Chapter 3

Overview of Tracking

We now begin discussion of the tracking systems for the CDF Upgrade. In this chapter we describe the general context of tracking measurements in CDF, and our plan for the Upgrade. The individual detector components are described in detail in Chapters 4, 5, 6. The projected performance of the proposed system is described in Chapter 7.

3.1 History and Capability

Charged particle tracking has played a major role in almost every physics analysis done with the CDF detector.

The CDF Run I tracking system consisted of a Central Tracking Chamber (CTC), used to measure charged particle momenta, a vertex drift chamber (VTX) used to measure event z vertices, and a silicon vertex detector (SVX) used to detect secondary vertices. The CTC, designed for $\mathcal{L} = 10^{30}\text{cm}^{-2}\text{s}^{-1}$ and in use since 1987, has performed well up to luminosities of $2\times10^{31}\text{cm}^{-2}\text{s}^{-1}$. This detector provides 84 measurement points over the radial range of 31 to 132 cm, covering the $|\eta|$ range ≤ 1.0. The VTX, installed in 1992, makes time projection r-z measurements at radii inside of 31 cm to find the vertex z position, which is important for stereo pattern finding in the CTC.

Track reconstruction in the CTC is highly efficient for the detection of charged particles down to momenta of 300 MeV/c, with a momentum resolution of $\delta p_T/p_T^2 \leq 0.002(GeV/c)^{-1}$. When combined with beam constraint or inner silicon tracker information, this improves to $\delta p_T/p_T^2 \leq 0.001(GeV/c)^{-1}$ at high momentum.

The correlation of CTC tracks with EM calorimetry and muon chamber information is the basis of lepton identification. Correlation at the trigger level allows low p_T thresholds for efficient collection of top candidates, W boson decays, and high rate B physics triggers. At the offline level, more precise versions of this correlation, using shower position and E/p for electrons, and stub position and slope for muons give high purity, high efficiency lepton selection.

The CTC is also used for *in situ* calibration of the central calorimeter. A J/ψ peak, recorded with low p_T muon triggers is compared with the world average J/ψ mass to normalize the momentum scale of the tracking system. This calibration is transferred tower-by-tower to the EM calorimeter using the electron tracks in a large sample of inclusive electrons. The response of the hadron calorimeter is measured using a large sample of isolated tracks, and this is combined with test beam data to normalize the absolute scale. The scale of the hadron system is then checked against the EM calibration using events where a single jet recoils against a well-identified photon or a $Z \to e^+e^-$ decay.

In 1992, a silicon vertex detecor (SVX) was added to CDF. This device provided r-ϕ points with resolution of approximately 10 μm at four radii between 3 and 10 cm. For high momentum tracks the extrapolated impact parameter resolution is $\approx 15\mu$m. Midway through Run I, the SVX was replaced with a new device, SVX$'$, of similar geometry but using AC-coupled silicon detectors and a radiation-hard chip. In this report, "SVX" is sometimes used to refer to either of the Run I silicon devices.

Precise measurement of the track impact parameter and azimuth in the SVX is complementary to the precision measurement of p_T and dip angle in the CTC. The combination of these measurements allows the identification of secondary vertices in jets and the measurement of particle lifetimes and masses. This capability has been key to many of the Run I physics highlights at CDF:

- The ability to identify displaced vertices was crucial in the first direct observation of Top in 1994. The top samples isolated using the SVX b-tagging are very pure, with a signal to noise ratio of almost 4 to 1, and ultimately lead to accurate measurements of the $t\bar{t}$ production cross section and the top mass.

- The combined CTC-SVX tracking system has been used to isolate a number of exclusive B decays, including the world's largest sample of B$\rightarrow J/\psi K_S$ events. This decay will be used for a CP asymmetry analysis in Run II.

- The combined CTC-SVX system has been used to measure the lifetime and masses of B hadrons. Exclusive measurements at CDF are competitive with the combined results of the four LEP experiments.

3.2 Run I Tracking Strategy, and Shortcomings of the System

In Run I, the tracking strategy was fully dependent upon the performance of the CTC. Tracks were found in the CTC by first looking for segments in the axial super-layers. These segments were then linked together and an r-ϕ or 2D track was formed. Since each stereo super-layer had only 6 wires (compared to 12 in an axial super-layer), segment finding in these layers, in a manner similar to the axial super-layers, was not practical. Instead, attaching stereo hits to the r-ϕ CTC track required the additional external input of the z_0 supplied by the VTX. Once 3D tracks were found in the CTC, the resulting helix parameters were then used to extrapolate tracks into the SVX. Hits were attached to the CTC track in each layer of the SVX, beginning with the outermost. At each layer where a hit was found, the helix parameters were recalculated, and the search continued into the next innermost layer. This procedure leads to a multiplication of efficiencies, with the primary loss being track reconstruction efficiency in the CTC. In addition, association of an incorrect SVX hit with a CTC track results in large errors in the measured track parameters.

This tracking strategy produced excellent physics, but as we have gained experience with this system, we have come to understand its intrinsic weakness. Looking ahead, in addition to the expected deterioration in tracking performance at high luminosity, we realize the limitations are inherent to the basic design of both the SVX and CTC.

- **Length of the SVX:**
  Both the SVX and SVX$'$ detectors were 50 cm long. Since the $p\bar{p}$ luminous region can be described by a Gaussian of width $\sim$ 30 cm, many events are not contained, and the overall geometrical acceptance is only 60%. This has a direct impact on analyses which depend critically on B identification (such as the top analysis), but also has a broader impact.

  If the SVX had covered the entire luminous region, then a CTC track which could not be linked to hits in the SVX would most likely be a conversion (from material outside the SVX) or a daughter of a long-lived particle such as a K_S. The presence or absence of hits can thus be an integral part of the pattern recognition. With a short SVX this is not possible.

- **Too few layers in the SVX:**
  Ideally, one would like to find track segments in the SVX, and link these with tracks found in the CTC, instead of the present scheme of a tree search in the SVX within a road defined by the CTC track. The efficiency and the accuracy with which one finds segments will depend on the number of points used in defining the segment. Both the SVX and SVX$'$ detectors had four single-sided layers. The average hit efficiency for each layer was $\sim$ 90%, dominated by the gap between barrels. Therefore the probability for a track within the acceptance of SVX to have four or three measurements was $\sim$ 60%, and $\sim$ 30% respectively. Since any three hits define a circle, only combinations of four hits are useful for identifying track segments, and 60% is an unacceptably small tracking efficiency. In addition, with only four hits, the fraction of fake SVX segments (those with at least one hit incorrectly assigned) is quite high. Finally, due to the short lever arm, the resulting momentum resolution of such tracks is poor.

- **No stereo in SVX:**
  The SVX was a two-dimensional device, providing measurements in the r-ϕ plane only. The addition of the SVX information to a CTC track improved the determination of the impact parameter and ϕ_0 dramatically. Lack of a stereo

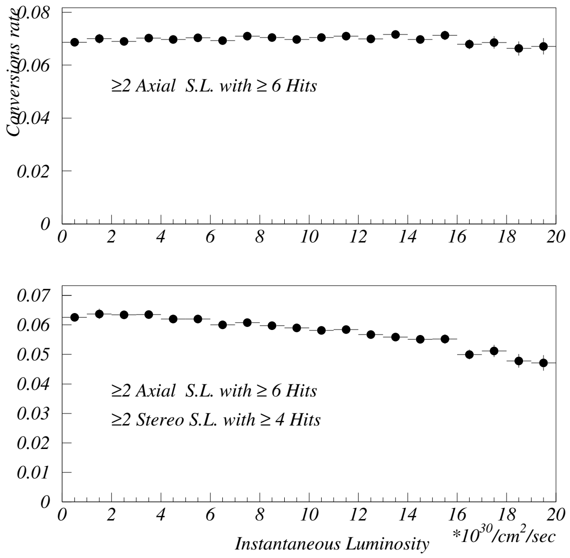

Figure 3.1: Conversion rate vs. luminosity in Run I.

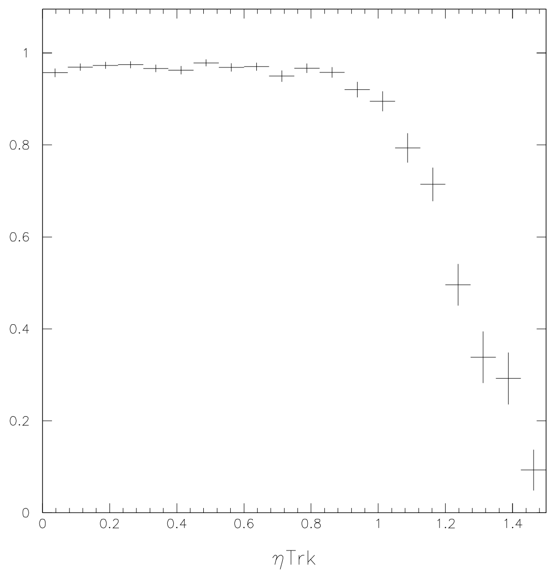

Figure 3.2: Tracking Efficiency vs. track η in CTC.

view in the SVX prevented similar improvement in the r-z parameters $\cot\theta$ and z_0.

- **Weak stereo in CTC:**
  The number of stereo measurements in the CTC is small, 24 out of the 84 total. These are arranged as four stereo super-layers of six wires each. In contrast, the CTC has five axial super-layers with 12 wires each. This choice lead to two effects. As mentioned above, the stereo view could not be completed without an externally supplied z_0. In addition, at high luminosity, the occupancy related efficiency loss on the inner stereo layers caused a significant decrease in 3D reconstruction efficiency. Figure 3.1 shows the rate of reconstructed conversion electrons as a function of instantaneous luminosity in Run I. In the upper plot we require at least two axial super-layers with six or more hits each. The rate is independent of luminosity up to 2×10^{31}. In the lower plot we apply the additional criterion of at least two stereo super-layers with four or more hits each. Now a decrease in efficiency with increasing luminosity is observed, demonstrating that the CTC performance is limited at high luminosity by the stereo reconstruction.

During Run I the only stand-alone tracker in CDF was the CTC. The SVX functioned only as a source of additional points to attach to tracks already found in the CTC, a particularly unfortunate arrangement in light of the fact that the SVX coverage extended to $\eta \geq 2.0$. In Fig. 3.2 we show the track finding efficiency vs η in the CTC. One can see a strong fall-off in efficiency at $\eta \geq 1.0$. Basically, at higher η tracks traverse fewer CTC layers, and the CTC pattern recognition has more difficulty reconstructing the track helix parameters. This affects many analyses. In the top analysis, approximately 40% of the acceptance in the lepton + jet channel is inaccessible due to inability to cleanly identify leptons with rapidity $\eta \geq 1.0$, and another 30% of the b-tagging in all events is lost because the b-jets are in this region.

A much more robust approach would be to have a tracking system with the ability to track not only from the outer tracker to the inner tracker, but also from the inner tracker to the outer. In what follows, we describe such a design.

3.3 Overview of the proposed system

CDF will upgrade the tracking system to accommodate the higher luminosities and shorter bunch crossing times planned for Run II and to correct the known limitations of our old system.

The proposed upgrades include a replacement of the CTC with a small cell, high luminosity variant - the COT, and a replacement of the SVX with a much more powerful silicon system. However, the baseline tracking configuration that we propose is extremely similar to that which worked successfully in Run I. It is a two component system comprising a silicon vertex detector at the smallest radii, and a large open cell drift chamber covering the radial range from 48 to 131 cm. Both of these detector types are well-proven technologies with which CDF has a great deal of experience. However, this system will have truly integrated pattern recognition and will almost double the tracking coverage.

The main parameters of the tracking system are summarized in Table 1.1 and reviewed briefly below in the context of our observations on tracking strategy. The component designs are described in detail in Chapters 4, 5, and 6, and a detailed study of the system performance is describe in Chap. 7.

- **Central Outer Tracker** The anchor of the Run II CDF tracking system is a large open cell drift chamber for charged particle reconstruction in the central region $|\eta| \leq 1.0$.

  The design goal of the COT is to reproduce the functionality of the CTC with drift times less than 100 ns by using smaller drift cells and a fast gas. The COT will use many of the construction techniques developed for the CTC, and occupies about the same volume. The basic drift cell will make 12 measurements along a radial track, but will have a maximum drift distance of ~ 0.9 cm. The CTC stereo deficiency will be removed by increasing the number of stereo measurements from 24 to 48. In the COT four axial and four stereo super-layers with 12 wires each will provide 96 measurements between 48 and 131 cm, using a total of 30,240 readout channels for the entire detector.

  The complete chamber is roughly 1.3% of a radiation length at normal incidence. The similarity of the device to the CTC is used extensively in our performance studies below, and also has a very practical impact in the economies of construction time, expense, and code development.

- **SVX II+ISL** For Tevatron Run II, we propose a "second-generation" silicon detector which is optimized for the CDF/Tevatron environment. SVX II is composed of three cylindrical barrels with a total length of 96 cm. It covers $\sim 2.5\sigma$ of the luminous region, raising the geometrical acceptance for b-tagging from the present 60% to almost 100%. Each barrel supports five layers of double-sided silicon microstrip detectors between radii of 2.4 and 10.7 cm. One side of all layers is r-ϕ; on the other sides three layers are r-z and two are small angle stereo.

  The Intermediate Silicon Layers (ISL) use similar technology to that of SVX II, from the silicon itself, through the readout electronics. In the central region, a layer of double-sided silicon is placed at a radius of 22 cm. In the region $1.0 \leq |\eta| \leq 2.0$, two layers of double-silicon are placed at radii of 20 cm and 28 cm. All layers make an r-ϕ and a small angle stereo measurement.

This system of COT+SVX II+ISL addresses all of the shortcomings of the Run I configuration mentioned in the previous section:

- The inner detectors, SVX II+ISL, cover the entire luminous region.

- The inner tracker now has stand-alone capability, with 6 layers in the central region, and 7 in the forward region. With at least 6 possible measurements there is very good efficiency for $\geq$ 5, where the signal to noise ratio for stand-alone segments is very good.

- All of the silicon layers have stereo capability.

- The stereo capability of the outer tracker, the COT, is doubled in comparison to the CTC.

With this system, we can envision two primary tracking scenarios:

- COT+ISL+SVX II:
  In this case, we can get a good estimate of the tracking performance based on our current experience. However the SVX II+ISL will form an additional "anchor" for track finding, hence boosting tracking efficiency, as well as track resolution.

- ISL+SVX:
  This is a new feature. It allows tracking at high rapidity, and addresses the fact that many analyses suffer from the fall-off in tracking efficiency at $|\eta| \geq 1$. All of the capability described in Section 3.1 previously possible only in the central region, can now be extended to the plug region.

Comparisons of this system proposed for Run II with the system we actually used for Run I demonstrate that the Run II tracking system, if used with Run I algorithms, will perform at least as well as our Run I system. However, the new system is much more powerful. In Run I, we could find tracks in the COT and extrapolate inwards, but for Run II we will be able to link to *segments* not just individual hits in the SVX II + ISL system. In addition, we can envision finding track segments in the six (or seven) layer SVX II + ISL, and then extrapolating these outward to link with segments found in the COT. In the forward region, where there is no COT, seven silicon points give a good stand-alone momentum measurement. The rapidity coverage of the COT + ISL + SVX II system should almost double compared to that of Run I, with efficient and precise tracking out to $|\eta| \leq 2$.

Instead of a tracking strategy which is critically dependent on the performance of the outer tracker, CDF II will use a truly integrated tracking system, described in the next four chapters.