ plane. The CFT consists of 8 cylinders, each of which contains one doublet layer of fibres in the beam direction and a second doublet layer at a stereo angle in ϕ of $+3$ or -3° . The outermost layer of the CFT covers the region up to $|\eta| \approx 1.7$. Wavelength shifting optical fibres transport light to visible light photon counters (VLPCs) located in cryostats

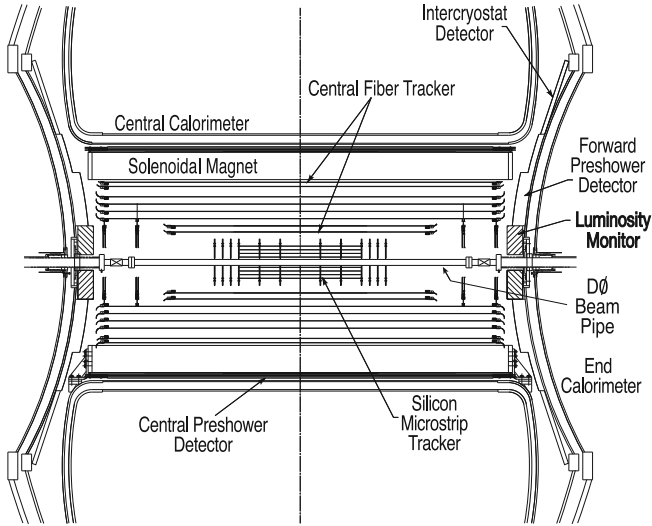


Fig. 2.3 View of the inner tracker region of the detector in the $r - z$ plane (from Ref. [4])

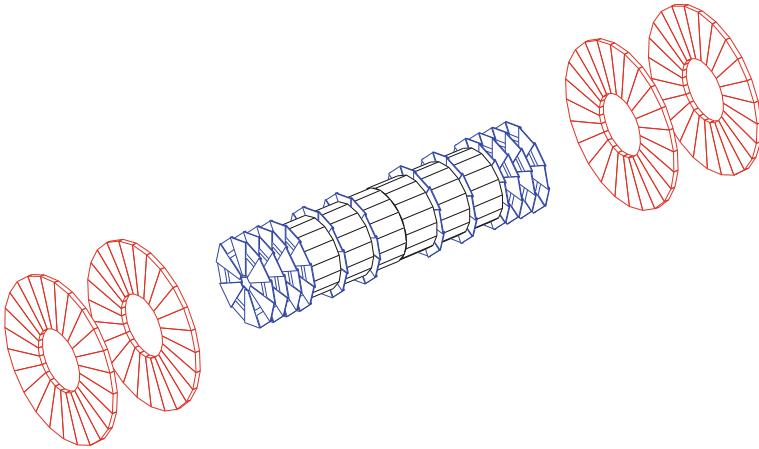
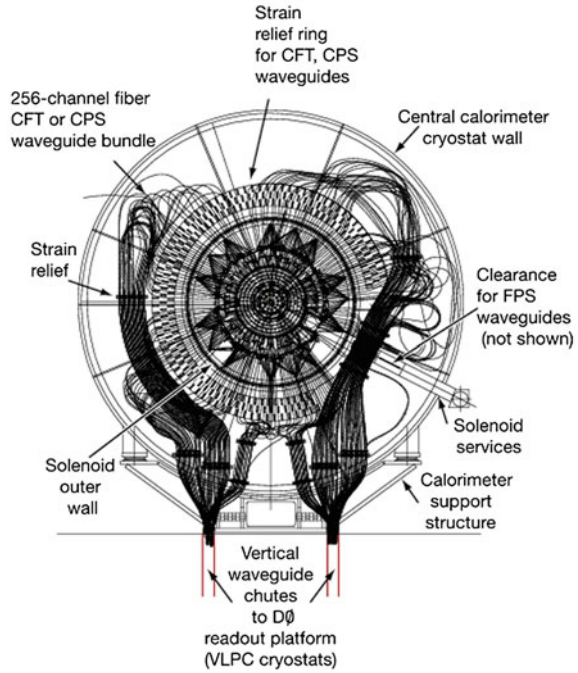


Fig. 2.4 Layout of the SMT (from Ref. [5]). The barrels are coloured black, F-disks in blue, and H-disks in red (Color online)

underneath the detector. The region $\phi \approx \pi/4$ requires longer fibres to reach the VLPC cryostats. We shall later see that this introduces a significant ϕ dependence of the track reconstruction efficiency.

A solenoidal magnet provides a field strength of roughly 2 T, and is designed to have a uniform field throughout its bore. In order to minimise the effect of detector charge asymmetries (e.g., due to mis-alignments) on physics analyses, the magnet polarity is reversed at regular intervals.

Fig. 2.5 End view of the central calorimeter and CFT waveguides that transport the scintillator light down to the VLPC cryostats underneath the detector (from Ref. [4])



Additional preshower detectors, the central preshower detector (CPS) and forward preshower detector (FPS) cover the regions $|\eta| < 1.3$ and $1.5 < |\eta| < 2.5$ respectively. The CPS sits between the solenoid and the central calorimeter. The FPS is mounted on the outside of the end cap calorimeter cryostat. Both preshower detectors share the same VLPC and readout technology as the CFT.

2.2.2 Calorimeter

Figure 2.6 shows an isometric view of the calorimeter, which is contained in three separate cryostats. The central calorimeter (CC) covers the region up to $|\eta| \approx 1.1$, and the two end caps (ECs) extend the coverage to $|\eta| \approx 4$. There are three layers: electromagnetic (EM), fine hadronic (FH) and coarse hadronic (CH). The region $1.1 < |\eta| < 1.5$ has little or no EM coverage, and limited hadronic coverage. This region is additionally instrumented with scintillator tiles, called the inter-cryostat detector (ICD).

Figure 2.7 shows the layout of a single calorimeter cell. Each cell alternates layers of uranium absorber (iron in the CH layers) and copper resistive plates with a high voltage (roughly 2kV) in between. The gaps between plates are filled with liquid argon. An electron takes on average 400ns to drift across the gap [7]. The average

Fig. 2.6 Cut away view of the calorimeter (from Ref. [4]). The three cryostats, and the different layers (*electromagnetic, fine and coarse hadronic*) are labelled

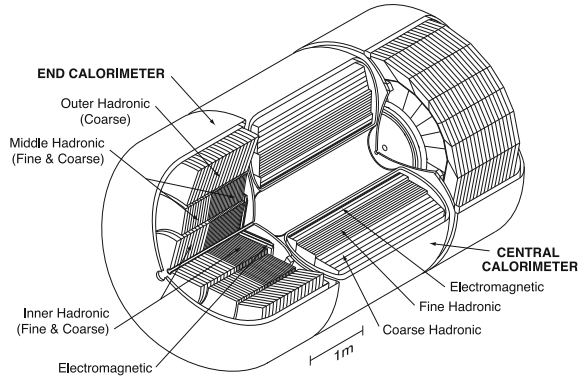
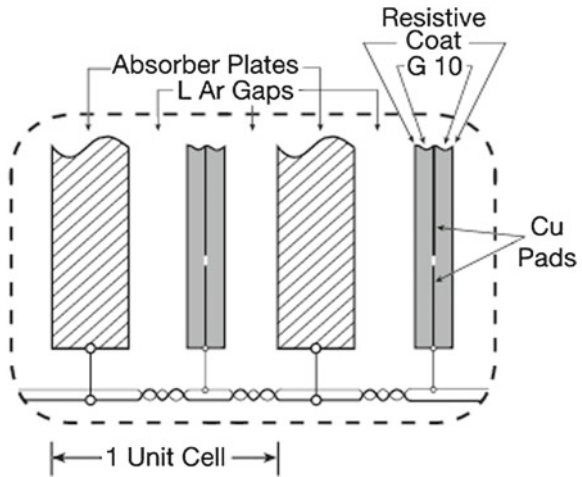


Fig. 2.7 Layout of a single calorimeter cell (from Ref. [4]). The absorber plates are grounded and the resistive plates are connected to a positive high voltage (roughly 2 kV)



electron drift time across the gap is comparable to the 396 ns bunch spacing in Run II of the Tevatron. Charge integration is therefore a significant problem.

The calorimeter cells are arranged such that “towers” of constant η can be drawn projecting from the centre of the detector through the centre of the cells. This “pseudo-projective” geometry is shown for one quarter of the calorimeter in Fig. 2.8. Cells have an angular size of $\Delta\eta = \Delta\phi = 0.1$, apart from the extreme forward region, where the cells are larger in $\Delta\eta$. In addition, cells in the third EM layer, corresponding to the shower maximum for electrons and photons, have a smaller size of $\Delta\eta = \Delta\phi = 0.05$ in order to improve the spatial resolution of electromagnetic cluster centroids.

There are four EM layers in both the CC and EC, with increasing absorber thickness (1.4, 2.0, 6.0, 9.8 X_0 in the CC and 1.6, 2.9, 7.9, 9.3 X_0 in the EC, where X_0 is one radiation length). In the EM layers, the absorber is almost 100 % pure depleted uranium. The FH layers use roughly 6 mm thick uranium-niobium alloy, and the CH layers use 46.5 mm thick copper (CC) or brass (EC) plates.

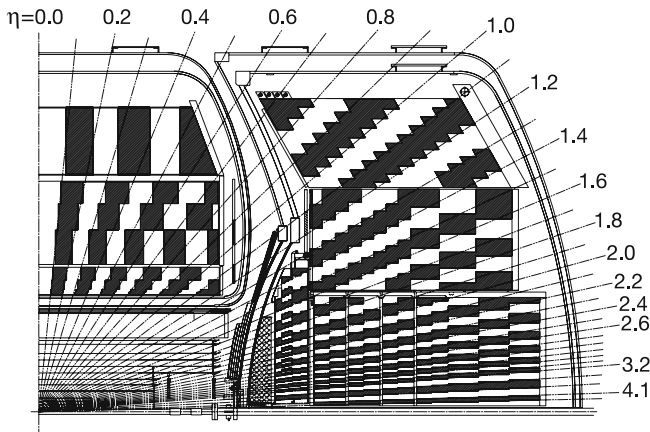


Fig. 2.8 Cross section of one quarter of the calorimeter, viewed from the side (from Ref. [4]). Notice the pseudo-projective geometry with constant cell size in $\Delta\eta$ (apart from the extreme forward region of the EC)

Cells are arranged in modules, one of which is shown in Fig. 2.9. In the CC, there are 32 EM modules, and 16 FH and CH modules, as shown in Fig. 2.10. The EM energy response is degraded near to the poorly instrumented CC module boundaries (ϕ -gaps). This is more problematic with the shorter Run II bunch spacing since the electric field is non-uniform near to the ϕ -gaps, leading to significant losses in charge integration. In Chap. 4, we determine corrections for these energy losses and improve the accuracy with which they are modelled in the MC simulation.

2.2.3 Muon System

Figure 2.11 shows an exploded view of the muon system, which is instrumented with wire drift tubes and plastic scintillator detectors. The wire chambers of the central ($|\eta| < 1$) muon system are called proportional drift tubes, and those of the forward ($1 < |\eta| < 2$) muon system are called mini drift tubes, due to their relative compact size. A 1.8 T toroidal magnet allows a momentum measurement that is independent of the central tracking system, and is used in the level-1 trigger (more later). The toroid polarity is regularly reversed such that roughly equal size datasets are recorded for the four combinations of solenoid and toroid polarities. The muon system is divided into three layers: the A layer sits inside the toroid, and the B and C layers sit outside the toroid. The central region underneath the detector is relatively poorly instrumented with muon detectors (particularly the A layer and C layer scintillators) to make space for the detector support structure and much of the readout hardware, including the VLPC cryostats described in Sect. 2.2.1. Both the central and forward muon systems

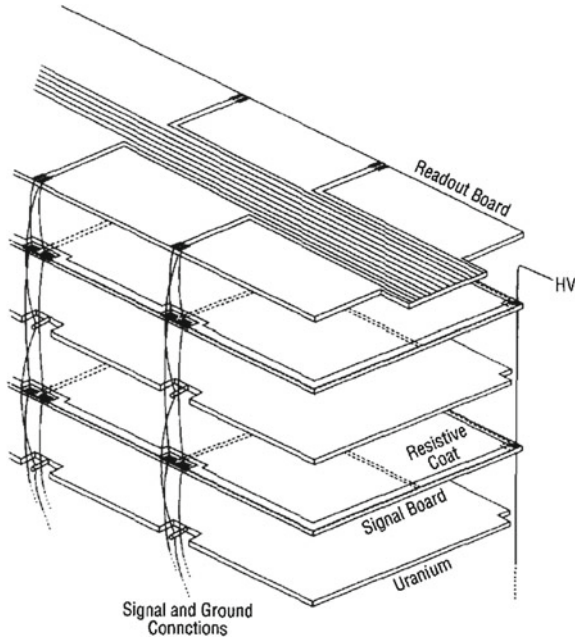


Fig. 2.9 View of a CC module, with the absorber, signal and readout boards labelled (from Ref. [4])

are divided into eight so-called “octants” in ϕ , with limited instrumentation in the boundaries separating the octants.

2.2.4 Trigger

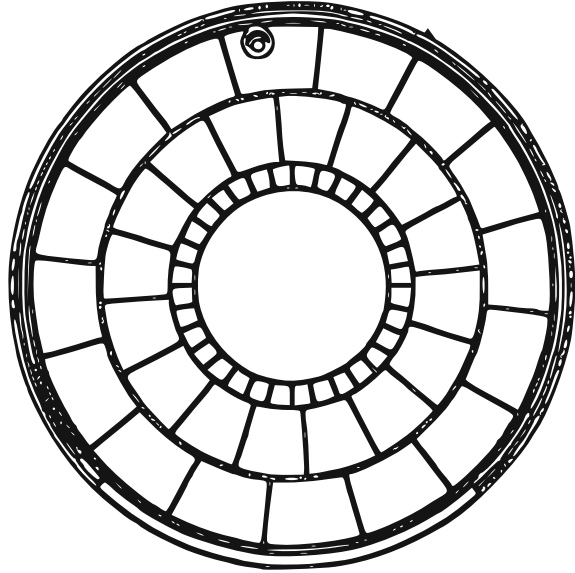
A three-level trigger system is required to reduce the event rate from the roughly 1.7 MHz bunch crossing frequency to around 200 Hz at which events can be recorded. The two analyses presented in this thesis mostly rely on triggers that require one or two high transverse momentum, p_T , electrons or muons.

Level-1 Trigger

The level-1 trigger is based on fast hardware decisions and reduces the rate to around 2 kHz.

- **Central track trigger (CTT)** The CTT looks for predefined patterns in the CFT, CPS, and FPS, consistent with the passage of a charged particle. A limited number of equations (96) for different p_T thresholds can be programmed into the readout.

Fig. 2.10 End view of the CC, showing the module structure (from Ref. [4])



- **Calorimeter trigger (L1Cal)** The L1Cal looks for individual towers above pre-defined E_T thresholds, for efficient triggering on high p_T electrons, photons and jets.
- **Muon trigger (L1Muons)** The L1Muons reconstructs track stubs with both scintillator and wire hits, or connects wire hits with seed central tracks from the CTT.

Level-2 Trigger

The level-2 trigger refines the energy and momentum measurements from level-1, and combines information from different detector sub-systems to make global decisions. Seed tracks from the L1CTT are fed to the L2 silicon track trigger (STT), which improves the momentum resolution of the CTT tracks. The STT is also able to reconstruct the impact parameter of tracks, which allows tagging of b -flavoured hadrons. A global L2 trigger combines information from all detector subsystems, to calculate object correlations, e.g., invariant masses of particle pairs. The event rate is reduced from 2 kHz to around 1 kHz.

Level-3 Trigger

The level-3 trigger fully reconstructs events using simplified versions of the offline software, and reduces the rate to around 200 Hz, at which events are recorded.

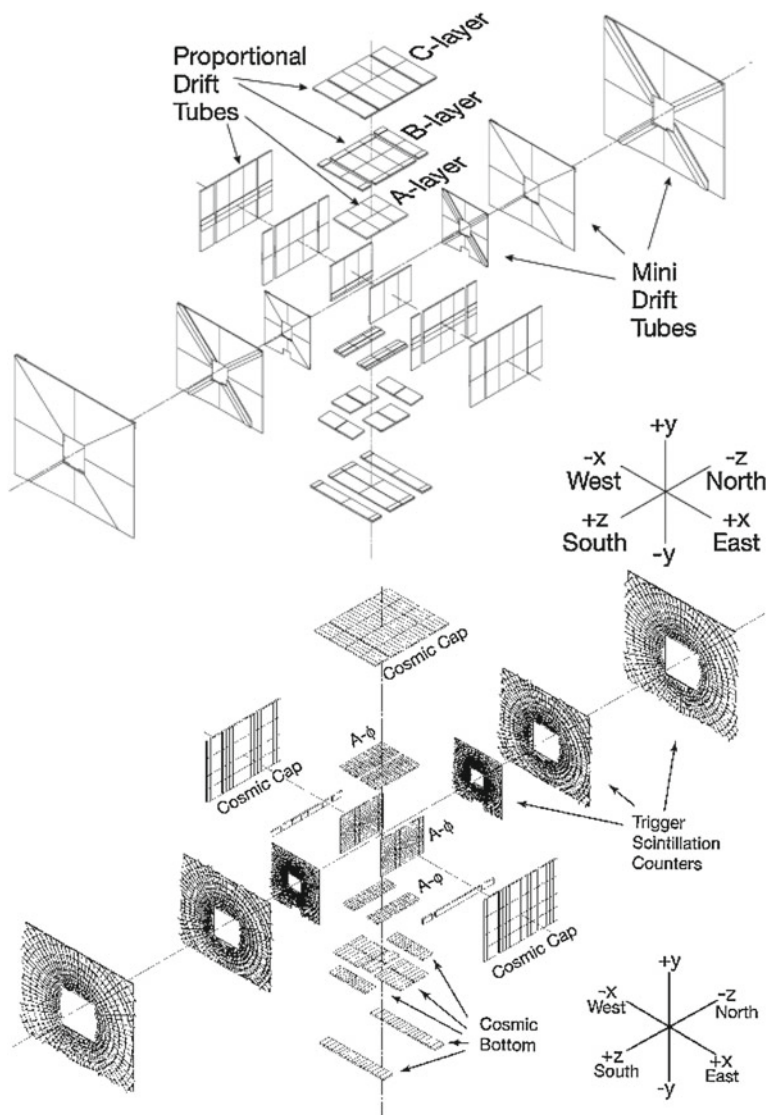


Fig. 2.11 Layout of the wire (*upper*) and scintillator (*lower*) muon detectors (from Ref. [4])

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