Chapter 2

Physics Goals

2.1 Overview

In this chapter we will outline the physics prospects of CDF II at the Tevatron + Main Injector, and the connection between the physics and the detector design. Our physics plan encompasses five complementary lines of attack on the open questions of the Standard Model:

- characterization of the properties of the top quark
- a global precision electroweak program
- direct search for new phenomena
- tests of perturbative QCD at Next-to-Leading-Order and large Q^2
- constraint of the CKM matrix with high statistics B decays

This physics program is comprehensive in its methods and its scope. It has classic precision measurements, such as m_W and α_s, taken to a new level of accuracy; it has a survey of newly discovered territory, in the first complete study of the top quark; and it extends our reach for new phenomena into a regime where current theoretical speculation suggests new structure. We believe that power of the CDF II detector combined with the sensitivity of the Run II data sets will result in a significant advance in our understanding of the behavior of matter at high energy, if not outright discovery of new physics beyond the Standard Model.

In this chapter we will justify this claim. We begin with a summary of our conclusions and then turn to each of the five topics in detail. Since CDF II re-uses or extends many of the same detector technologies and strategies as its predecessor, the physics analyses of Run II will employ many of the techniques refined during Run I. The physics projections and detector specifications will therefore frequently appeal to a brief review of the current status. We note in this vein that our conclusions have the power of direct extrapolations from a well tuned device in a well measured environment.

2.1.1 Summary of CDF II Physics

Table 2.1 shows the expected yields for some benchmark processes with 2 $\text{fb}^{-1}$of Tevatron collisions recorded by the CDF II detector. These are the numbers of identified events available for offline analysis. The statistical precision of Run II, combined with capability of the CDF II detector, will provide rich programs of measurement in each of the five sub-fields, summarized below.

2.1.1.1 Properties of the Top Quark

A sample of almost 1,000 b-tagged, identified events will allow a detailed survey of the properties of the top quark. A review of this program is given in Section 2.2.

The top mass will be measured with a precision conservatively estimated to be 3.5 GeV/c^2. The total cross section will be measured to 9%, and non-standard production mechanisms will be resolvable down to total cross sections of $\sim$ 90 fb. The branching fraction to b quarks will be measured to 3%, decays to non-W states may be explored at the level of 9%, and branching ratios to the various W helicity states will be measured with uncertainties of order 5%. The magnitude of any FCNC decay will be probed down to branching fractions of 1% or less. We will isolate the electroweak production of single top, allowing determination of , $(t \rightarrow Wb)$ to 26%, and inference of $|V_{tb}|$ with a precision of 13%.

Mode	Yield (2 fb^{-1})
TOP	
dilepton	150
$W + 3j * b$	900
$W + 4j * b$	725
$W + 4j * bb$	180
VECTOR BOSONS	
$W \rightarrow l\nu$ (e,μ)	4.3M
$Z \rightarrow l^+l^-$(e,μ)	600K
$W\gamma, W \rightarrow e\nu$	4.0K
$Z\gamma, Z \rightarrow e^+e^-$	1.8K
$W^+W^- \rightarrow l\nu l\nu$	200
$W^+Z^- \rightarrow l\nu ll$	50
QCD	
j + X, $|\eta| \leq 1.0, E_T \geq$300 GeV	6.4K
jj + X, $M_{jj} \geq$ 600 GeV	30K
γ + X, $p_T(\gamma) \geq$ 25 GeV	6.0M
$\gamma\gamma$ + X, $p_T(\gamma_1, \gamma_2) \geq$ 12 GeV	14 K
$W+ \geq 1j$, $E_T(W) \geq$ 100 GeV	10K
$Z+ \geq 1j$, $E_T(Z) \geq$100 GeV	1.0K
B	
$B^0 \rightarrow J/\psi K_S$	15K
$B^0 \rightarrow \pi^+\pi^-$	10K
$B_s \rightarrow J/\psi\phi$	9K

Table 2.1: Representative yields for known processes, after selection. We use the CDF Run I selections modified for increased coverage of the CDF II detector (see text) and we assume 2.0 TeV collisions. $j \equiv$ jet, and $j*b \equiv$ b-tagged jet.

The final top physics program will undoubtedly be richer than this list, which should be interpreted as a catalog of probable sensitivities for the baseline top survey and whatever surprises the top may have in store.

2.1.1.2 A Precision Electroweak Program

The study of the weak vector bosons at the Tevatron is anchored in the leptonic decay modes. The new plug, intermediate muon system and integrated tracking will give triggerable electron coverage out to $|\eta| = 2.0$, triggerable muon coverage out to $|\eta|$ of at least 1.2 and taggable muon coverage out to $|\eta| = 2.0$. This will double the number of $W \rightarrow e\nu$ events and *triple* the acceptance for Z's and dibosons in the electron and muon channels. A data set of 2 fb^{-1}in combination with the acceptance and precision of the CDF II detector results in the comprehensive program in electroweak physics discussed in detail in Section 2.3.

One of our main goals is the measurement of m_W with a precision of $\pm$40 MeV/c^2. The combined precision on m_W and m_{top} will allow inference of the Standard Model Higgs mass m_H with precision of $\sim 2m_H$.

The W decay width, , $_W$ will be measured to 30 MeV, a factor of six improvement on the LEP-II expectation. The precision on A_{FB} at the Z^0 pole will be adequate to measure $sin^2\theta_W^{eff}$ to comparable precision to LEPI and SLD, and measurement off the pole will be sensitive to new phenomena at high mass scales. Limits on anomalous WWV and ZZγ couplings, bolstered by the forward tracking and lepton identification, will be comparable and complementary to those of LEP-II. The W charge asymmetry measurement, also augmented by unambiguous lepton ID in the plug region, will provide much improved constraints on parton distribution functions.

2.1.1.3 Search for New Phenomena

At the Tevatron+Main Injector, CDF II will search for new objects at and above the electroweak scale. There is at present a great deal of theoretical activity focussed on new phenomena in this regime, with predictions from models invoking supersymmetry, technicolor, and new U(1) symmetries. The magnitude of the top quark mass and speculation about an excess in the top cross-section have led to other theoretical predictions about phenomena well within our reach in Run II, such as topcolor. Search strategies for these and other models are discussed in Section 2.4.

We will be sensitive to charginos up to 130 GeV/c^2, to gluinos up to 270 GeV/c^2, and to stop squarks up to 150 GeV/c^2. Second generation lepto-quarks can be observed up to masses of 300 GeV/c^2, new vector bosons can be probed up to masses of 900 GeV/c^2, and excited quarks up to 800 GeV/c^2. Quark compositeness can be observed up to a scale of approximately 5 TeV. These are all model dependent limits, and, as in the case of the top survey above, we believe that our catalog of prospects here is best interpreted as a list of probable sensitivities for the real surprises waiting at the electroweak scale.

2.1.1.4 Precision QCD at Large Q^2

The QCD sector of the Standard Model will be stringently tested using the production and fragmentation properties of jets, and the production properties of W/Z bosons, Drell-Yan lepton pairs, and direct photons. We will evaluate the precision of QCD calculations beyond leading order (higher order perturbative calculations and soft gluon resummation corrections), and determine the fundamental input ingredients, namely parton distribution functions and the running coupling constant α_s.

The precision of QCD measurements at CDF II with 2 fb^{-1}will provide sensitivity to many sources of new physics. For example, the strong coupling constant α_s will be measured over the entire range $(10\text{'s}\, GeV)^2 < Q^2 < (500\, GeV)^2$, and deviations from the Standard Model running could signal loop contributions from new particles. A direct search for the substructure of quarks at the level of 10^{-19}m will be possible with high E_T jets and the production angular distribution of di-jets. Finally a broad range of searches will be carried out for the decays of massive particles to various combinations of jets, W/Z bosons, photons and neutrinos via missing E_T. A survey of the sensitivity of these QCD studies to new physics is presented in Section 2.5 of this report.

2.1.1.5 Constraining the CKM Matrix

CDF II plans to take advantage of the copious production of the various species of b hadrons at the Tevatron to make measurements which will test the consistency of the Standard (CKM) Model of weak quark mixing and *CP* violation. By extending the capabilities developed in Run I into Run II, CDF II expects to be able to measure *CP* asymmetries in $B^0 \to J/\psi K_S$ and $B^0 \to \pi^+\pi^-$ decays with a precision comparable to the e^+e^- colliders. Complementary information will come from a sensitive search for *CP* violation in $B_s \to J/\psi\phi$ decays. The effects of mixing in the $B_s^0 - \bar{B}_s^0$ system will be measured, allowing a determination of the ratio of CKM elements $|V_{td}/V_{ts}|$ over the full range allowed by the Standard Model.

In addition CDF II will continue to improve the precision on measurements of b hadron decay properties (*e.g.* B^0 vs. B^+ lifetimes) and pursue the observation and study of rare decays (*e.g.* $B^0 \to K^{*0}\mu^+\mu^-$). The physics of heavier b hadrons, for instance B_c, will be the exclusive domain of the Tevatron collider for at least the next decade. An overview of CDF II expectations for B physics in Run II is given in Section 2.6.

2.1.2 Physics and Detector

Exploitation of the statistical precision available in Run II will depend heavily on a thorough understanding of the detector. Two aspects are critical: the identification of objects that make up each signature, and the understanding of the calibration and resolution of the detector.

The objects for which we have already a good understanding of the efficiencies and fake-rates are those for which tracking is essential: electrons, muons, tau's, b's, and photons (*i.e.*, a high confidence of the absence of a track), all in the central region. Much of our discussion below concerns our ability to maintain, improve, and extend tracking capabilities pertinent to each of the physics objects.

Similarly, the energy scale and resolutions of the calorimeters, critical to the reconstruction of masses, are well understood in the central region, where the precision tracking information can be used to calibrate the calorimeters. This calibration procedure relies on an interlocking set of samples and capabilities, and exemplifies the power of the "general purpose" strategy (see Sec. 1.3.2). Further description of the calorimeter calibration can be found in Sec. 3.1.

In CDF II, the integrated tracking, the new plug calorimeter, and the intermediate muon system will extend the 'good' region where tracking is robust for e, μ, τ, γ and b identification, and will provide the precision calorimeter calibration out to $|\eta| = 2$.

2.1.3 Detailed Discussion

The scientific prospects for CDF II are discussed in more detail in the following sections of this chapter.

The physics opportunities detailed here provide much of the rationale for the CDF II Upgrade design choices, and the discovery prospects detailed here underscore our excitement about completing this upgrade and returning to high luminosity data taking at the Fermilab Tevatron Collider as quickly as possible.