Fermi National Accelerator Laboratory

TM-1697

Fermilab Physics Program for the 1990's *

K. C. Stanfield
Fermi National Accelerator Laboratory
P.O. Box 500
Batavia, Illinois 60510

October 15, 1990

* Presented at the Second International Conference on Medium- and High-Energy Nuclear Physics, Taipei, Taiwan, May 14-18, 1990.

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

FERMILAB PHYSICS PROGRAM FOR THE 1990's

K. C. Stanfield
Fermi National Accelerator Laboratory
Batavia, Illinois 60510 USA

Following a brief introduction to Fermilab facilities and a review of the accelerator status and plans, the physics potential for the Fermilab III upgrade program is discussed for both the fixed target and collider modes.

INTRODUCTION TO FERMILAB, ACCELERATOR STATUS AND PLANS

The Fermilab accelerator complex operates in two distinct modes: 800 GeV fixed target and 1.8 TeV pbar-p collider. At the present time there are eighteen approved fixed-target experiments covering the following topics: electroweak, weak decays and CP, heavy quarks, hard collisions and QCD. The collider program for the next collider run will include two large detectors. The CDF detector is a large 4π detector with excellent tracking in a solenoidal magnetic field. The D0 detector is a large 4π detector emphasizing lepton detection and hermetic liquid argon calorimetry. The recent collider run, which ended May 31, 1989, was extremely successful. Almost 10 pb^{-1} of integrated luminosity were delivered to the CDF detector with nearly 5 pb^{-1} written to tape exceeding the goal of the run by nearly a factor of 10. After an initial commissioning period the machine delivered approximately 300 nb^{-1} per week. The average peak luminosity achieved was 1.6×10^{30} $cm^{-2}s^{-1}$ and the highest peak luminosity achieved was 2.07×10^{30} $cm^{-2}s^{-1}$.

At the time of this conference the accelerators are being operated for a fixed-target run which began in February. Before the run began a rather lengthy shutdown was scheduled to prepare for the fixed-target run. Near the end of the collider run a variety of accelerator studies related to future upgrades were carried out. Future collider runs will have increased luminosity by virtue of a decreased beam-beam tune shift. This will be achieved by allowing the beams to collide at only the two locations of interest for the detectors. To achieve this, helical orbits will be introduced with electrostatic separators. During study periods with one each horizontal and electrostatic separators installed, helical orbits were established with 36 proton bunches and 1 anti-proton bunch in the machine. In addition, no sparks were observed on the horizontal separator set at 50KV/cm during 30 hours of operation. These tests encourage us to believe that the operation of the separators will be successful as designed during the next collider run. Another upgrade goal is to achieve full 2 TeV operation of the Tevatron collider. Cold compressor tests conducted in one sector of the machine taught us that the Tevatron magnets will achieve the necessary field under refrigeration conditions achievable in the tunnel.

During the shutdown there were many detailed activities underway in preparation for the present fixed-target run. The single most important activity was the repair of a number of Tevatron superconducting dipoles involving an improved restraint of their leads. The fixed-target run will have a duration of approximately nine months with an extracted beam intensity approaching 2×10^{13} protons per cycle.

FERMILAB III: UPGRADE PLANS FOR THE TEVATRON

Fermilab III is the name given to upgrade plans whose purpose is to extend the discovery potential of the Tevatron during the period leading up to utilization of the SSC. At present, the Standard Model is intact with three generations of quarks and leptons. The Top quark is the only member yet to be discovered. CDF has recently set an 89 GeV lower limit for its mass. Existence of the ν_τ has been inferred; it has not been observed directly. There is a lot of potential for further verification or failure of the Model through precision measurements of the Top mass, $\sin^2\Theta_W$, $(M_Z\text{-}M_W)$, investigation of the Higgs sector, measurements of the CKM matrix elements through charm, bottom and top spectroscopy and CP violation. Beyond the Standard Model may be a more complete (Grand Unified) picture but there is no direct evidence for it so far. Proton decay and neutrino oscillations are as yet unobserved. Possible extensions of the Standard Model yield higher mass W's and Z's, new quark families, supersymmetry, technicolor, compositeness or totally new phenomena and these are also not yet observed. The motivations for extending the discovery potential of the Tevatron are clear and numerous. None of these is so compelling as the observation that the Tevatron is now clearly the only existing machine with sufficient energy to produce Top. There will be more on this later.

The physics goals of Fermilab III are then to guarantee the observation of Top within the framework of the Standard Model, double the mass reach for as yet unobserved particles and produce sufficient luminosity to provide a factory domain for W's, b's, and perhaps t's depending on its mass. The higher machine intensities available will extend the sensitivity in heavy quark spectroscopy and structure functions in the Tevatron fixed target program. In addition, a new capability for producing modest energy, high intensity fixed target beams would yield Kaon factory capabilities (2μA proton beams at 120-150 GeV). Such beams make possible significantly higher precision measurements in the Kaon system and open new opportunities for precision measurements of $\sin^2\Theta_W$ and searches for both short and long base-line neutrino oscillations. The goal of discovering a Standard Model Top (mass up to ~250 GeV) requires an integrated luminosity of approximately 1 fb^{-1}. This translates into a machine goal in excess of 10 pb^{-1} per week and a peak luminosity of 5×10^{31} $cm^{-2}s^{-1}$.

In order to achieve this ultimate goal a phased approach has been adopted which will yield a steadily increasing luminosity scenario over the next three collider runs. The two detectors will also necessarily be improved in order to take advantage of these higher rates. In the first phase, separators and new low β insertions will be installed so that a peak luminosity of 5×10^{30} $cm^{-2}s^{-1}$ is expected. In the second phase, the energy of the Linac injector is doubled resulting in a luminosity of 10^{31} $cm^{-2}s^{-1}$. Finally, the old main ring conventional accelerator will be replaced by a new MAIN INJECTOR in a separate tunnel. Many advantages accrue from this final phase. There is an improved admittance into the Tevatron and an improved cycle rate for pbar production. This yields an ultimate peak luminosity in excess of 5×10^{31} $cm^{-2}s^{-1}$. Losses in the present main ring produce backgrounds at the detector locations. This is expected to be especially severe at D0 where the existing bypass does not remove the main ring from the detector. Placing this injector in its own separate tunnel will remove a major source of background for the detectors. With the Main Injector it will be possible to provide year around simultaneous operation of the collider program and 120 GeV external beams. Kaon factory type physics and test beam operation will thus become possible year around without the present hiatus in fixed target operation due to collider operation. The new Main Injector will also substantially (x3) increase the intensity available for Tevatron energy fixed target beams.

CHARM

There is a long history of heavy flavor physics at Fermilab. This began with the advent of Silicon Vertex Detectors which made possible the separation of secondary vertices, which in turn increased signal to background ratios. Very clean signals for charm have been observed. This program continues to bear fruit. In this section I will briefly review the status of this program and make some projections for the 1990's.

At Fermilab fixed target energies the photoproduction cross-section for charm is about 0.5% of the total hadronic cross-section. For proton collisions the number is closer to 0.1%. Present experiments, those that have completed data taking in previous runs, have studied charm states with branching ratios of $<10^{-2}$ with samples of 10^4 fully reconstructed events. By contrast, the expectations from next to leading order calculations suggest that beauty photoproduction is down by a factor of ~600 and the hadroproduction cross-section is down by a factor of ~4000. On the other hand, at 1.8 TeV where the Fermilab collider operates, the beauty production cross-section has risen to 0.1% of the total which is at the same level where present fixed target experiments are quite successfully studying charm. The physics which has been addressed at the present level of sensitivity includes: charm particle lifetimes, exclusive decays (multibody and Cabibbo suppressed), semi-leptonic decays, D^o - $\bar{D}^o$ mixing (r_m < 0.4%, 90% confidence level), spectroscopy including charmed baryons, and the dynamics of photoproduction and hadroproduction.

The next generation of experiments, those taking data in the present fixed target run (1990-91) and the following one (1993), are expected to accumulate fully reconstructed charm samples of $\sim 10^5$ events. There are several different approaches. Two experiments employing multiparticle spectrometers and open triggers should study very high statistics charm samples and begin to study beauty through the decay chain $b \to c \to s$. One experiment concentrates on charmed baryons by looking for diffractive production in a hyperon beam. Two experiments have been approved specifically to study beauty. The first of these, E771, will rely on a ψ trigger in a multiparticle spectrometer. The second, E789, employs silicon in front of a high rate pair spectrometer to search for $b \to u$ directly in dihadron final states.

Beyond 1993 it is believed that without the introduction of new technology it will be possible to accumulate charm samples of $\sim 10^6$ events. This would be achieved by the use of micro-processor farms (such as are presently in use in E791) to move the filtering on-line. I refer the reader to the proceedings of the Breckenridge summer study for further consideration of this subject.[1] The physics topics of interest with such a sample include (in addition to those mentioned above) limits on rare decays ($D \to ee$, $e\mu$, $\mu\mu$) as tests of the Standard Model and doubly suppressed Cabbibo decays. There also remains a great deal to do in the area of charmed baryons. In his paper in Ref. 1 Bigi suggests searching for non-Standard Model CP violation in the charm system. It is clear that with the potential for two orders of magnitude increase in statistical power available to the Fermilab fixed target program the physics of high statistics charm will remain an essential and important part of the Fermilab program through the decade.

THE CHALLENGE AND PROMISE OF B PHYSICS AT FERMILAB

Unlike the case of e+e- collisions, the production rate of B's is not the issue in hadron collisions at Fermilab energies. Instead, the challenge is in detector performance: event rates, data-set size, event filtering, triggering, etc. B's are produced copiously at Fermilab. In a 500 GeV fixed-target pion beam or an 800 GeV proton beam and a total luminosity yielding 10^{14} interactions (10^7 seconds and 10^7 interactions per second) 10^6 to 10^7 beauty pairs are produced depending on the choice of target. At the collider before the era of the Main Injector, when we can expect 50 pb^{-1} in a single run, 2×10^9 B pairs are produced. With the Main Injector and an integrated luminosity of 500 pb^{-1} 2×10^{10} pairs are produced. The challenge then is to develop the necessary detector techniques to exploit the copious B production rates in the presence of the large hadronic total cross-section. This program is in many ways a natural extension of the ongoing detector R&D efforts associated with the Charm program and the program of high p_T physics at the collider. The program of Charm and Beauty physics at Fermilab is both an R&D effort in detectors, data acquisition, triggering and filtering and a very productive ongoing physics program.

The list of physics topics of interest in the B system includes: cross-sections, lifetime measurements, exclusive (rare) decays, B_s mixing and ultimately CP violation. The pursuit of these measurements will be a major goal for high energy physics in this decade and beyond. At Fermilab in the fixed target program one can expect measurements of the cross-sections, lifetimes to ~10%, perhaps mass measurements of B_s and Λ_b depending on branching ratios, and branching ratios down to 10^{-4} for certain two body modes. B_s mixing and CP violation may be beyond the reach of these experiments, although some proponents would argue the point.

At the Tevatron Collider, there exists a great deal of optimism regarding the potential for B physics. CDF has shown that even in the data from the last run where no special attempt to trigger on B's was implemented it has been possible to establish B signals in several modes. Indeed, fully reconstructed samples of B's have been seen in the mode, $B \rightarrow \psi K$, ψK^* (see Fig. 1). For CDF and D0 the ultimate challenges of addressing mixing and CP violation will require the addition of vertex detectors, lower p_T triggers, DAQ upgrades, and the Main Injector. The necessary R&D has begun. During the next collider run, scheduled to begin in July of 1991, CDF will install and operate a silicon strip micro-vertex detector. This device, whose main emphasis will be to tag Top quark decays by looking for detached vertices from B decays, will provide valuable experience in operating a vertex detector in a high luminosity hadron collider environment. The full exploitation of the potential of the Tevatron with the Main Injector for B physics may well require a dedicated B detector. Experience with the fixed target experiments and with CDF and D0 will guide the way in determining the parameters of such a detector. The recent successes of CDF give us a great deal of encouragement to believe that B physics will play an important role in the Fermilab program through the entire decade and well into the 21st century.

THE MAIN INJECTOR FIXED-TARGET PROGRAM

Many of the same properties that make the Main Injector necessary for higher luminosity collider physics make it an ideal machine for experiments requiring high intensity, medium energy and excellent duty cycle slow spill beams. The potential for

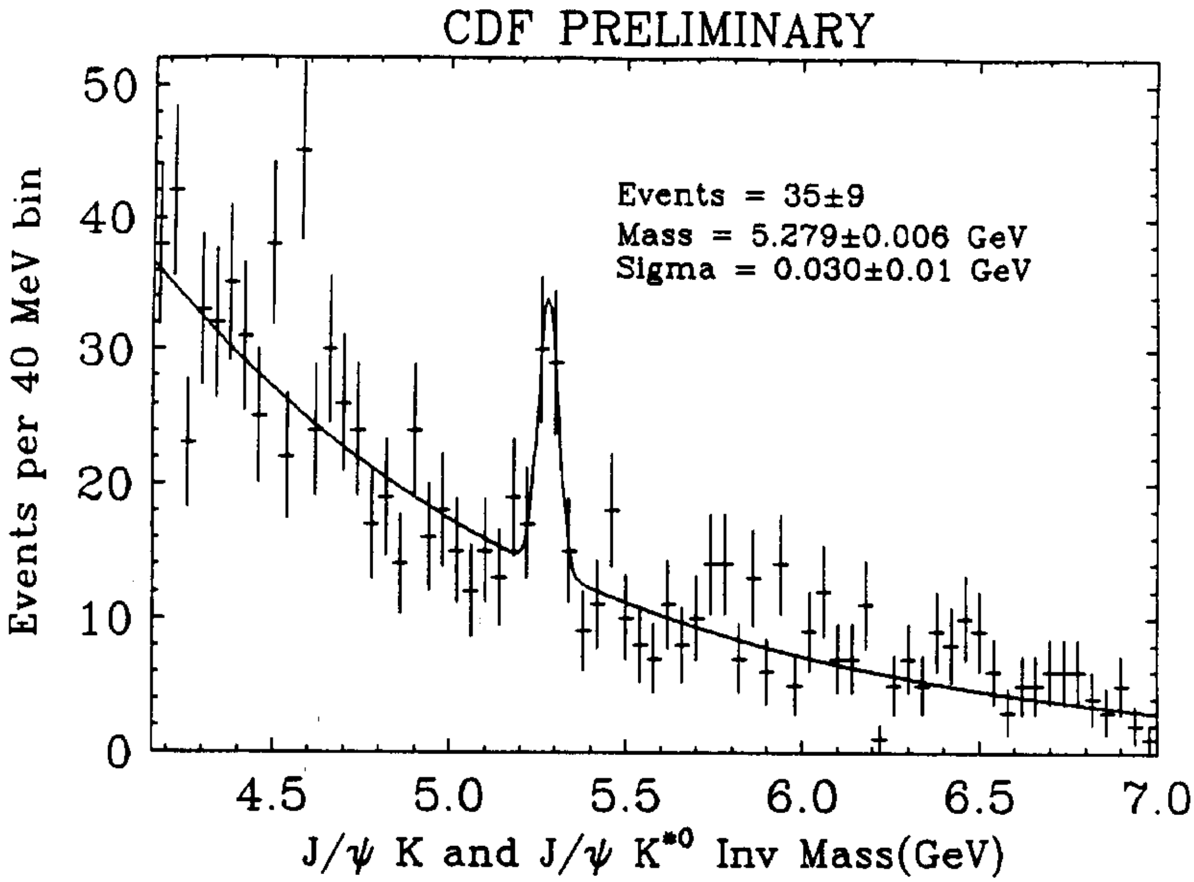

Figure 1: **A histogram of events from the $J/\psi \to \mu^+\mu^-$ sample, which shows evidence for $B^- \to J/\psi K^-$ and $B^0 \to J/\psi K^{*0}$, $K^{*0} \to K^+\pi^-$ (and charge conjugate modes).**

experiments utilizing these properties has been recognized and studied at a "Physics of the Main Injector Workshop" held at Fermilab in May of 1989.[2] Fermilab has received several letters of intent for fixed-target experiments which use the proton beam directly from the Main Injector to make beams of Kaons or neutrinos. The properties of such beams make it possible to achieve new levels of sensitivity for rare K decays and CP violation studies, neutrino oscillations, and precision measurements of electroweak parameters. Studies indicate that a K^o beam with a debunched flux of 2.2 GHz can be produced. At 20mr the neutron background would be 1.9 GHz. In a 20m decay volume there would be 130 MHz of K^o decays with an average K^o energy of 20 GeV. The high average energy of the K^o is an important consideration for experiments which must measure processes containing a π^o in the final state. Incredibly high average intensity neutrino beams with a substantial flux above τ threshold can also be produced. For a wide-band beam, a nine month run and a realistic duty factor one would expect 280K ν_μ charged current events per ton of detector. This compares to 6K events per ton in the present Lab E detector. For $\nu_\mu e$ elastic scattering one would expect 36 events per ton as compared to 2.8 for CHARM II. Thus, high precision $\sin^2\Theta_W$ experiments are feasible. The high average energy provides a unique capability in the arena of very high sensitivity ν_τ appearance oscillation experiments.

P803 is a letter of intent for an experiment to improve the limits for $\nu_\mu \rightarrow \nu_\tau$ neutrino oscillations. This experiment would employ a 1500 lb emulsion detector embedded in the magnetic field of the 15' Bubble Chamber magnet. τ's would be identified as muonless kinks in the emulsion. The experiment would see 380K neutrino interactions in a single run and would be sensitive to transmutations at the 2 x 10^{-4} level. This would extend the limits on $\sin^2(2\alpha)$ and δM^2 by orders of magnitude. The expected sensitivity probes a mass range which is relevant for astrophysics and cosmology at very small mixing angles (e.g. $\delta M^2 < 10$ eV^2 and $\sin^2(2\alpha) < 0.00022$). An interesting byproduct of this measurement would be the determination of Vcd to +-2.5%. By measuring the charm production in the threshold region the "slow rescaling" parameters would be precisely determined thus making it possible to reduce the systematic uncertainty in measurements of $\sin^2\Theta_W$.

P804 is a letter of intent which proposes an exciting program of K^o physics at the Main Injector. This experiment has as its goal the measurement of ε'/ε to a statistical precision of 0.5 x 10^{-4} and a systematic precision of 0.3 x 10^{-4}. The modes $K_L{}^o \rightarrow l^+l^-$ and $K_L{}^o \rightarrow \mu e$ could be studied with a sensitivity of 10^{-13}.

P805 is a letter of intent for a long baseline neutrino oscillation experiment using a high intensity neutrino beam from the Fermilab Main Injector and the IMB water Cherenkov detector in Cleveland. The IMB, originally built for a proton decay experiment, is a large underground water detector with an effective mass of 24,000 tons. It has good muon and electron detection and is 581 km due east of Fermilab. The proposed experiment would look for ν_μ disappearance and for oscillations of the type $\nu_\mu \rightarrow \nu_e$. Detection of τ's would be more problematic. Because of the extreme distance, sensitivity to δM^2 down to 0.01 eV^2 and $\sin^2(2\alpha) \sim 0.01$ could be achieved.

HIGH MASS, HIGH P_T COLLIDER PHYSICS

Table I summarizes the status of CDF results as of this conference. They include precision tests of QCD, new limits on quark compositeness, B physics, precision determination of electroweak parameters, and new limits on the mass of the Top quark. This is the departure point from which we embark upon future collider runs. An essential ingredient in the future program of increased luminosity is the upgrade of the CDF and D0 detectors. Time does not allow me to present a detailed description of these ambitious upgrade programs. Instead, I would like to discuss the highlights of the physics program that will be undertaken by these upgraded detectors in the era of the Main Injector. In order to do so I will consider a single run with the Main Injector. This would provide an integrated luminosity conservatively estimated to be $\sim 200 pb^{-1}$ in the 1995 time frame.

Consider first the results anticipated in the precision determination of electroweak parameters. In such a data sample CDF would expect to observe 300,000 events in each of the modes: $W \rightarrow e\nu$ and $\mu\nu$. There would be 30,000 events in each of the modes $Z \rightarrow ee$ and $\mu\mu$. The M_Z, M_W mass difference would be determined to a statistical precision of 30 MeV. Using E/p the calorimetry energy scale of CDF is determined to 50 MeV. The tracking chamber scale is known to better than 100 MeV and cancels to first order in the mass ratio. We could expect an accuracy in the mass difference which is less that 100 MeV. The high statistics will allow one to use the data to study the missing E_T resolution and the p_T distribution of the W's. A measurement to this accuracy will constrain the Standard Model to $\sin^2\Theta_W$ to +-.002 and M_{Top} to

Table 1

Summary (CDF)

1988-1989 Run

Jets

1. Inclusive jet cross section, fragmentation, dijet angular distribution, M_{JJ} distribution, 3 jet cross sections etc. described well by QCD.

2. Compositeness: $\Lambda > 950$ GeV ($\sim 2 \times 10^{-19}$m), 95% C.L., using 0.8 pb^{-1} of data.

B Physics

1. Analysis of B jets just beginning.

2. D^* observed in B jets.

3. Dilepton rates consistent with QCD production of B jets.

ElectroWeak

1. $M_{Z^\circ} = 90.0 \pm 0.3$ (stat. + syst.) $\pm$ 0.2 (scale) GeV
   width = 3.8 ± 1.1 (stat.) $\pm$ 1.0 (syst.) GeV

2. Preliminary

$$\begin{aligned} M_W &= 79.81 \pm 0.33\,(\text{stat.}) \pm 0.24\,(\text{syst.}) \pm 0.34\,(\text{scale})\,\text{GeV electrons} \\ & 79.86 \pm 0.58\,(\text{stat.}) \pm 0.31\,(\text{syst.}) \pm 0.16\,(\text{scale})\,\text{GeV}\ \mu \end{aligned}$$

   Combined CDF value: 79.83 ± 0.44 (stat. + syst. + scale) GeV

3. Preliminary: $\sin^2\theta_W = 0.230 \pm 0.009$ from M_W/M_Z.

4. $R = \frac{\sigma_W(W \to e\nu)}{\sigma_Z(Z \to ee)} = 10.2 \pm 0.8$ (stat.) $\pm$ 0.4 (syst.) $\Rightarrow \Gamma_W = 2.19 \pm 0.2$ GeV.
   (Standard Model with $M_W = 80$ and $\alpha_s = 0.13 \Rightarrow \Gamma_W = 2.07$ GeV).

5. $\sin^2\theta_W = 0.216 \pm 0.015$ (stat.) $\pm$ 0.010 (syst.) from charge asymmetry in $p\bar{p} \to e^+e^-$.

Top

1. $40 < M_{top} < 77$ GeV excluded 95% C.L. from $e + \geq 2$ jets search.
   $30 < M_{top} < 72$ GeV excluded 95% C.L. from $e\mu$ search.

2. Preliminary from $e\mu$, ee, $\mu\mu$, and search for additional low $p_T\,\mu$ from b decay.
   $M_{top} < 89$ GeV excluded 95% C.L.

+-20 GeV. The Z sample will allow the determination of $\sin^2\Theta_W$ to a statistical precision of +-.0015 from the charge asymmetry measurement. The dominant uncertainty at present comes from the systematic error introduced due to lack of precision in the measurement of the structure functions. By 1995 this could be expected to be reduced to +-.001 so that an overall determination of +-.002 can be expected. Γ_W as determined from the ratio of $\sigma_W(W\rightarrow e\nu)/\sigma_Z(Z\rightarrow ee)$ would be determined to 2 to 2.5%.

As a final topic, consider the search for the Top. By now there is a wealth of evidence within the Standard Model that limits the Top mass to <250 GeV. I refer the reader to J. Rosner's paper in Ref. 1. CDF has set a lower bound of >89 GeV. The Tevatron is the only machine with enough energy to fully cover the range of Top masses allowed by the Model. It is thus imperative to search this mass region and either discover the Top or rule out its existence as a Standard Model object. The allowed range of masses would be probed on the time scale of ~1997 after the second run with the Main Injector. What is the program of Top physics with the Main Injector? First, discover it as an excess of W pairs plus two jets. Then prove that it really is Top. Are the W pairs accompanied by two B jets? Do the W and B form a particular mass at the correct cross-section? The mass needs to be determined precisely to +-10 to 20 GeV and compared to the expectation from the precision measurements of electroweak parameters. In addition, non-standard decays should be sought. Does the Top decay to a charged Higgs and b? Look for bumps in the t-tbar mass distribution. What is produced with t-tbar? Certain pair produced lepto-quarks could decay into t-tbar $\tau\tau$. In general, with the mass of Top so large it is wise to "expect the unexpected". This will be an exciting program of physics for which the Tevatron is uniquely situated. One can even speculate that the mass of the W and the mass of the Top will be known sufficiently well that interesting limits could be placed on the mass of a Standard Higgs.

CONCLUSION

The recently completed collider run was spectacularly successful. The potential for the next decade and beyond in both fixed targets and the collider will be assured with the construction of the Main Injector. One can guarantee that with such a capability Top will either be discovered at the Tevatron or its existence as a Standard Model entity will be ruled out. The next ten years will indeed be an exciting time at Fermilab.

ACKNOWLEDGEMENTS

I am pleased to acknowledge the many contributions of my colleagues in the Fermilab community to this work. As is customary, those of us in the Directorate have access to the transparencies of our colleagues. I have benefitted greatly from this tradition in the preparation of this talk. I especially want to thank Steve Holmes, Jeff Spalding and Mel Shochet in this regard. This work has been supported by the U. S. Department of Energy.

REFERENCES

1. *Physics at Fermilab in the 1990's*, edited by D. Green and H. Lubatti (World Scientific, 1990).

2. *Proceedings of the Workshop on Physics at the Main Injector,* May 16-18, 1989, edited by Stephen D. Holmes and Bruce D. Winstein, Fermi National Accelerator Laboratory, Batavia, Illinois, 60510.