Physics Capabilities of the DØ Upgrade Detector

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Abstract

The DØ detector at Fermilab is being upgraded to meet the demands imposed by high luminosity Tevatron running planned to begin in 1998. The central tracking detectors will be replaced with silicon and scintillating fiber tracking systems inside a solenoidal magnetic field and a preshower detector will be added to aid in electron identification. The design and performance of these systems are described and detailed simulations of the physics capabilities of the upgraded detector are presented. In particular we focus on the study of electroweak boson properties and top quark physics and briefly describe the b-physics capabilities.

1. Introduction

The future physics program at Fermilab will be greatly enhanced by the Tevatron upgrade which will result in an increase in luminosity by a factor of about 10-20. For the run planned to start in the Fall of 1998 (after installation of the Main Injector) the luminosity will be $\approx 10^{32}$ cm^{-2} s^{-1}. This upgrade will be accompanied by a decrease in the bunch crossing time from the current value of 3.5 μs to 396 ns and finally to 132 ns as the number of bunches is increased in stages.

To take full advantage of the new physics opportunities and to contend with the much higher radiation environment and shorter bunch crossing times, an extensive ugprade of the DØ detector is being undertaken[1].

The existing tracking systems and TRD are based on gaseous detectors and will be significantly degraded by radiation damage at 10^{32} cm^{-2} s^{-1} luminosity. Also, the typical drift time is $\approx$1 μs which will prevent operation with the short bunch crossing times. These considerations require completely replacing all the existing tracking detectors.

The upgraded tracking system has been designed to meet several goals: momentum measurement by the introduction of a solenoidal field; good electron identification and e/π rejection (to compensate for the loss of the TRD); tracking over a large range in pseudorapidity ($\eta \approx \pm 3$); secondary vertex measurement for identification of b-jets from top and for b-physics; first level tracking trigger; fast detector response to enable operation with a bunch crossing time of 132 ns; and radiation hardness. The design chosen to meet these requirements consists of an inner silicon tracking system and an outer scintillating fiber tracker enclosed within a 2 T superconducting solenoid. A preshower detector based on scintillating strips with fiber readout will be placed outside the solenoid. Fig. 1 shows an $r-z$ view of the DØ upgrade.

Other parts of the DØ detector will also be upgraded: a cosmic ray scintillator shield will be added and upgrades to readout electronics, trigger and data acquisition systems will be implemented.

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2. Silicon Tracking

The silicon tracking system[2] is based on 50 μm pitch silicon microstrip detectors providing a spatial resolution of approximately 10 μm in $r\phi$. The high resolution is important to obtain good momentum measurement and vertex reconstruction. The detector consists of a system of barrels and interleaved disks designed to provide good coverage out to $\eta \approx 3$ for all tracks emerging from the interaction region, which is distributed along the beam direction with $\sigma_z \approx 25$ cm.

The barrel has 7 sections, each 12 cm long and containing 4 layers. The first and third layers are made of single-sided detectors with axial strips and the second and fourth layers are made from double-sided detectors with axial and 2° stereo strips. The small angle stereo design provides good pattern recognition with a resolution in $r-z$ at the vertex of 0.5–1.0 mm, allowing separation of primary vertices from multiple interactions.

The detectors are ac-coupled – each strip has an integrated coupling capacitor and polysilicon bias resistor. This technology has been shown to be sufficiently radiation hard[3]. The front end readout

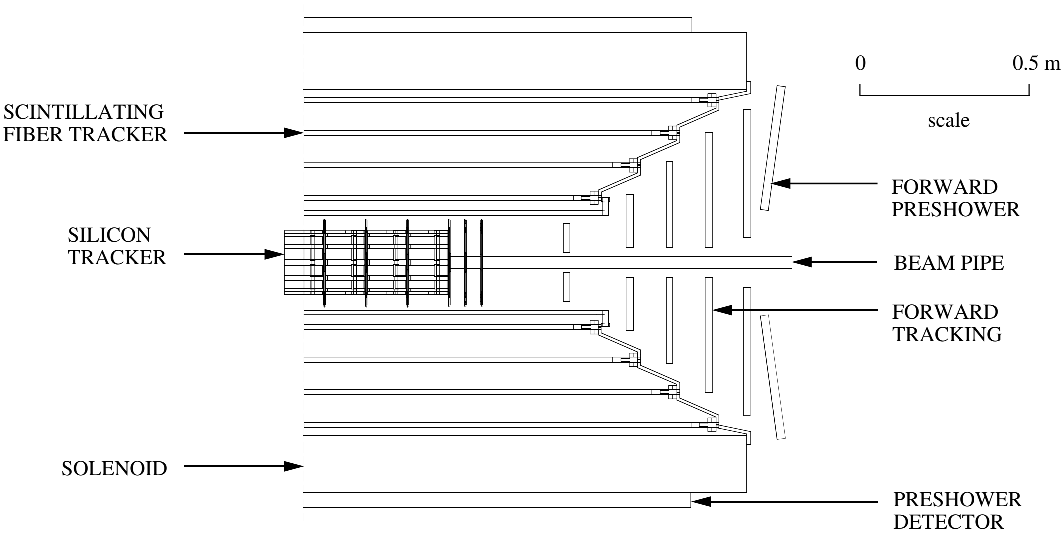

Figure 1. Schematic $r-z$ view of the DØ upgrade tracking systems and preshower detector.

chip (SVX II) has been prototyped in CMOS technology. It contains 128 channels, each channel comprising a double-correlated sampling amplifier, a 32-cell analog pipeline, and an analog-to-digital converter. The chip also contains sparse readout circuitry to limit the total readout time. The SVX II chips are mounted on a kapton high density circuit which is glued to the surface of the silicon detector. The detectors are mounted on beryllium bulkheads which serve as a support and provide cooling via water flow through beryllium tubes integrated into the bulkheads. The silicon tracker has a total of 837,000 channels.

3. Scintillating Fiber Tracker

The outer tracking in the central region is based on scintillating fiber (SciFi) technology with visible light photon counter (VLPC) readout[4]. The SciFi tracker consists of 4 superlayers, each containing 4 fiber doublets in an $xuvx$ configuration (x = axial fibers and u, v = $\pm$ small angle stereo fibers). Each doublet consists of two layers of 830 μm diameter fibers with 870 μm spacing, offset by half the fiber spacing. The inner axial doublet is separated from the other doublets by a 1.5 cm thick carbon fiber support cylinder. This configuration provides very good efficiency and pattern recognition and a position resolution of $\approx$ 120 μm in $r\phi$.

The fibers are up to 2.5 m long and the light is piped out by 8 m clear fibers to the VLPC's outside the tracking volume. The VLPC's are solid state devices with a pixel size (1 mm) matched to the fiber diameter. The fast risetime, high gain and excellent quantum efficiency of these devices makes them ideally suited to our application.

The SciFi tracking system has a total of about 81,000 channels. Since this technology is rather novel we have done extensive testing. This includes the characterization of over 4,000 channels of VLPC's and the setup of a cosmic ray test stand consisting of 3 superlayers with over 3,000 fully instrumented fibers. The measured photoelectron yield, a critical measure of the system performance, was found to be 19 photoelectrons per doublet. This is well above the requirement of 5 photoelectrons needed for fully efficient tracking based on detailed GEANT simulations. The tracking efficiency measured with the cosmic ray stand is shown in Fig. 2 – for a fiber doublet it is above 98%. Also shown is a histogram of the track residuals in the SciFi superlayers for the 3-superlayer setup. The rms residual is 170 μm giving a resolution per superlayer of 139 μm, close to the predicted value of 120 μm.

4. Detector Performance and Physics Capabilities

The momentum resolution of the proposed upgrade tracker is shown in Fig. 3. At $\eta = 0$ the resolution is approximately $\delta p_T/p_T$ = 17% for p_T = 100 GeV. With this resolution the upgrade tracking will enable E/p matching for electron identification, improve the muon momentum resolution, provide charge sign determination for charged particles and help in calorimeter calibration.

Another important use of the tracking will be the tagging of displaced secondary vertices for $t\bar{t}$ physics and b-physics. Fig. 4 shows the resolution of the 2-dimensional impact parameter b as a function of pseudorapidity. The resolution is less than 20 μm

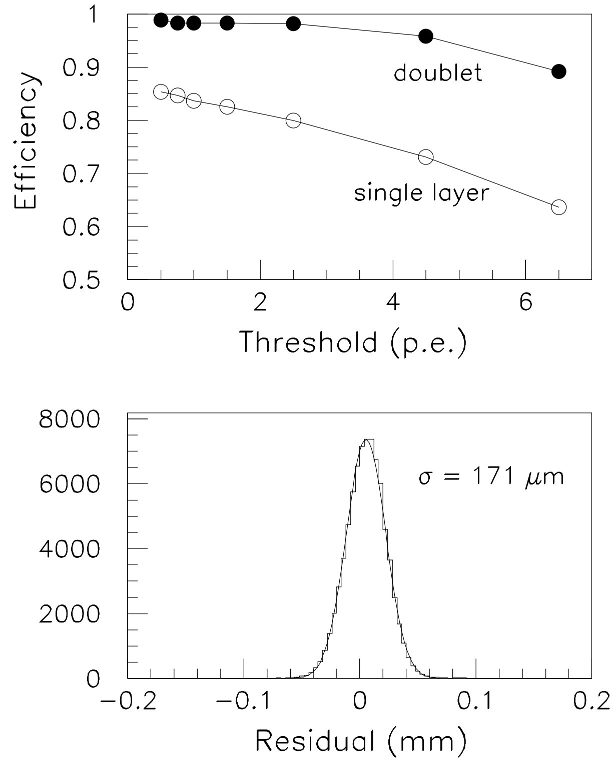

Figure 2. Measured SciFi efficiency and resolution.

for tracks with $p_T < 1$ GeV over the approximate range $\eta \leq 2$, which is the region of interest for tagging b-jets from top decays. A detailed study was carried out to determine the efficiency per event for tagging top events in the lepton plus jets decay channel using the impact parameter measurement. Events were generated and processed through a GEANT upgrade detector simulation and the signed impact parameter $b_\pm$ was obtained for tracks within jets in each event. A minimum of 3 tracks was required to be within a jet. Fig. 5 shows the tagging efficiency per event as a function of the $b_\pm$ significance cut. Also shown is the tagging efficiency for W + jets events. A signed impact parameter significance cut of 3 results in tagging 50% of the $t\bar{t}$ events and only 2% of the W + jets background.

One of the primary goals of the DØ upgrade physics program is the measurement of the top quark mass. This can be achieved using events in the lepton plus jets channel where the b-jets are tagged using the silicon tracker. The invariant mass of the $W + b$ can then be obtained. Studies have shown that the expected precision from this method is about $\delta m_t = 5$ GeV and with sufficient statistics $\delta m_t = 3$ GeV may be possible.

Another important goal is the measurement of the W mass. With the large data samples expected ($>$ 1 fb^{-1}) the level of statistical precision will be of order 10 MeV and systematic errors in the measurement and model will dominate. We estimate that the overall error will be approximately $\delta m_W = 50$ MeV.

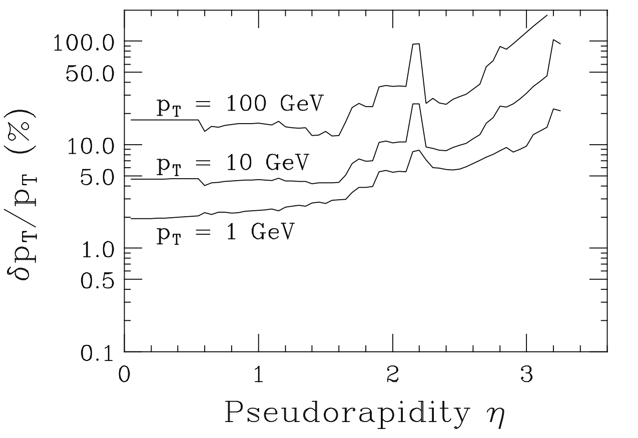

Figure 3. Transverse momentum resolution vs. pseudorapidity.

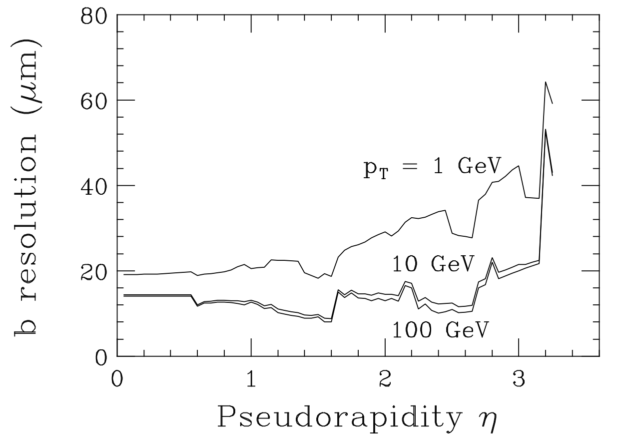

Figure 4. 2d impact parameter resolution vs. pseudorapidity.

The measurement of the forward-backward asymmetry (A_{FB}) will be possible in DØ utilizing $Z \to \ell^+\ell^-$ events. A preliminary study has shown that an estimated error on $\sin^2\theta_W$ of ≤ 0.001 is achievable using events on the Z pole only. We can improve this measurement by exploiting the variation of A_{FB} with the e^+e^- invariant mass due to $\gamma - Z$ interference. Studies are in progress to determine the ultimate sensitivity of this method and we expect that the error on $\sin^2\theta_W$ will be competitive with the LEP measurements.

The parameters m_t, m_W and A_{FB} are all linked through the Standard Model and it will be important to use the very precise measurements of these quantities from DØ to overconstrain the SM and search for new physics. This is shown in Fig. 6, where we used $m_t = 130$ GeV and a Higgs mass of $m_H = 1$ TeV. The region of overlap is small, indicating that DØ can make a sensitive search for physics beyond the SM.

Using the measured Z mass from LEP we may relate m_t and m_W for a given m_H as shown in Fig. 7 (solid curves). The DØ measurements of m_t and m_W (dashed lines) may yield valuable information on the Higgs mass, as illustrated in the plot.

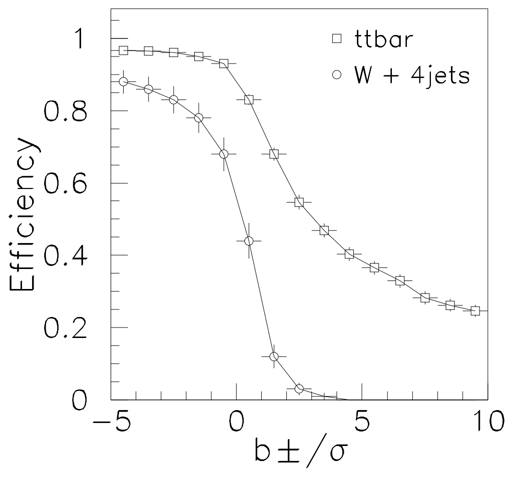

Figure 5. Tagging efficiency per event vs. signed impact parameter significance cut for $t\bar{t}$ events (squares) and W + 4 jet events (circles).

Some other important topics in the high p_T physics program include: measurement of the trilinear gauge boson couplings via the production of di-boson pairs; search for a charged Higgs via $t \rightarrow H^+ b$; search for the Higgs via $H^0 \rightarrow b\bar{b}$; and the search for non-SM particles e.g. supersymmetric particles.

For an integrated luminosity of 1 fb^{-1} at the Tevatron approximately 5×10^{10} b-quark pairs will be produced. Therefore, a wide range of b-physics studies will be possible. These include b-quark cross sections, rare B decays, B_s mixing and CP violation in the $B\bar{B}^0$ system. In contrast to high p_T physics, B mesons are produced at relatively high η and low p_T. Therefore, tracking and vertexing out to $\eta \approx 3$ is important for b-physics studies. Simulations using 1 fb^{-1} indicate that B_s mixing could be detected for values of the mixing parameter x_s up to 20 and that CP violation could be accessible with an error on $\sin(2\beta)$ of about 0.24.

5. Summary

The upgrade of the DØ detector is well underway and is planned to be complete by mid 1998. Conceptual designs for all the subsystems have been completed and construction of some components has already begun. The upgrade will considerably extend the physics reach of DØ. With ≥ 1 fb^{-1} of data, we expect to measure the top mass to within 5 GeV and the W mass to within 50 MeV.

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Figure 6. Plot of m_t vs. m_W showing the expected errors on the masses and the constraint from the A_{FB} measurement.

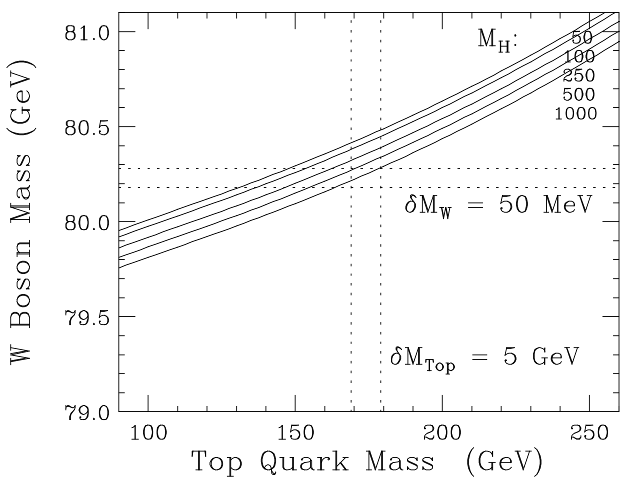

Figure 7. Plot of m_t vs. m_W showing the expected errors and the SM curves for different m_H using the Z mass from LEP. The curves are from ref. 5.