Prospects of Heavy Quark Physics in Run II with the DØ Detector

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After a successful Run I, DØ is poised for an encore performance in Run II. This article summarizes the essential features of the DØ upgrade that involve a central magnetic field, a new tracking system, upgraded muon detection, and enhancements to muon, calorimeter and the data acquisition electronics. The goals for top quark physics for Run II are outlined along with issues affecting the precision measurement of top quark mass and single top quark production. The prospects and issues determining the B physics capabilities of DØ in Run II are addressed briefly and a study of the CP sensitivity in the mode $B_d^0 \to J/\psi K_s^0$ is also presented.

1. INTRODUCTION

DØ had a very successful Run I. While the analysis of data is still in progress, DØ has already made many important contributions in heavy quark physics (top and beauty), electroweak physics, strong interactions and physics beyond the Standard Model. It has been credited (along with CDF) with the discovery of top quark and measurement of its mass (172.1 ± 7.1 GeV/c^2) and production cross section ($\sigma_{t\bar{t}} = 5.9\pm$ 1.7 pb) [1]. Along with measurements of b-quark production and precision tests of QCD (jet productions, color coherence, rapidity gaps), important electroweak parameters (W boson mass and width, trilinear gauge couplings) have also been measured. Some of the world's best limits on new phenomena such as supersymmetry and monopoles have been set by DØ [2].

After an overview of the DØ upgrade in Section 2, the top physics goals for Run II are described in Section 3. The prospects for B physics, including measurement of CP violation are examined in Section 4.

2. THE DØ UPGRADE

The DØ Run II upgrade is aimed at enhancing physics opportunities at high p_T (precision measurements of M_W, m_t, Higgs search) and developing capabilities at low p_T for B physics. This will also improve the search for new phenomena such as SUSY and quark substructure.

For Run II, the Main Injector at Fermilab will become operational and the Tevatron parameters will be significantly different [4]. The instaneous luminosity will change from $1 - 2.5 \times 10^{31}$ to $1 - 2 \times 10^{32}$. Meanwhile, the bunch crossing time will evolve from 3.5 μs to 396 ns at the beginning of Run II to 132 ns at the end. The high interaction rate will impact on event pile-up and radiation damage of the detectors. Many systems must therefore be either upgraded (the calorimeters, muon detection, trigger and the data acquisition) or replaced (the tracking system). The solutions involve new detector technologies such as Silicon Microstrip detectors, Scintillating Fiber tracking and faster electronics.

The DØ upgrade also involves significant improvements to the muon detection system. There are three layers of scintillator pixel counters for additional forward coverage, and two layers of pixel counters in the central region for trigger enhancement and redundancy. The forward Proportional Drift Tubes have been replaced by new Mini Drift Tubes with increased granularity and coverage to $|\eta| = 2$. Additional shielding is added to reduce the background from particles scattered by the beam pipe, low beta quadrapoles or the calorimeter walls. The calorimeter readout system is replaced by faster electronics with an order of magnitude improvement in bandwidth.

2.1. Tracking System

The tracking system for Run II consists of four major components: The Silicon Microstrip

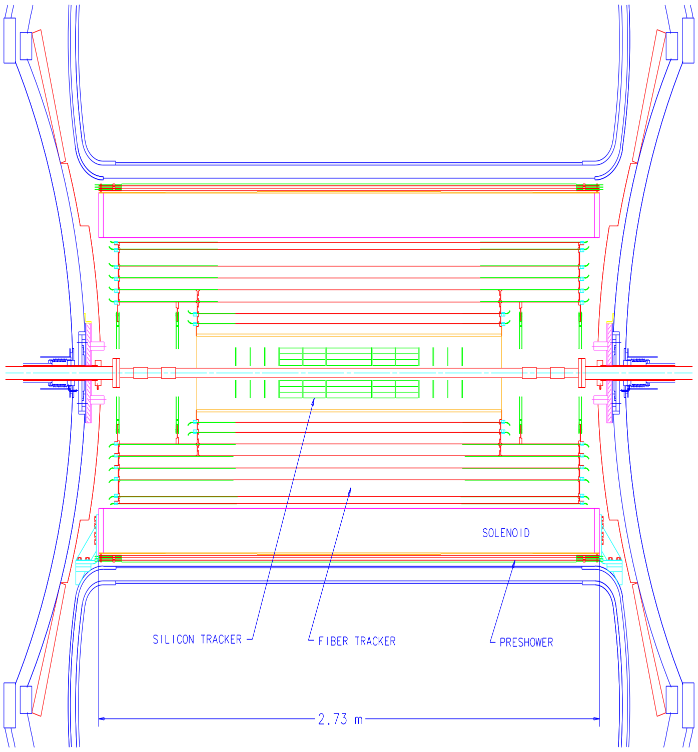

Figure 1. Schematic cross sectional view of the new tracking elements for the DØ Run II detector.

Tracker, The Scintillating-Fiber (Sci-fi) Tracker, The Preshower Detector and The Solenoid. These are illustrated schematically in Figure 1.

The silicon tracker consists up of 6 modules, each made up of 4 layers parallel to the beam axis (barrels) and 12 interspersed double-sided disks perpendicular to the beam. The layers 2 and 4 are composed of double-sided silicon devices with 2^0 stereo angle strips. While the layers 1 and 3 are made of double-sided 90^0 stereo strips on the inner four modules, those of the 2 outer modules contain single-sided devices with axial strips. For additional coverage in the forward region ($|\eta| \approx 3$), there are 8 larger H-disks for a total of over 800,000 channels. The silicon wafers are designed to operate at a maximum temperature of 15^0C for a radiation hardness of 1 Mrad and are read out with 128-channel SVX IIe chips [3].

The fiber tracker surrounding the silicon detectors is designed to provide momentum measurement and track reconstruction up to $|\eta| = 1.7$, and a first level trigger. The Sci-fi tracker is made of 74,000 (835 μm) scintillating fibers mounted on 8 concentric cyclinders at radii from 21-52 cm. Each of the eight concentric cycliders has two axial layers and two layers oriented at an angle of $\pm 2^0$ depending on the super layer. The sci-fi tracker is readout using new visible photon light counters (VLPC) [5] with a response time of $\tau <$ 100 ps, and quantum efficiency $\approx$ 80%.

The central preshower detector provides fast energy and position measurements for the electron trigger and for offline use. This consists of 6 (u, v, and axial) planes made up of 6,000 triangular scintillator strip channels. The 16,000 channel forward preshower ($1.4 < |\eta| < 2.5$) detector provides a factor of 2-4 rejection for the electron trigger. Both the central and forward preshower detectors are read out using VLPCs.

Finally, the 2T field central superconducting solenoid will enhance calorimeter calibration, electron identification, improve b tagging at low p_T and provide full reconstruction of B mesons.

2.2. The Upgrade Performance

The combination of silicon microstrip detectors and the scintillating fiber tracker will greatly enhance track reconstruction and identification of secondary vertices. The secondary vertex resolution is expected to be 40 μm in r-ϕ and 100 μm in r-z, thereby providing momentum resolution of $\delta p_T/p_T$ = 5% (18%) for p_T = 10, (100) GeV/c. Also, the addition of a silicon track trigger has high potential for improving b tagging.

The upgraded muon system will allow lower thresholds for single muon trigger to p_T of ≤ 4 GeV/c and for dimuon trigger down to p_T of < 3 GeV/c. The improved muon detection and additional shielding will reduce backgrounds subtantially.

With newer electronics, the calorimeter is expected to have comparable performance to that in Run I and allow calibration in *situ* using energy/momentum discrimination for electrons. The data acquisition rate will be an order of magnitude higher in bandwidth reaching up to 10 kHz at L1, 800 Hz at L2, and 10-20 Hz to tape.

3. THE GOALS FOR TOP QUARK PHYSICS IN RUN II

The goals for top quark physics in Run II are defined by the following factors. The top cross section goes up by 40% as the Tevatron energy increases from 1.8 to 2.0 TeV. A factor of 20 gain in integrated luminosity is expected from the Main Injector and other improvements. The lepton p_T resolution and muon tagging efficiency will improve by at least a factor of 2. Magnetic tracking and advances in the algorithm will provide needed enhancements to τ identification. Table 1 provides a summary of projected yields of top events in different channels for $\int \mathcal{L}\, dt = 2$ fb^{-1}.

3.1. Measurement of the Top Quark Mass

In Run I, the top quark mass measurement is limited by both statistics ($\pm$ 5.2 GeV/c^2) and systematics ($\pm$ 4.9 GeV/c^2). The systematic uncertainity is dominated by the jet energy scale (4.0 GeV), modeling of background (2.5 GeV) and Monte Carlo (1.9 GeV). But in Run II, the mass measurement will be limited mostly by systematic uncertainties. The systematics can be improved by means of: (a) calibration of the jet energy scale using data: $Z + jet$, $\gamma + jet$, $W \rightarrow jj$, (b) reduction of jet combinatorics by using events with 2 b-tags, and (c) constraining top-production models using data.

The expected uncertainity on the top quark mass (3 GeV/c^2) in Run II will be from statistics (1 GeV/c^2), jet energy scale (2.6 GeV/c^2), Monte Carlo modeling of the top quark production (1.9 GeV/c^2), and backgrounds (0.5 GeV/c^2). The precise determination of the mass of the top quark combined with the W-boson mass provides more stringent constraints on the mass of the Higgs as shown in Figure 2.

3.2. Single Top Quark Production

The study of electroweak production of single top is important for several reasons: (a) The direct meaurement of the width of the top quark; (b) V_{tb} can be measured directly because the cross section $\sigma(q\overline{q} \rightarrow tb)$ is proportional $|V_{tb}|^2$; and (c)

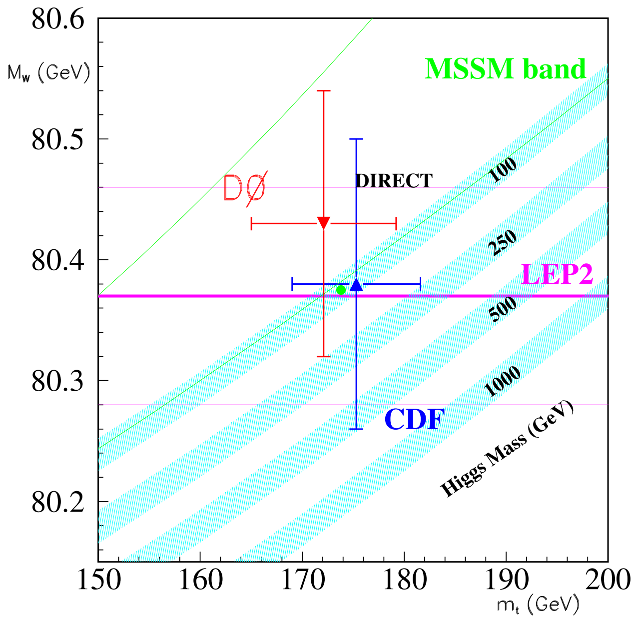

Figure 2. Constraint on Higgs mass from Run I DØ, CDF and LEP2 (indirect) top quark mass measurements.

can provide a cross check for the top quark mass measurement because of fewer uncertainties from multi-jet combinatorics.

In Run II, for $\int \mathcal{L}\, dt = 2$ fb^{-1}, the following measurements can be made: (1) σ(single top) to a precision of 19%, (2) $\Gamma(t \rightarrow W+b)$ to a precision of 27%, and (3) $|V_{tb}|$ to a precision of 14%.

3.3. Top Physics: Run II Topics

For a top quark sample of over 2,000 reconstructed $t\overline{t}$ events, a rich variety of measurements can be made. We expect to measure the Wtb vertex coupling to $\delta B(t \rightarrow bW_{long}) \approx 3\%$ and probe the signature of physics beyond the Standard Model. As the top quark decays before hadronization, spin correlations in the decay products can be investigated. The measurement can be used to set a lower limit on the width of top quark. Besides measuring branching fractions, rare top quark decays will be sought, such as listed below [6]:

Standard Model:
(1) $t \rightarrow Wb + g/\gamma$ (g/γ angular distribution)

Table 1
The expected yields of top events in Run II for $\int \mathcal{L}\, dt = 2$ fb^{-1}.

	Event Yield	Signal:Bkg.
Dilepton channels	200	5 : 1
Lepton + ≥ 3 jets / b tag channels	1400	3 : 1
Lepton + ≥ 4 jets / $b - \bar{b}$ tags channels	600	12 : 1
Single top (all channels combined)	330	1 : 2

(2) $t \to Wb + Z$ (near threshold)
(3) $t \to Wb + H^0$
Non Standard Model:
(1) $t \to c/u + g/\gamma$ (FCNC)
(2) $t \to c/u + Z$ (FCNC)
(3) $t \to c/u + H^0$ (FCNC)
(4) $t \to H^+ + b$ (SUSY)
(5) $t \to \tilde{\tau} + \tilde{Z}$ (SUSY)

4. THE PROSPECTS OF BOTTOM-QUARK PHYSICS IN RUN II

Despite the lack of a central magnetic field and silicon vertex detector, DØ has made significant contributions to B physics in Run I. The J/ψ [7] and inclusive $b-$quark production cross sections have been measured in the central and forward regions. Their dependence with rapidity and energy has also been studied [8]. For example, the rapidity dependence of the inclusive cross section is shown in Figure 3. Recently, a search for the rare B decay $b \to X_s \mu^+ \mu^-$ has yielded a branching limit of $< 3.2 \times 10^{-4}$ at 90% CL [9].

4.1. Projected Measurements for Run II

The DØ upgrade impacts all areas of B physics, including triggering, reconstruction and b tagging. With a $b\bar{b}$ production cross section close to 100μb at $\sqrt{s} = 2.0$ TeV, a huge number of b's are produced in the detector allowing a variety of B physics studies in Run II. A few of the possible measurements are:

- Masses and lifetimes of $B^{\pm}$, B^0, B_s, B_c, and Λ_b hadrons.

- Time integrated CP asymmetry in $B_d^0 \to K_s^0 + J/\psi$ decay can provide the angle β of the CKM unitary triangle.

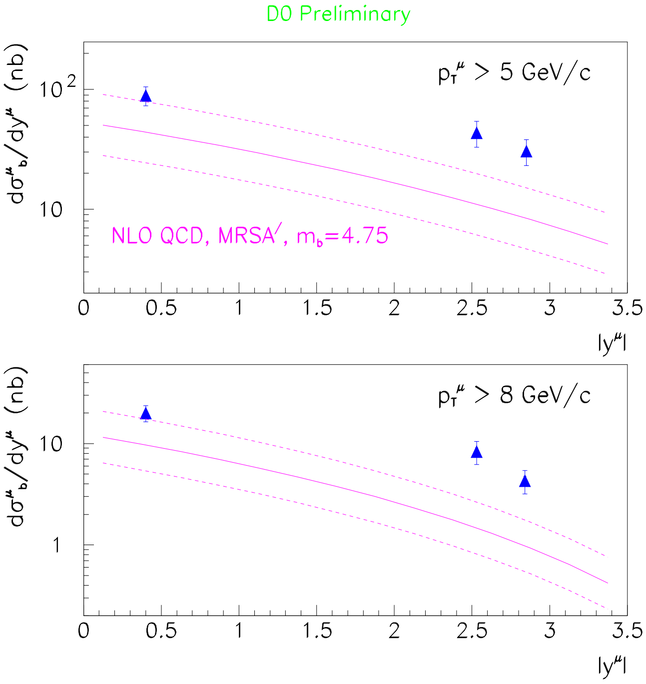

Figure 3. The differential muon cross section from b production as a function of muon rapidity. The observed results are 2 times (central region) and 4 times (forward region) higher than theoretical predictions.

- Search for B_s mixing in $B_s^0 \to D_s + n\pi^{\pm}$ or $B_s^0 \to D_s^- + l^+ + X$ decays.

- Search for rare B meson decays such as $b \to X_s \mu^+ \mu^-$ and $B \to \mu^+ \mu^-$.

4.2. CP Asymmetry Study: $B^0 \to J/\psi\ K_s^0$

Much effort is presently focussed to understand and enhance the CP sensitivity in the mode $B^0 \to J/\psi K_s^0$ in Run II. An estimation of the sensitivity for measuring sin2β is given below. The observed asymmetry A_{obs} is given by [10]:

$$A_{obs} = D_{mix} D_{tag} D_{bkg} A_{CP} \qquad (1)$$

$$A_{CP} = \frac{N(B_d^0 \to \psi K_s^0) - N(\overline{B}_d^0 \to \psi K_s^0)}{N(B_d^0 \to \psi K_s^0) + N(\overline{B}_d^0 \to \psi K_s^0)} \qquad (2)$$

$$= -D_{t-int} \sin 2\beta \qquad (3)$$

where the dilution factors $D_{mix} = 0.73$, $D_{tag} = 1 - 2p_{mistag}$, $D_{bkg} = \sqrt{S/(S+B)}$. The time integration asymmetry D_{t-int} is given by $x_d/(1+x_d^2)$ where x_d is the mixing parameter for B_d mesons when the time integration starts at $t = 0$. Then the sensitivity for measuring $\sin 2\beta$ is:

$$\delta(\sin 2\beta) = \frac{1}{D_{mix} D_{tag} D_{t-int}} \frac{1}{\sqrt{\epsilon_{tag} N_{rec}}} \sqrt{\frac{S+B}{S}} \qquad (4)$$

with ϵ_{tag} being the flavor tagging efficiency and N_{rec} the number of reconstructed events.

Using ISAJET, $b\bar{b}$ events were generated at $\sqrt{s} = 2.0$ TeV with $p_T(b/\bar{b}) = 2 - 100$ GeV, and forced decays, $B^0 \to J/\psi K_s^0 \to \mu^+\mu^- \ \pi^+\pi^-$. With kinematic cuts of $|\eta_{\mu,\pi}| < 2.0$ and $p_T^\mu > 1.5$ GeV, and $p_T^\pi > 0.5$ GeV, a sample of 33,000 events survived before trigger and reconstruction restrictions for $\int \mathcal{L}\, dt = 2$ fb^{-1}.

Assuming a trigger efficiency of 32%, and a reconstruction efficiency of 95% per particle provides about 9000 reconstructed decays. Using single-muon, dimuon, and silicon track triggers along with flavor tagging, using one muon ($p_T^\mu > 1.5$ GeV, $|\eta_\mu| < 2.0$), the figure of merit for flavor tagging $\epsilon_{tag} D_{tag}^2$ becomes:

$$\epsilon_{tag} = 5.6\%; \ D_{tag} = 0.5; \ \epsilon_{tag} D_{tag}^2 = 0.014.$$

With a conservative value for the ratio of signal/background of 1, the CP sensitivity is $\delta(\sin 2\beta) = 0.28$. But if we include other possible flavor tagging algorithms such as jet charge, same side pion, and electron to increase the $\epsilon_{tag} D_{tag}^2$ to 5%, the resulting sensitivity is $\delta(\sin 2\beta) = 0.15$.

5. SUMMARY AND OUTLOOK

The DØ upgrade is well on its way, and matched to the schedule of the Main Injector project. Run II is expected to start in the Spring of 2000. While it builds on the good features of the present DØ detector, adding high-precision tracking and central magnetic field will enhance the physics capabilities of the detector. All system are designed to run at a high luminosity of $10^{32}\ cm^{-2} s^{-1}$ and reduced bunch spacing of 132 ns. Due to excellent muon detection, secondary vertex resolution, and improved b tagging, the DØ detector is poised to become an important facility for heavy quark physics in Run II.

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