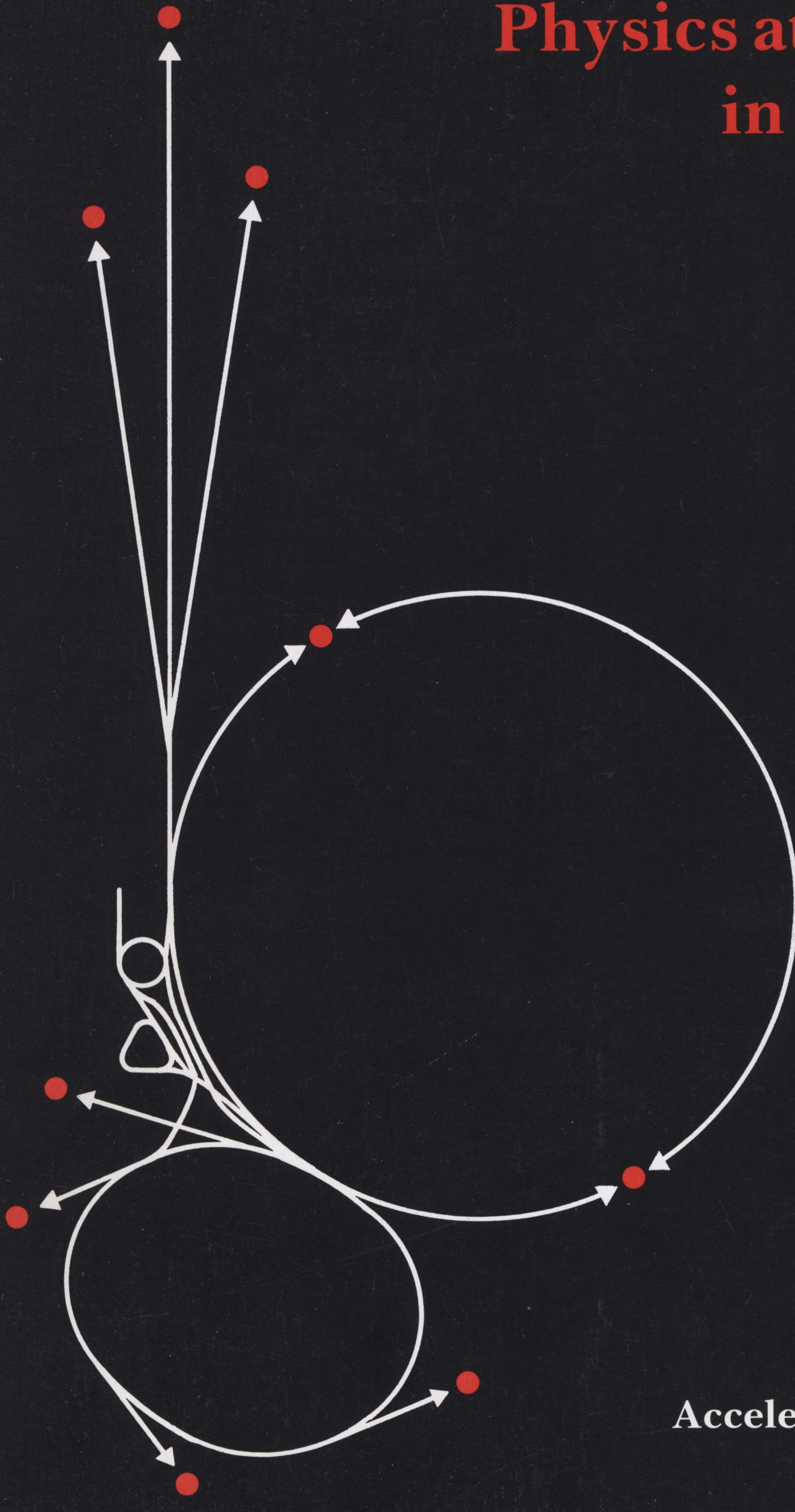
Physics at Fermilab in the 1990's



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PHYSICS AT FERMILAB

IN THE 1990's

A Summary of Fermilab's

Presentations to the

HEPAP Subpanel on the

U. S. High Energy Physics Research Program

for the 1990's

March 19, 1990

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INTRODUCTION TO PHYSICS AT FERMILAB IN THE 1990'S

The Tevatron will define the shape of experimental particle physics in the U.S. during the 1990's. It is easily the highest energy collider in the world and will remain so until the end of the decade when the SSC and LHC begin operation. It also provides the highest energy proton beams for fixed target experiments. This latter distinction will be lost to UNK when it comes into operation in the middle of the decade. All of these distinctions flow from the fact that the Tevatron, after seven years of operation, is still the only synchrotron operating with superconducting magnets. It is the only forefront accelerator facility in the U.S. with a capability that significantly exceeds the capabilities of counterpart facilities in Europe.

The mastery of superconducting magnet technology was not the only thing that Fermilab's accelerator builders accomplished during the decade of the 1980's. The Tevatron luminosity reached 2×10^{30} cm^{-2} sec^{-1} in 1989, a factor of two above the design goal. The integrated luminosity delivered to CDF during the 1988-89 collider run was 9.6 pb^{-1}, greater than the 9.2 pb^{-1} delivered to UA-2 by the CERN $Sp\bar{p}S$. During the next Collider run, the Tevatron should deliver a higher peak luminosity to both CDF and D0 than the $Sp\bar{p}S$ will deliver in its next run. In addition to the Tevatron, Fermilab built its Antiproton Source, the CDF detector and two small Collider detectors. The physics results from these efforts are now appearing in publication. During the same period, all of the fixed target beams were entirely rebuilt to handle either the 800 GeV primary protons or the higher energy secondary beams that are produced with 800 GeV protons. The construction of roughly fifteen major fixed target detectors was initiated. Nearly all were finished, and the few remaining detectors that were started before 1988 will come on line this spring. The first physics results from the most recent fixed target run have already been published and many new results are nearing publication.

The quality of the work was first class. There was a long dry period between 1981 and 1987 when all of the aforementioned were being constructed. The size of Fermilab's budget did not allow a vigorous physics program to be carried out during that six year construction period. The physics drought has passed. The sum of the physics results from all of these new detectors is ample justification for building both a strong Collider program and a strong Fixed Target program.

Physics moves on. None of us can stand still. The challenge for Fermilab is to maintain the Tevatron as the forefront facility for experimental high energy physics in the United States until the SSC begins operation. The date of the initial operation of the SSC is probably the year 2000. High energy physicists working in the U.S. cannot be placed in the deep freeze for a decade and then thawed. By the end of the decade, at least 25% of us will leave the field because of other interests, retirement, or death. If our subfield is to remain productive, at least 500 physicists must be trained to build accelerators and detectors, to analyze the data from those detectors and to find their place among the mature productive physicists of the first decade of 21st century.

Fermilab proposes Fermilab III as the way to provide continuity in the base program, while the decade long transition is made to the SSC program. As the subsequent chapters of this document will point out, the continuity is not one of marking time. Rather, it is an opportunity to make the important discoveries of some of the missing ingredients in our understanding of the twenty year old Standard Model. The knowledge of these missing ingredients is an important part of the preparation for the use of the SSC. The development of detectors for the Fermilab program form a crucial intermediate step that must be taken if the community is to use the potential of the SSC luminosity and energy. By substantially improving the luminosity capability of the CDF and D0 detectors, Fermilab III will be providing today's postdoctoral fellows and graduate students the experience that they need to use the SSC and become movers of the field in the year 2000.

Fermilab III consists of improvements to the Tevatron to make it a platform for a luminosity in excess of $5 \times 10^{31} cm^{-2} sec^{-1}$: the upgrade of the Linac, the construction of the Main Injector and the upgrade of the CDF and D0 detectors to handle the increased luminosity. It is also the construction of a neutrino beam line and a neutral K beam line to use the intense proton beams that the Main Injector can provide when it is not providing protons to the Tevatron and the Antiproton Source production target. It includes the continuation of improvements to the major Fixed Target detectors and it should include the construction of a few new Fixed Target detectors. If the development of detectors and data acquisition systems for detecting B's at the Tevatron Collider and fixed target experiments is successful, then serious consideration will be given to building a Collider detector dedicated to B physics at Fermilab (or the SSC). In short, Fermilab III defines the resources needed to keep Fermilab at the forefront of high energy physics throughout the nineties and to put Fermilab in a position to have a vigorous experimental high energy physics program at the start of the 21st century. Of all of the elements of Fermilab III, the Main Injector is the most visible because it makes the physics happen and it is the most expensive single element. And yet, the \$180 million total project cost (TPC) is a small fraction of the value of Fermilab as it exists today.

If the Main Injector is built in a timely way, the integrated luminosity delivered by the Tevatron to both CDF and D0 will be in excess of 1 fb^{-1} per detector by 1998. With that luminosity, either CDF and D0 will discover the top quark somwhere in the range between 90 GeV and 300 GeV, or we will have the first evidence that nature did not choose the minimal Standard Model. Precise measurements of the electroweak parameters, such as the ratio of the W mass to the Z mass and $\sin^2\theta_W$ determined from deep inelastic neutrino scattering, will independently locate the top quark mass within that range. A definitive search for the top and precise measurements of the properties of the W boson are two examples of things that can be done at the Tevatron if its luminosity is increased by a factor of fifty.

As the following sections will show, Fermilab III will provide many opportunities to do high energy physics in the U.S. during the 1990's. The plan of the remainder of this document is briefly to present the technical arguments that demonstrate that the increase in luminosity is feasible, to describe the Main Injector, and then to outline how four of the existing physics programs at Fermilab might evolve during the 1990's. These latter sections will make the physics case for the Main Injector. Finally, a summary, like a good waiter, will discreetly present the bill.

TEVATRON LUMINOSITY IN THE 1990's

INTRODUCTION

This discussion takes as its starting point the collider run planned to begin in mid-1993. The 1991 collider run, which has a luminosity goal of $5x10^{30}/cm^2/sec$, will not be discussed. For the 1993 collider run, most of the improvements currently planned for the Linac, Antiproton Source, and Tevatron will be in place. A brief summary of these improvements will be presented below, together with some remarks on their current status. This will be followed by a discussion of how these modifications to the various components of the accelerator complex combine to achieve the luminosity goal of $10^{31}/cm^2/sec$ for the 1993 run. The limitations to the luminosity, and the areas of unfulfilled potential improvement, will be spelled out explicitly. It will then be explained how these limitations can be overcome, and how a luminosity in excess of 5 $x10^{31}/cm^2/sec$, can be realized using the Main Injector.

ACCELERATOR IMPROVEMENTS PRIOR TO 1993

Introduction

During the 1989-90 Tevatron collider run, the accelerator delivered almost 10 pb^{-1} of integrated luminosity to the CDF experiment in the B0 straight section. The peak initial luminosity exceeded $2x10^{30}/cm^2/sec$, more than twice the original Tevatron I Project design goal. This excellent performance, both in terms of technical components and personnel, is evidence of the extremely strong base upon which the upgrade program is founded.

The luminosity of the Tevatron collider can be expressed in terms of accelerator-related quantities by the following proportionality:

$$L \propto \frac{N_p N_{\bar{p}} B}{\beta^*(\varepsilon_p+\varepsilon_{\bar{p}})} E$$

In this equation, N_p and $N_{\bar{p}}$ are the proton and antiproton bunch intensities, respectively; ε_p and $\varepsilon_{\bar{p}}$ are their respective transverse emittances; B is the number of bunches; β^* is the machine lattice function at the interaction point; and E is the machine energy. The limitations to the luminosity can be described in terms of the limitations on the proton transverse density (N_p / ε_p), the antiproton transverse density ($N_{\bar{p}} / \varepsilon_{\bar{p}}$), the machine lattice function at the interaction point (β^*), and the machine energy (E). The limitation on each of these quantities is directly addressed by one or more components of the accelerator upgrade program. The description of the components of the accelerator upgrades planned for 1993 will be catalogued here in terms of these fundamental quantities which directly determine the collider luminosity.

Proton Transverse Density

The principal limitation on the proton transverse density during the 1988-89 collider run involved the beam-beam interaction. Although the beam-beam interaction in hadron colliders is a subject which is too complex to treat in detail here, the essence of the limitation may be simply stated in terms of the total beam-beam strength parameter, ξ. For the Tevatron collider, this quantity is numerically

$$\xi = .00733\, n_c \frac{N}{\varepsilon}$$

where n_c is the number of bunch crossings per revolution, N is the bunch intensity in units of 10^{10}, and ε is the beam 95% invariant transverse emittance in π mm-mrad. The essence of the beam-beam limitation in the Tevatron is to restrict ξ to be less than the distance in tune space from the working point to the nearest resonance of order 10 or lower. At the nominal working point, this implies a value for ξ of $< .025$. Because the antiproton transverse density is normally much smaller than that of the protons, the beam-beam effect of the protons on the antiprotons is dominant and the limit on ξ restricts the proton transverse density. During the 1988-89 collider run, this restriction was satisfied by deliberately increasing the proton emittance prior to antiproton injection into the Tevatron.

Separators. The effects of the beam-beam interaction will be substantially reduced by the separated orbit scheme planned for implementation in 1991. This is done by reducing the number of bunch crossings per revolution from 12 to 2, thus reducing the total beam-beam strength parameter by a factor of 6. In this scheme, 22 electrostatic separators of length 3m each are placed into the Tevatron and operated at electric fields of up to 35 kV/cm (at 900 GeV) to produce helically separated orbits for protons and antiprotons. On these orbits, protons and antiprotons are separated by an average distance of >5σ, and they collide head-on only twice per revolution (at B0 and D0).

For the practical realization of this system, there are a number of issues which must be confronted. These include beam dynamics issues such as linear aperture on the helical orbits; tune, coupling and chromaticity control on these orbits; and the effects of multiple "long-range" (i. e., 5σ) beam-beam interactions. The operational complexity of the collider will increase, because of the interrelationship between the separators and the machine lattice: adequate beam separation must be maintained throughout acceleration and the low-β squeeze. There is a short period of time as the beams are brought into collision during which they will interact at B0 and D0 with a small separation; this must be studied carefully. There are also questions related to the separator hardware. The devices must be reliable enough to provide relatively high electric fields in the Tevatron beam environment for extended time periods. In addition, the impedance which they present to the beam must be consistent with the overall machine impedance budget.

Many of these issues have been addressed both through calculations and accelerator experiments. Calculations are in progress, both analytical (in collaboration with CERN) and numerical, to study the long-range beam-beam effects. A series of accelerator study periods during the 1988-89 collider run, and at the start of the 1990 fixed target run, have begun to address a number of questions which can best be settled experimentally. These studies have demonstrated that there is sufficient linear aperture on the separated orbits and that independent tune and coupling control of protons and antiprotons is necessary and will be possible using new sextupole circuits. During two of the study periods, Tevatron operation at 150 GeV with protons and antiprotons on electrostatically separated orbits allowed a start to be made on the study of the complex issues related to the long-range beam-beam interaction. Results to date are encouraging and no fundamental difficulties with the separated orbit scheme have been uncovered. These studies have also provided some experience with the use of electrostatic separators in the Tevatron beam environment. Operation at 50 kV/cm, well in excess of the design values for the separators, has been routine; although the total effective operating time during the studies has been short (less than two weeks with only two separators), the reliability of the separators installed to date has been excellent.

Construction of the complete complement of 22 separators with 4 spares is now underway and will be completed in time for the 1991 collider run. Additional sextupole circuits will also be implemented on that time scale to provide independent control of the proton and antiproton tunes and coupling.

Multibunch Operation. In addition to providing the potential for a substantial increase in the proton transverse density , the separated orbit scheme provides for the possibility of operation with as many as 36 bunches. For a fixed value of the total number of antiprotons in the Tevatron ($BN_{\bar{p}}$), the luminosity is independent of the number of bunches. However, there are two indirect benefits of more bunches. First, the antiprotons will be distributed over a larger number of bunches, i.e., a larger longitudinal area, so the requirements on antiproton longitudinal density in the Accumulator are less severe. Second, the number of interactions per crossing is substantially reduced for the same integrated luminosity, which should ease some of the requirements on the CDF and D0 detectors.

In order to implement this possibility, it will be necessary to rebuild the fast kickers which are used to inject antiprotons into the Tevatron. The present kicker system does not have a sufficiently fast rise time to accommodate multibunch injection. The new injection kicker is planned to be operational for the 1993 collider run.

Linac Upgrade. The Linac upgrade is an approved project to increase the Linac energy from 200 MeV to 400 MeV by a replacement of the last four drift tube cavities with more efficient, higher gradient side-coupled cavities. The new cavities will operate at four times the drift-tube linac frequency, 805 MHz, and will provide up to three times the gradient (about 7 MV/m). The motivation for this upgrade is to reduce the space-charge induced emittance growth presently suffered just after Booster injection, which occurs for Booster intensities in excess of 1.5×10^{12}. The intensity threshold for the onset of space-charge emittance growth is expected to rise by a factor of 1.7.

The increase in proton transverse density sustainable in the Booster is expected to be able to be preserved through the Main Ring and into the Tevatron. Thus, the overall impact on collider performance will be an increase in the proton transverse density by a factor of about 1.7. With the separated orbit scheme in place, this increase should pay off directly in a factor of 1.7 in luminosity.

Moreover, since the present 120 GeV proton intensity available for antiproton production is limited by the finite aperture of the Main Ring at 8 GeV, an increase in the transverse density of the beam will result in an increase in 120 GeV proton intensity by the same factor of 1.7, and hence in the antiproton stacking rate (see below). For the same reason, fixed-target operation will also benefit.

The Linac upgrade is being implemented as a line-item construction project which began in FY1990, and is expected to be complete near the end of FY1992. The total project cost is estimated at $22.8M. R&D efforts to date have concentrated on the development of the prototype high-gradient accelerating structure and the associated 805 MHz, 12 MW power source (klystron). A prototype structure, built at Fermilab, has run routinely at gradients more than 10% in excess of the required design gradient with an acceptable sparking rate.

Antiproton Transverse Density

The antiprotons used in the Tevatron collider originate in the Accumulator core: the number of antiprotons per bunch at low-β in the Tevatron is the product of the number of antiprotons in the core, the fraction of the core which is rf-unstacked per bunch, and the antiproton transfer efficiency. Because the transverse emittance is approximately preserved in the transfer process, the antiproton emittance at low-β is determined primarily by the emittance of the Accumulator core.

Debuncher upgrade. The number of antiprotons stacked into the Accumulator core per hour is called the antiproton stacking rate. These antiprotons are produced by targeting 120 GeV Main Ring beam onto a copper production target and collecting the antiprotons which are produced into a storage ring called the Debuncher. The major reason for the shortfall between the stacking rate which has been achieved to date (about $2x10^{10}$ antiprotons/hr) and the Tevatron I project design (10^{11} antiprotons/hr) is believed to be an overestimate (by about a factor of 2.5) in the antiproton production cross section upon which the original design was based. However, the number of antiprotons collected into the Debuncher can be increased by increasing the transverse aperture of the storage ring.

This aperture increase was accomplished during the 1989 shutdown by increasing the physical separation of the Debuncher transverse stochastic cooling system electrode gaps. At the same time, the system power was doubled and a momentum cooling capability was added: the momentum cooling system allows the full use of the physical Debuncher momentum aperture. Coupled with aperture improvements in the Debuncher injection line and an increase in the lithium lens gradient, an overall improvement in the antiproton yield (i.e., the ratio of antiprotons collected to protons on target) of a factor of 1.8 is expected. The resulting increase in the antiproton stacking rate will result in more antiprotons in the Accumulator core for a fixed stacking period and hence potentially a larger antiproton transverse density in the Tevatron.

Accumulator core cooling upgrade. As noted above, the antiproton emittance in the Accumulator core basically determines the antiproton emittance at low-β in the Tevatron. The core emittance grows linearly with core intensity as a result of the balance between various beam heating mechanisms and the cooling provided by the core stochastic cooling system. This system operated during the 1988-89 run over the 2-4 GHz frequency range. An upgrade was installed and commissioned in late 1989: the system bandwidth was increased to 4-8 GHz. The result of this should be a reduction in the beam emittance for a given core intensity by a factor of two. This will provide a direct increase in the antiproton transverse density at low-β in the Tevatron.

In a real sense, this upgrade was also necessary to be able to make any further improvements in antiproton intensity in the Tevatron. This is because, with the old system, the transverse emittance of the core was beginning to exceed the admittance of the Main Ring at 8 GeV for core sizes in excess of about 65×10^{10}. For transfers from cores much larger than this, the transfer efficiency dropped dramatically. Improvements in stacking rate to provide more antiprotons in the core would have been effectively useless without this improvement in core emittance. The core size at which we saturate with the 4-8 GHz system will be about twice the old saturation point, or about 140×10^{10} antiprotons.

Cycle rate increase. During the 1988-89 collider run, the antiproton production cycle rate was limited to 0.385 Hz by restrictions imposed by the Main Ring; the design rate specified in the Tevatron I project was 0.5 Hz. Techniques to increase the cycle rate are under investigation. These include improvements to the Main Ring power supplies (specifically those of the overpass) to enable the machine to cycle more rapidly and implementation of the "multi-batch" operation of the Main Ring. This latter scheme, which offers in principle the possibility of an average antiproton production rate approaching 0.5 Hz, has been tried experimentally but has suffered various problems which have prevented its use for routine operation. It is not clear at present whether either of these techniques will allow operation at 0.5 Hz.

Targeting for antiproton production. With the advent of the Linac Upgrade, the proton intensity available for antiproton production will rise by a factor of 1.7. This will result in a similar increase in the antiproton stacking rate provided that this beam can be targeted without difficulty. Because the proton beam is focused to as small a spot size as possible to maximize the antiproton yield, the principal issue here is the development of very large peak energy densities associated with hadron showers in the production target. These large energy densities can cause thermal shock waves which may result in mechanical failure of the target. There are several approaches to a solution to this problem.

The simplest is just to increase the transverse size of the proton spot on the target; however, there is a small (roughly 10%) penalty paid in antiproton yield as a result. Other approaches which are under investigation include a sophisticated mechanical support structure around the target (such as has been implemented at CERN) which will make it resistant to shock wave destruction; or a system of fast kickers to sweep the proton beam across the target (and simultaneously track the collection system acceptance), thus distributing the beam energy during the beam spill and lowering the peak energy density deposited in the target.

Tevatron Insertions

Tevatron low-β upgrade. During the 1988-89 collider run, the lattice insertion at B0 allowed a value of $\beta^* = 0.55$ m to be achieved. However, the dispersion at B0 was not zero, and the insertion was not matched to the rest of the Tevatron lattice. In addition, the existing system does not leave sufficient warm space for the separators required near B0.

Hence, two identical, new low-β systems are being constructed for installation at B0 and D0. The systems will provide a variable β^* in the range of 1.7 to 0.25 m. The new insertions are properly matched to the lattice and provide zero dispersion at the IP. Each system will use 12 new 1.4 T/m quadrupoles of a cold iron, two shell design, and 6 new 0.7 T/m trim quadrupoles located in new spool pieces. The optical design is such that even when operating at 25 cm, the maximum β will be not greater than that of the 1988-89 collider run. However, operation at 25 cm, which does in principle provide a factor of 1.6 gain in luminosity, is not assumed in any of the luminosity estimates quoted for the upgrade. This is because operation in this mode will require somewhat higher separator fields, and we await operational experience before claiming that the new low-β system can be pushed to 25 cm with separated orbits.

Construction of the cold iron superconducting quadrupoles and spool pieces is currently underway in the Technical Support Section. Most of the spool pieces and several of the new quadrupoles have been completed. Measurements of the field error harmonics in the quadrupoles constructed to date indicate that the error fields are comparable to those in the present low-β magnets. It is planned to install the B0 part of the new low-β system during the shutdown planned for late this summer. A sufficient number of separators will also be installed to allow further tests of separated orbit operation in conjunction with the new low-β system during collider study periods in the fall.

Tevatron Energy

Ringwide operating temperature reduction. During a short study period after the end of the 1988-89 collider run, an experimental system of cold helium vapor compressors was installed in F sector of the Tevatron and used to operate the F sector Tevatron magnets at a temperature about 0.4° K lower than their normal temperature. With this temperature reduction, F-sector was ramped to 1024 GeV; one weak magnet in the sector had to be changed to accomplish this.

A complete system of cold compressors in all Tevatron sectors is planned to be in place for the 1993 collider run. In addition, it is expected that some number of weak Tevatron magnets whose operating limits are determined not by temperature but by mechanical limitations will have to be changed. If this number is manageable and the changes can be implemented by 1993, the Tevatron collider energy could rise to 2 TeV for the 1993 collider run.

TEVATRON COLLIDER PARAMETERS IN 1993

The operating parameters of the collider during this run are based on an extrapolation from operation during the 1988-89 collider run, including the expected improvements discussed above.

Table 2.1: Luminosity Parameters in the 1993 Collider Run

	1988-89 Collider Run	1993 Collider Run	Improvement factor
Number of bunches	6	36	
Total energy (TeV)	1.8	2	1.1
Protons/bunch ($\times 10^{10}$)	7	10	1.4
Antiprotons (total, $\times 10^{10}$)	18	56	3.1
Proton emittance (95%, π mm-mrad)	25	15	1.7
Antiproton emittance (95%, π mm-mrad)	15	19	0.8
β^* (m)	0.55	0.5	1.1
Initial Luminosity (10^{30}/cm^2/sec)	**1.6**	**10.6**	**6.6**

Table 2.1 presents a comparison between the 1988-89 collider run and the 1993 collider run for the fundamental parameters which determine the luminosity. The last column in the table shows the improvement factor for each parameter. For the protons, the growth in intensity is due to the Linac Upgrade. To understand the reduction in transverse emittance, it must be remembered that during the 1988-89 collider run, the proton transverse emittance was deliberately increased to the number shown in the table in order to control the beam-beam interaction. With the separator system in place, this will no longer be necessary; hence the smaller emittance (which corresponds to that available from the Booster) shown in the table for the 1993 collider run.

For the antiprotons, the growth in total number is due to the improvements in the Antiproton Source related to the stacking rate and to the Linac Upgrade. This is seen more clearly in Table 2.2, which shows some of the details related to the antiproton source:

Table 2.2: Parameters related to the Antiproton Source in 1988-89, and in 1993

	1988-89 Collider Run	1993 Collider Run
Number of bunches	6	36
Antiprotons/bunch ($x10^{10}$)	2.9	1.5
Peak antiproton stacking rate ($x10^{10}$/hr)	2	7
Required stacking time (hrs)	24	17
Antiproton core before transfer ($x10^{10}$)	64	125
Antiproton core after transfer ($x10^{10}$)	38	40
Fraction of antiproton core transferred (%)	41	71
Antiproton transfer efficiency (%)	67	63

The antiproton stacking rate grows by more than a factor of 3. Moreover, partially because of the improved core cooling system in the Accumulator and partially because of the large number of bunches, a larger fraction of the stack will be able to be transferred to the Tevatron. The overall result is a growth of more than a factor of three in antiproton intensity. There is a small increase expected in the antiproton emittance. Without the upgrade to 4-8 GHz for the core cooling, the emittance would be roughly twice the projected number and would never fit through the Main Ring.

LUMINOSITY LIMITATIONS IN 1993

With the upgrades for the 1993 collider run which have been discussed above, it is natural to ask what the limitations to the luminosity are expected to be during that run.

With the separator system acting to limit the number of head-on beam-beam crossings to two, the beam-beam strength parameter, which was 0.025 during the 1988-89 run, will be only 0.01 for 1993. It is therefore arguable that there is substantial room for an increase here. This would require a higher proton intensity, but we are limited by the Main Ring. The Linac upgrade and the existing Booster are capable of providing single batch intensities to the Main Ring in excess of $5x10^{12}$. The limit,in fact, is related to a coupled bunch longitudinal instability in the Booster which, if brought fully under control, would allow even higher intensities to be delivered to the Main Ring. However, because of its restricted admittance, the Main Ring will be limited to single batch intensities of no more than about $3x10^{12}$ (intensities per bunch of about $4x10^{10}$). Longitudinal emittance growth in the Main Ring during the acceleration cycle and inefficiencies in the coalescing process limit the expected coalesced proton bunch intensities to about 10^{11}, as shown in Table 2.1.

The restriction in proton intensity imposed by the Main Ring also limits the luminosity through the antiproton stacking rate. With the upgrades to the Antiproton Source discussed above, the stacking rate of about $7x10^{10}$/hour is still substantially below the Tevatron I project design. Having rebuilt the Debuncher transverse cooling system and implemented momentum cooling, the Debuncher acceptance is limited by the physical apertures of the ring magnets themselves. Thus, there are no remaining simple methods for significant improvements in the antiproton yield. However, the stacking rate could be increased by targeting more protons: the improvements to the targeting systems discussed above are designed to allow targeting as much beam as the Booster can provide, i.e., $5x10^{12}$/batch. The Main Ring, of course, will not allow this. Alternatively, the stacking rate could be increased by cycling the Antiproton Source more rapidly. Again, the Main Ring restricts this option. The present Main Ring has not yet even reached the Tevatron I design goal of 0.5 Hz in terms of cycle rate, and it is not clear if it ever will.

Even if the stacking rate could be increased substantially, the Main Ring still imposes a bottleneck during antiproton transfer. The Accumulator core cooling system upgrade to 4-8 GHz pushed the saturation limit core size to about $140x10^{10}$. Further upgrades to the bandwidth of this system (to 8-16 GHz, for example) are technologically very challenging, and in addition are of limited effectiveness because of the onset of Schottky band overlap at these high frequencies. Thus, the Main Ring aperture fundamentally limits the useful core sizes to about $140x10^{10}$, which is what is shown above for the 1993 run. Even for these conditions, a significant price is being paid due to the Main Ring. The 63% transfer efficiency results from losses which are dominantly at 8 GeV in the Main Ring.

One of the major consequences of the necessity of operating the Main Ring with beam sizes so close to its admittance is the inevitable generation of losses during injection and acceleration. The major problem caused by these losses is background at the collider detectors, which are sensitive to loss rates of a few kilohertz (one part in 10^8 of the Main Ring beam intensity). Because the losses are due to a complex combination of limited transverse dynamic and physical aperture and limited momentum aperture in both planes, they are very difficult to understand and, hence, to isolate and control. The need to control the losses puts severe operational restrictions on the Main Ring. These will only become worse as the beam intensity increases. In addition, there are operational restrictions and performance limitations imposed on the collider detectors themselves.

It should be clear from the above discussion that virtually all the limitations to the luminosity expected in the 1993 collider run are related in one form or another to the Main Ring. The Main Ring is the fundamental obstacle to further luminosity improvements after 1993. It is this fact which forms one of the primary motivations for the Main Injector proposal.

TEVATRON OPERATION WITH THE MAIN INJECTOR

The Main Injector is a 150 GeV synchrotron in a new tunnel which replaces the Main Ring in all its functions. It has a radius about half that of the Main Ring and uses some of the same components. It is proposed as a line-item construction project beginning in FY1992, with completion in time for the 1995 collider run. The principal features of the Main Injector which will allow the limitations discussed above to be overcome are:

1. Improved admittance: The transverse admittance at 8 GeV will be 40 π mm-mrad, vs about 12 π mm-mrad for the Main Ring. Also, improved longitudinal aperture and reduced machine impedance, which will reduce

longitudinal emittance growth during the acceleration cycle and reduce inefficiencies during coalescing. These improvements remove the intensity bottleneck and will allow the delivery of the full intensity of the Linac/Booster injectors to the Antiproton Source for antiproton production, and to the Tevatron for use in the collider. The increase in transverse aperture also removes the limitation on efficient antiproton transfers from cores of greater than 140×10^{10}.

2. Improved cycle rate for antiproton production: The rate will be 0.67 Hz, vs .385 Hz for the present Main Ring. This will result in a direct increase in stacking rate. Since this cycle rate exceeds the design specifications of the Antiproton Source, it is anticipated that there will have to be some improvements in the Source. In particular, the stack-tail cooling system will probably need a bandwidth upgrade to 2-4 GHz.

3. Removal of the major source of background from the environment of the collider detectors. Not only will this improve the environment, but it will also obviate the need for periodic gating off the detector and, thereby, will increase the physics live-time.

Table 2.3: Luminosity Parameters in the 1995 Collider Run

	1993 Collider Run	1995 Collider Run	Improvement factor
Number of bunches	36	36	
Total energy (TeV)	2	2	1.0
Protons/bunch ($\times 10^{10}$)	10	33	3.3
Antiprotons (total, $\times 10^{10}$)	56	134	2.4
Proton emittance (95%, π mm-mrad)	15	30	0.5
Antiproton emittance (95%, π mm-mrad)	19	22	0.9
β^* (m)	0.5	0.5	1.0
Initial Luminosity (10^{30}/cm^2/sec)	**10.6**	**54.4**	**5.1**

Table 2.3 details the fundamental parameters related to the luminosity which are specified for operation with the Main Injector. The overall increase in luminosity is about a factor of five. There is a factor of 3.3 growth in the proton intensity and a factor of 2.4 growth in the antiproton intensity. Although these factors alone produce more than a factor of 7 potential increase, this is not fully realized above for two reasons.

First, the inevitable growth of the antiproton emittance with stack size results in a larger antiproton emittance than in the 1993 collider run. Table 2.4 shows the antiproton source parameters expected with the Main Injector:

Table 2.4: Parameters related to the Antiproton Source in 1993 and in 1995

	1993 Collider Run	1995 Collider Run
Number of bunches	36	36
Antiprotons/bunch ($x10^{10}$)	1.5	3.7
Peak antiproton stacking rate ($x10^{10}$/hr)	7.6	16.8
Required stacking time (hrs)	17	12
Antiproton core before transfer ($x10^{10}$)	125	198
Antiproton core after transfer ($x10^{10}$)	40	57
Fraction of antiproton core transferred (%)	71	71
Antiproton transfer efficiency (%)	63	95

The antiprotons are extracted from a stack of almost $2x10^{12}$, but are transferred with high efficiency because of the improved Main Injector aperture. The stacking rate has increased by more than a factor of two as a result of the increase in beam intensity on target for antiproton production and the increased Antiproton Source cycle rate.

The second reason that a simple factor of 7 improvement is not realized is related to the proton emittance. Table 3 shows the proton emittance as 30 π mm-mrad. In fact, this is about 10-15 π mm-mrad larger than what will be available from the Booster. This emittance growth has been deliberately introduced in order to control the beam-beam strength parameter ξ. The parameter attains the value .017 for the conditions corresponding to table 3. This value is comfortably less than the .025 with which we have demonstrated that we can operate. For the conditions shown in table 3, the proton emittance is about 8 π mm-mrad larger than that of the antiprotons. This situation was found to be favored operationally during the 1988-89 run. For head-on collisions, this keeps most of the weak (antiproton) beam distribution within the relatively linear part of the fields generated by the strong (proton) beam. For the antiprotons, this reduces the strength of non-linear resonance excitation by the beam-beam interaction. There are some recent results from CERN which indicate that operation with equal emittances may be possible under some circumstances, even in the weak-strong regime. We have not assumed that here. However, if it is indeed possible, then the proton emittance can be reduced to 22 π mm-mrad and the luminosity will rise by 20%.

Although the parameter ξ will be smaller in the 1995 collider run than in the last run, the beam-beam strength parameter per bunch crossing, ξ/n_c, will be about .008, vs. about .002 in the 1988-89 run. Nevertheless, all operational experience with both the Tevatron and the CERN SPS colliders is compatible with the following statement: the only relevant requirement is that the <u>total</u> beam-beam strength parameter ξ be sufficiently small that the tunes do not overlap resonances of order 10 or lower. In fact, the CERN SPS collider has operated recently with separated beams, and with a value of ξ/n_c of .006, and has observed no evidence to contradict the above statement.

With 36 bunch operation and separated beams, there will be 2 head-on collisions and 70 long-range beam-beam interactions per revolution. The long-range interactions will occur with an average separation of greater than 5σ. Although the number of long-range collisions is large, the beam-beam forces are small for each interaction. Analysis has indicated that, at least for particles near the center of the distribution, the nonlinear effects of the long-range collisions are small compared to those of the two head-on collisions. The linear effects of the long-range interactions (e.g, closed-orbit distortions and tune shifts) are also small and can be corrected using the separator system and associated sextupole correction circuits.

Because of the complexity of the long-range beam-beam phenomena, beam studies such as those discussed in the first section of this presentation will continue to be crucial to the development of a full understanding. It should be noted that separated orbit operation of a hadron collider has been demonstrated during 1988-89. The CERN SPS collider operated with horizontally separated beams. There were 3 head-on collisions and 9 long-range collisions at an average separation of about 5σ. The value of ξ was about .018.

The single bunch proton intensities presented in Table 3 are more than 4 times those of the 1988-89 collider run. Nevertheless, these intensities correspond to peak instantaneous bunch currents which are comparable to or less than those routinely used today in the CERN PS and SPS for colliding beam operation. This fact is persuasive that, at least in principle, beam instability issues should be able to be brought under control. This will require careful attention to the Tevatron impedance budget, especially with regard to new devices installed for colliding beam operation (separators, new kickers, etc.). New systems for chromaticity control, active transverse and longitudinal damping, and the implementation of Landau damping, will all have to be considered. There do not, however, appear to be any fundamental instability problems associated with the bunch intensities and emittances specified for the 1995 collider run.

CONCLUSION

A brief outline of the accelerator improvements which are expected to be in place for the 1993 Tevatron collider run has been presented. The extrapolated performance specifications of the collider during this run, which are based on the measured performance during the 1988-89 run and the expected gains associated with the improvements, were enumerated. The limitations to further improvements beyond 1993 were shown to be virtually all related to fundamental problems with the Main Ring. These limitations will be overcome with the Main Injector, which is proposed to be in place by the 1995 collider run. The improved

Tevatron collider performance with the Main Injector was discussed in detail; issues related to the beam-beam interaction and beam stability were briefly reviewed.

The accelerator improvements leading up to the 1993 collider run, followed by the Main Injector, will allow the Fermilab collider and fixed target programs to continue forefront research to the end of the 1990's. Future improvements to Fermilab's accelerators must evolve from previous developments in a direction which optimizes the capability for operation at the energy frontier for as long as this capability is unique, but at the same time is consistent with Fermilab's role in the US high energy physics program after the energy frontier passes to the SSC Laboratory. A program of advanced accelerator R&D is planned to be initiated in the Accelerator Division to help develop the expertise, talent and vision which will be necessary to plan for these future possibilities. In addition, strong support for the development of young accelerator physicists, in the areas of junior staff, postdoctoral and Ph.D. students, will continue to be a vital ingredient of the Fermilab Accelerator Division's contribution to the laboratory's mission.

THE MAIN INJECTOR AND PHYSICS USING ITS BEAM

The Fermilab Main Injector is a new accelerator designed to support a luminosity in excess of $5 \times 10^{31} cm^{-2} sec^{-1}$ in the TEVATRON $\bar{p}p$. Collider. At the same time, it can provide significantly enhanced external beams to extend Fermilab's physics reach.

Construction of the Main Injector will remove once and for all the Main Ring bottleneck which restricts both our ability to deliver high intensity proton and antiproton beams to the Tevatron and our ability to deliver more protons onto the $\bar{p}$ production target. The concept of this machine has been developed over the past two years. A Contruction Project Data Sheet (Schedule 44) and Conceptual Design Report have been prepared and submitted to the Department of Energy requesting construction funds starting in FY 1992. The total estimated cost (TEC) of the Main Injector is $158M. Incorporation of associated R&D, pre-operating, and capital equipment leads to a total project cost (TPC) of $181M. Development work on the new dipole magnets required for this ring was initiated on October 1, 1989. A three day comprehensive review of the entire project was completed by the Department of Energy in January of 1990. It is proposed to complete the project over a 38 month period starting on October 1, 1991. Construction will require a seven month disruption to the Fermilab High Energy Physics program starting on April 1, 1994.

ROLE IN FERMILAB III

The Main Injector (MI) is specifically designed to carry out in a much more efficient manner the support functions currently being provided by the Main Ring. The Main Injector will be constructed tangent to the TEVATRON in a separate tunnel on the southwest corner of the Fermilab site. The Main Injector is roughly half the size of the existing Main Ring yet will boast greatly improved performance. The MI will allow the production of about five times as many antiprotons per hour as are currently possible using the Main Ring and will have a capability for the delivery of three times as many protons to the TEVATRON. The Main Injector is anticipated to support a luminosity of at least $5\times10^{31}cm^{-2}sec^{-1}$ in the collider, a factor of 30 larger than the current operation.

In addition to furthering the collider based search for the top quark and potential high-mass extensions to the Standard Model, construction of the Main Injector will simplify and enhance operations of the Fermilab complex. By removing the Main Ring from the vicinity of the TEVATRON (these two accelerators presently share a common tunnel) interferences with the experimental detectors studying $\bar{p}p$ interactions will be eliminated. The Main Injector will support the delivery of very intense proton beams to existing experimental areas where they can be used for state-of-the-art studies of quantum number conservation laws and for experiments designed to search for transmutation between different neutrino generations. Finally, low intensity proton beams emanating from the Main Injector will support test and calibration beams required for the development of new experimental detection devices which will be required both at Fermilab and at the SSC.

PERFORMANCE

The Main Injector is designed to perform all duties currently required of the Main Ring. Following construction of the Main Injector operation of the Main Ring will cease. In fact many Main Ring components, including the RF, quadrupole magnet/power supply, and the correction element systems, will be recycled into the Main Injector. The construction of the Main Injector will simultaneously result in significant enhancements to the Fermilab collider and fixed target programs. Benefits expected to accrue from construction of this machine include:

1. An increase in the number of protons targeted for $\bar{p}$ production from 5.0×10^{15}/hour (following the linac upgrade) to 1.2×10^{16}/hour.

2. An increase in the total number of protons which can be delivered to the Tevatron to 6×10^{13}.

3. The ability to accelerate efficiently antiprotons originating in stacks containing 2×10^{12} $\bar{p}$'s for injection into the Tevatron Collider.

4. The ability to produce proton bunches containing up to 3×10^{11} protons for injection into the Tevatron Collider.

5. The reduction of backgrounds and deadtime at the CDF and D0 detectors through removal of the Main Ring from the Tevatron tunnel.

6. Provision for slow extracted beams at 120 GeV year around. Such beams would be used both for detector development test beams, and to support the development of very high intensity, high duty factor ($>1 \times 10^{13}$ protons/sec at 120 GeV with a 34% duty factor) beams for use in high sensitivity K decay and neutrino experiments.

The Main Injector parameter list is given in the accompanying table. The Main Injector will perform at a significantly higher level than the existing Main Ring as measured either in terms of protons delivered per cycle, protons delivered per second, or transmission efficiency. For the most part, expected improvements in performance are directly related to optics of the ring. The MI ring lies in a plane with stronger focussing per unit length than the Main Ring. This means that the maximum betas are half as big and the maximum (horizontal) dispersion a third as big as in the Main Ring, while vertical dispersion is nonexistent. As a result, physical beam sizes associated with given transverse and longitudinal emittances are significantly reduced compared to the Main Ring. The elimination of dispersion in the RF regions, raising the level of the injection field, elimination of sagitta, and improved field quality in the dipoles will all have a beneficial impact on beam dynamics. The construction of new, mechanically simpler magnets is expected to yield a highly reliable machine.

Main Injector Parameter List

Circumference	3319.419	meters
Injection Momentum	8.9	GeV/c
Peak Momentum	150	GeV/c
Minimum Cycle Time (@120 GeV)	1.5	sec
Number of Protons	$3x10^{13}$	
Harmonic Number (@53 MHz)	588	
Horizontal Tune	22.42	
Vertical Tune	22.43	
Transition Gamma	20.4	
Natural Chromaticity (H)	-27.5	
Natural Chromaticity (V)	-28.5	
Number of Bunches	498	
Protons/bunch	$6x10^{10}$	
Transverse Emittance (Normalized)	20π	mm-mr
Longitudinal Emittance	0.4	eV-sec
Transverse Admittance (at 8.9 GeV)	40π	mm-mr
Longitudinal Admittance	0.5	eV-sec
βmax (Arcs)	57	meters
βmax (Straight Sections)	80	meters
Maximum Dispersion	2.2	meters
Number of Straight Sections	8	
Length of Standard Cell	34.3	meters
Phase Advance per Cell	90	degrees
RF Frequency (Injection)	52.8	MHz
RF Frequency (Extraction)	53.1	MHz
RF Voltage	4	MV
Number of Dipoles	300	
Dipole Length	6.1	meters
Dipole Field (@150 GeV)	7.3	kGauss
Dipole Field (@8.9 GeV)	1.0	kGauss
Number of Quadrupoles	202	
Quadrupole Gradient	196	kG/m
Number of Quadrupole Types	3	
Number of Quadrupole Busses	2	

The Main Injector is seven times the circumference of the Booster and slightly more than half the circumference of the existing Main Ring and Tevatron. Six Booster cycles will be required to fill the MI and two MI cycles to fill the Tevatron. The MI is designed to have a transverse aperture of 40π mm-mr (both planes, normalized at 8.9 GeV/c). This is 30% larger than the expected Booster aperture following the 400 MeV Linac upgrade, and a factor of three to four larger than that of the existing Main Ring. It is expected that the Linac upgrade will yield a beam intensity out of the Booster of $5\text{-}7\times10^{12}$ protons per batch with a $20\text{-}30\pi$ mm-mr transverse and a 0.4 eV-sec longitudinal emittance. (All emittances are quoted as 95% normalized values.) A single Booster batch needs to be accelerated for antiproton production while six such batches are required to fill the MI. The MI should be capable of accepting and accelerating these protons without significant beam loss or degradation of beam quality. Yields out of the MI for a full ring are expected to lie in the range $3\text{-}4\times10^{13}$ protons ($6\text{-}8\times10^{13}$ delivered to the Tevatron.) By way of contrast, the existing Main Ring is capable of accelerating 1.8×10^{13} protons in twelve batches for delivery to the Tevatron.

The power supply and magnet system is designed to allow a significant increase in the number of 120 GeV acceleration cycles which can be run each hour for antiproton production, as well as to allow a 120 GeV slow spill with a 35% duty factor. The cycle time at 120 GeV can be as low as 1.5 seconds. This is believed to represent the maximum rate at which the Antiproton Source might ultimately stack antiprotons and is to be compared to the current Main Ring capability of 2.6 seconds. The dipole magnets to be used are designed with twice the total cross section of copper and half as many turns as existing Main Ring dipoles. This is done to keep the total power dissipated in the dipoles during antiproton production at roughly the same level as in present operations while keeping the number of power supplies and service buildings low.

OPERATING SCENARIOS

Four different operation scenarios have been identified for the Main Injector and are summarized below. Simultaneous antiproton production and slow spill operation will be possible under normal circumstances, i.e. the antiproton stack has not recently been lost. It should be noted that delivery of beam from the Main Injector to all experimental areas is compatible with TEVATRON Collider running, while delivery of beam to the dedicated K/ν line is compatible with TEVATRON Collider and Fixed Target operations.

Operational Mode	Energy	Cycle	Flattop	Power
Antiproton Production	120 GeV	1.5 sec	0.05 sec	7.1 MW
Fixed Target Injection	150	3.0	0.05	6.2
Collider Injection	150	9.0	3.0	10.9
Slow Spill	120	2.9	1.0	11.9

THE MAIN INJECTOR FIXED TARGET PROGRAM

While the Main Injector was primarily designed to boost the luminosity in the TEVATRON Collider, it has been recognized for some time that the high intensity, moderate energy capability presents a unique opportunity for investigation of the high energy behavior of the Standard Model as manifested in subtle effects at modest energies. To this end a slow spill capability has been incorporated into the machine design.

Many possibilities for HEP based on the Main Injector were explored at a "Workshop on Physics at the Main Injector" held in May of 1989. Interest centered on the physics of rare K decays and CP violation, and on neutrino physics including oscillations. To date, Fermilab has received three letters of intent for experiments based on beam emanating from the Main Injector. The physics of these are explained below.

HIGH PRECISION, HIGH SENSITIVITY K^0 PHYSICS

The search for the origin of CP violation has been a major effort at Fermilab over the last decade. The most recent efforts have focussed on a search for direct CP violation in K to two pion decay -- a means of distinguishing the Superweak hypothesis from the Standard Model through measurement of the quantity ε'/ε. The published result from a 20% analysis of Fermilab experiment E731 (-.0004 ± .0015) does not confirm the NA31 experiment claim of significant evidence for direct CP violation (+.0033 ± .0011). Some recent calculations of ε'/ε tend toward lower amounts of direct CP violation, $\varepsilon'/\varepsilon \leq 0.001$. A heavy top quark might also account for a small ε'/ε within the Standard Model.

What lies ahead? If the full analysis of the E731 data converges within a standard deviation or so of the current central value, the question of Standard Model versus Superweak remains open. Experimental efforts aimed at addressing this question will be pursued well into the 90's, first at the Tevatron and then at the Main Injector as described below.

Along the way there will continue to be many byproduct physics results and needed gains in detector development. Byproducts of the first 20% of the E731 data of include published measurements of the phase difference between η_{+-} and η_{oo} and a CPT test with a precision of 3 degrees -- equal to CERN's result from a dedicated experiment. The full data analysis should reach a sensitivity of about 1.5 degrees. The best measurement of $K \rightarrow \pi^o\gamma\gamma$ to date (BR < $2.7\text{x}10^{-6}$) also comes from the 20% sample with an expected sensitivity of the full data set at several times 10^{-7}. This is near the predictions of chiral perturbation theory and is an important measurement for the untangling of the CP violating and CP conserving contributions to the decay $K_L^o \rightarrow \pi^o e^+ e^-$. A recently submitted E731 measurement of the upper limit for this mode ($7.5\text{x}10^{-9}$) is competitive with the recent and currently best limit from a dedicated BNL experiment ($5.5\text{x}10^{-9}$). There is significant sensitivity to many other modes containing π^o's and γ's including $K \rightarrow \pi\pi\gamma$ and a novel technique to measure $\pi^o \rightarrow e^+e^-$decays using "tagged" π^o's from observed $K \rightarrow 3\pi^o$ decays.

During the next three years at the Tevatron there will be continued movement toward higher sensitivities along with development of needed techniques and byproduct physics. E773 will measure both $\Delta\phi$ and ϕ+- to 0.5 degree. Significant new detector elements include a high rate trigger processor and fully active regenerators to produce K shorts. E799, a dedicated rare decay experiment, will push the branching ratio sensitivity of $K_L \rightarrow \pi^o e^+ e^-$ to $1\text{x}10^{-11}$ -- the level expected from the Standard Model. An extensive Monte Carlo study of backgrounds using real E731 data has simulated about 20 background modes at the 10^{-12} level. Tests of two new materials for high rate electromagnetic calorimetry, BaF and PbF_2, will be made. A new TRD system for electron/pion separation will be included. The measurement of $K \rightarrow \pi^o e^+ e^-$ will be completed during the early test run of this experiment and many other byproduct measurements of decays containing gammas and π^os are expected.

To push beyond today's levels of ε'/ε and the E799 reach for $K_L \rightarrow \pi^o e^+ e^-$ will require a new generation of kaon beam and spectrometer. A clean and bright beam of neutral kaons and a high rate, high (4-body) acceptance spectrometer are needed. These must combine to yield statistical sensitivities of 10^{-10} per hour, along with corresponding controls of systematic effects. The Main Injector with 120 GeV protons will provide a unique and copious source of neutral kaons of sufficient energy to make the necessary detection (and vetoing) of photons for these measurements possible. A letter of intent and the results of the Breckenridge summer study describe the plans for measuring ε'/ε to 10^{-4} and ultimately pushing below $1\text{x}10^{-13}$ on $K_L \rightarrow \pi^o e^+ e^-$. Eight institutions are committed and a letter of intent, P804, was submitted last June. Significantly, the signatories include members of four formerly distinct kaon physics collaborations.

As in the current Tevatron program, there would be a blend of physics results and detector R&D as the sensitivities are pushed from Standard Model limits to Standard Model measurements (always mindful of possible surprises along the way). A large, high rate electromagnetic calorimeter will be needed. The E799 BaF and PbF_2 experience will guide the development. A measurement of ε'/ε to a precision of $5\text{x}10^{-5}$ using 10^{20} protons in a 3000 hour run would be done using the technique of E731 with an E773 style, fully active regenerator. A pair of small solid angle K_L beams (0.20 micro steradians) will contain 16 MHz of

Kaons (and roughly the same rate of neutrons). Almost 1 MHz of Kaon decays in a 20 meter decay region would yield 200 K $\rightarrow 2\pi^0$ decays and 500 K $\rightarrow \pi^+\pi^-$ decays per spill. Combined singles rates from K decays and neutron interactions for this first-phase measurement would be around 3 MHz. A byproduct measurement of $K_L \rightarrow \pi^0 e^+ e^-$ to 3×10^{-12} will serve as the launching point for the next phase where this mode would be measured in a hotter (larger solid angle) beam containing 10 times the flux. Thus phase 2 pushes to 3×10^{-13} in statistical sensitivity. Another factor of 10 in beam (again an increase in beam solid angle to a modest 20 microsteradian) will allow a statistical sensitivity of 3×10^{-14}, based on >100 MHz of K decays.

MUON NEUTRINO TO TAU NEUTRINO OSCILLATIONS

P803 is a hybrid emulsion-electronic experiment in which tau and charm decays can be directly observed with high efficiency on an event-by-event basis. This experiment can push 90% CL limits on muon neutrino to tau neutrino mixing well below the mixing angles in the quark sector, and will be able to demonstrate the existence of a positive oscillation signal should one exist at this level of sensitivity.

By analogy with the quark sector one might expect that if neutrinos have mass, the third-generation neutrino would be heaviest and that mixing would be largest between adjacent generations. Interest is further enhanced by the fact that the tau neutrino, if massive, is the only known particle which could provide enough mass to close the universe. The best present limit on the mixing of muon and tau neutrinos in the high-mass limit comes from Fermilab Experiment 531, $\sin^2 2\alpha < .004$. P803 can improve this limit in a single run by a factor of 20, while also providing a limit on electron to tau neutrino oscillation of 8×10^{-3}. Presently, two runs are planned. With modest additional effort, the Kobayashi-Maskawa matrix element V_{cd} can be measured to ±2.5%, a precision comparable to unitarity estimates (~1%). Any discrepancy between the unitarity and direct measurements of V_{cd} could indicate a breakdown of the Standard Model. The best present knowledge of V_{cd} is extracted from the valence quark contribution to high-energy charm production by neutrinos, which is measured indirectly by observing dimuon signals. Depending on interpretation of systematic errors, this parameter is known to 8-13%. In P803, charm decays will be seen directly, avoiding dimuon systematics. Also, low neutrino energies ensure that production from the valence d quark will dominate due to "slow rescaling" suppression (from the massiveness of the charm quark) of the strange sea contribution. Finally, slow rescaling effects in low-energy antineutrino production of anticharm are large, allowing this effect to be carefully studied.

The large increase in sensitivity to neutrino oscillations relative to E531 comes from an eightfold increase in emulsion target mass and an eighteen-fold increase in protons on target provided by the rapid-cycling 120 GeV beam from the Main Injector in one eight-month running period. Although the portion of the neutrino beam below about 10 GeV is not useful in producing detectable taus (due to cross section suppression by kinematic and helicity effects), the huge flux per unit real time available from this beam more than compensates for its low energy. Further, low energy is a definite advantage in reducing potential sources of background.

To search for neutrino oscillations, the experiment will search for short (<2.5mm) one-prong decays of negative particles in events which have no identified muon or electron from the primary vertex (thus ruling out positive charm production by neutrinos, and all backgrounds from charged-current events). It will use an emulsion target 180 x 180 x 7.5 cm^3 in volume (0.84 tons), and a spectrometer designed to fit inside an existing large-aperture superconducting magnet (from the 15 foot bubble chamber). The spectrometer will have good tracking and electron- and muon-identification capability.

Backgrounds which limit the sensitivity are all measureable, and have kinematic features distinctly different from the signal. These include kaon and hyperon decays, anticharm decays from antineutrino contamination in the beam and single-prong interactions with no indication of nuclear breakup. The latter at present is considered to be potentially the largest source of background, and over the next several months will be studied through emulsion exposures at KEK and Fermilab. Non-charm backgrounds are nearly uniformly distributed in path length, while half of the taus decay in 0.5 mm. Anticharm backgrounds come from charged-current interactions which can be suppressed by rejecting events with positive primary electrons and muons.

At present, an experimental design exists which is based on full Monte Carlo simulations at the hit level. The final version will be submitted to Fermilab for further review at the June, 1990 Aspen meeting of the PAC.

LONG BASELINE OSCILLATION EXPERIMENT USING THE IMB WATER CERENKOV DETECTOR

IMB is a large, underground water detector originally constructed for a proton decay search. The effective mass for neutrino interactions is 24,000 tons. The IMB detector features very good muon and electron detection. The detector lies 581 km due east of the Main Injector. The Main Injector design includes an uninstrumented straight section capable of resonant extraction which points in the correct general direction for delivery of neutrinos toward IMB. The neutrino beam has to be aimed to 1 mr in order to strike the detector.

It is calculated that 12,000 ν_μ interactions could be observed per year with negligible background. This would provide a very good measurement of ν_μ disappearance and/or $\nu_\mu \rightarrow \nu_e$ oscillations with unprecedented sensitivity to Δm^2 (down to 0.01 eV^2) due to the long baseline. The proponents of this experiment are currently studying ways in which ν_τ's might be directly identified in their detector.

COST AND SCHEDULE

The total estimated cost (TEC) of the Main Injector is $158M. Incorporation of associated R&D, pre-operating, and capital equipment leads to a total project cost (TPC) of $181M. The exact allocation of money between the TEC and TPC (at the $15M level) is still under negotiation with the Department of Energy. The project cost does not include beamlines, buildings, and detectors associated with the Main Injector fixed target program. Subject to the vagaries of assigning costs to experimental efforts which are in the conceptual design stage, such costs are estimated at $50M.

Fermilab has proposed construction of the Main Injector over the period of October 1, 1991 through December 1, 1994. The construction schedule results in a seven month disruption to the High Energy Physics program starting on April 1, 1994. HEP can be reinitiated with Collider physics and Main Injector Fixed Target physics running concurrently.

SUMMARY

The construction of the Main Injector will guarantee a vibrant High Energy Physics program in the U. S. during the period leading up to utilization of the SSC. It will provide a proving ground for many of the experimental techniques which need to be developed for utilization of the SSC. It will also continue the training of young researchers with real physics research, research which will also sustain progress in our understanding of the basic structure of matter.

CHARM AND BEAUTY PHYSICS

INTRODUCTION

Heavy flavor physics has a very successful history at Fermilab in fixed target photo- and hadro-production of charm. Present data samples contain up to 10K fully reconstructed charm decays per experiment, over 30K decays in total. These high statistics samples are rich in physics, contributing significant measurements of:

- charm particle lifetimes
- relative branching ratios for exclusive final states
- semi-leptonic branching ratios and polarization
- D^0 mixing and double Cabibbo suppressed decays (limits)
- meson and baryon spectroscopy
- limits on rare and forbidden decays
- parameterization of total and differential cross-sections

These measurements lead to a detailed picture of the decay process at the quark level, and progress is being made in determining the form factors that describe the hadronization process. With high statistics, the search for rare and forbidden decays becomes a test of the standard model. The data on the charm cross-section are in good agreement with the recent next-to-leading order perturbative QCD calculations of K. Ellis et al., although for hadroproduction the issues of the A-dependence and the contribution of leading particle effects have yet to be fully resolved. The present experiments will study these issues and will tie down the parameters for the theoretical calculations.

The next generation of fixed target experiments are starting data-taking this spring. Those whose main objective is charm physics will each collect samples yielding over 100K fully reconstructed charm decays, an order of magnitude increase over the last fixed target run. This will increase the sensitivity to rare decay processes. With present detector and data-acquisition technology, it is likely that fixed target experiments could collect samples of 10^6 charm decays in the 1993 run, opening the possibility of measuring D^0 mixing. These and the dedicated B-experiments in the fixed-target program, along with the collider experiments, will study B decays. We expect that the scope of B-physics through the next decade will match that of charm through the last.

The ultimate goal for B-physics is to measure CP-violation in B-meson decays. This, along with other measurements including B_s mixing and B-lifetimes, leads to an overconstraint of the CKM matrix, and a rigorous test of the standard model. Both B_s mixing and CP-violation require the production of very large numbers of B-mesons, with either partial reconstruction of a very large number of decays, requiring very good knowledge of systematic effects and backgrounds, or the full reconstruction of exclusive states with very small branching ratios. These measurements are technically and intellectually challenging and will be a major thrust of particle physics through the 1990's.

HEAVY FLAVOR PHYSICS FOR THE 1990'S

At Fermilab fixed target energies ($\sqrt{s}$=30 GeV) the charm cross-section is 0.5% of the total hadronic cross-section for a photon beam, and 0.1% for a hadron beam. Mean charged track multiplicities are typically 9 and 15 respectively, in the forward cone. The present generation of experiments is sensitive to branching ratios of a fraction of a percent. One example of this is the observation of D^+ and $D_s^+ \to \pi^+\pi^+\pi^-$. Figure 4.1 shows the 3π mass spectrum observed in E691. A

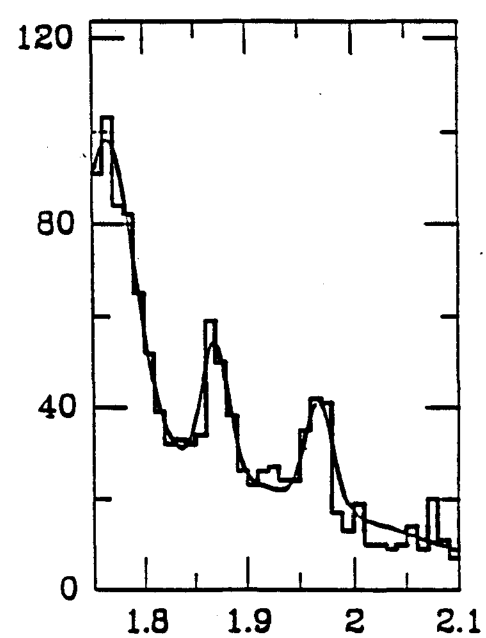

Figure 4.1. $\pi^+\pi^+\pi^-$ mass spectrum from E691, showing D^+ and D_s^+ signals.
$BR(D^+ \to \pi^+\pi^+\pi^-)/BR(D^+ \to K^-\pi^+\pi^+)$
$= 0.035 \pm 0.007 \pm 0.003$

clean signal is seen both for the D^+ and D_s^+. The key to the success of these experiments in extracting clean signals from the confusion of tracks and combinations is their use of precision vertex detectors.

The B cross-section at the collider ($\sqrt{s}$=2000 GeV) , like charm in fixed target experiments, is also about 0.1% of the total cross-section. However the branching to exclusive modes is in general much less than that for charm. Table 4.1 illustrates the rate of B-production at fixed target and collider energies. The Main Injector will provide two orders of magnitude increase in the B production rates for collider experiments over the present CDF data set, and will open new fixed target opportunities through higher beam energies and intensities.

	Fixed-Target 500Gev π or 800Gev p	pre-Main-Inj collider	Main-Injector collider
Luminosity/ int. rate 10^7 seconds	$10^6 - 10^7$ int s^{-1} $10^{13} - 10^{14}$ int	5×10^{30} 50 pb^{-1}	5×10^{31} 500 pb^{-1}
$b\bar{b}$ in 10^7 seconds	1-10 x 10^7 dep. on target	2×10^9	2×10^{10}

Table 4.1. B-production rates

Achieving the high data-rates and background rejection of such experiments will require an extensive R&D effort in detectors and data-acquisition systems, and in trigger or filtering schemes. Given the very high cost of new detectors, the only reasonable approach is to use existing detectors as platforms for the evaluation of future technologies. Our approach at Fermilab is to develop the technology and to test new ideas in experiments addressing increasingly challenging B-physics topics. There are important B-physics results which are more readily attainable, including the measurement of B_s and Λ_b mass, and lifetime measurements. The heavy flavor program at Fermilab is both an R&D program to learn how to reach rarer processes, as well as an on-going (and highly productive) physics program.

Table 4.2 contains a list of heavy flavor experiments and their physics topics for the next fixed-target and collider runs. The fixed target experiments range from general, open-geometry, nearly-open-trigger experiments which will collect very high statistics charm samples and will study B decays through D mesons, to experiments geared to run at the highest interaction rates and to study specific B decay modes. Both CDF and D0 will study B decays at collider energies. CDF will install a vertex detector for their next run which will allow the measurement of the B-decay vertex. Even without this, and with 5 pb^{-1} on tape, CDF has already seen strong evidence for B-production, as can be seen in Figure 4.2. It is clear that if CDF had had a vertex detector last run, they would have been measuring B-decay vertices. However, CDF and D0 are designed for high-p_t physics, although D0 will be able to extend to low p_t for multi-muon events. The distribution of B-decay products at the collider is forward and at low p_t (< 5 GeV/c). In order to maximize B acceptance, an experiment should be sensitive in these regions. A design concept for a dedicated B-physics collider detector was developed at the Snowmass workshops and became the BCD proposal. This effort is now focusing on design, simulation and detector R&D.

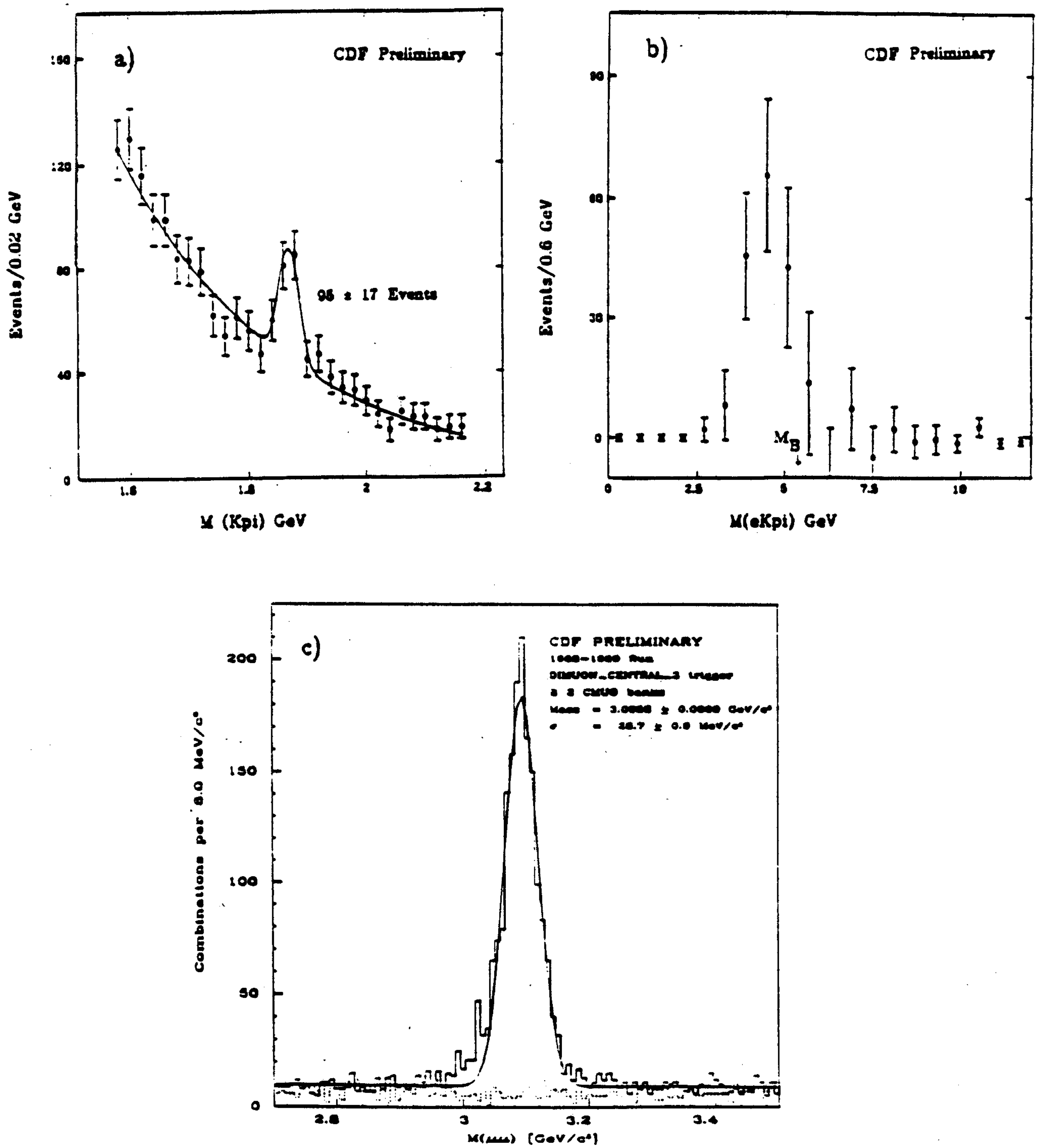

Figure 4.2. a) Two particle mass combinations, assuming K-π, within a cone η-ϕ < 0.6 around an electron candidate.
b) The K-π-e Mass, with the sidebands of the D^0 subtracted
c) Muon pair mass in the ψ region. Dashed histogram is the like-charged pair mass. Some fraction of these ψ's are thought to come from B. This measurement is underway.

Heavy Flavor Experiments		
E687	γ	very high statistics charm, some beauty
E690	p	diffractive production of high mass states
E706/672	π, p	prompt γ, plus charm and beauty via Ψ
E771	p	$B \to \Psi X$ Ψ trigger., high rate.
E781	Σ	charm-strange baryons
E789	p	$B \to h^+h^-$ Very high rates, limited geom.
E791	π	very high statistics charm, some beauty
CDF	$\bar{p}p$	high pt heavy flavor
D0	$\bar{p}p$	high pt heavy flavor (lower for multi-μ)
BCD	$\bar{p}p$	low and intermediate pt beauty; R&D

Table 4.2. Future Heavy Flavor Experiments

Table 4.3 illustrates the likely B-physics reach of these fixed target and collider experiments. Experiments running in the next couple of fixed target and collider runs will measure the total and differential B cross-section, the relative branching ratio for a few exclusive modes, and lifetimes to an accuracy of better than 10% for B_u and B_d, with less precise first measurements for B_s and Λ_b. In terms of R&D, these experiments will provide the opportunity to study triggers and filters based on vertex separation, and the experience with operating vertex detectors in a hadron collider and in a high rate fixed target environment. They will continue to push the performance of data-acquisition systems and the front-end electronics. These are essential steps in developing the ability to do high-statistics precision measurements in a very high luminosity environment.

For B_s mixing and CP-violation, a large sample of B's (10^{10} or more produced) will be needed. As Table 1 shows, the B production rate with the Main Injector is certainly adequate. The challenge is to develop the ability to collect and analyze very large data sets to exploit this resource. This push to high rates and large data samples is a learning process which is necessary for, and will continue through, the SSC era.

	Fixed Target Open Geom: via D (eg. E687, E791)	Fixed Target Open Geom: via J/Ψ (eg. E771)	Fixed Target Restricted Geom (eg. E789)	CDF and D0 Present and with Upgrades	Dedicated B-Collider Expt: eg. mini-BCD	Dedicated B-Collider Expt: eg. BCD
Cross-section (QCD)	measure total and differential cross-section		limited acceptance	for pt > 10 Gev (CDF) and 4 Gev (D0)	for pt > 1 Gev $2 < \lvert\eta\rvert < 4$	for pt > 1 Gev $2 < \lvert\eta\rvert < 4$
Lifetimes	reach <10% measurements in next couple of runs		B^0 limited statistics	next couple of runs with SVX <10% error	~ 1% statistical precision	
B_s mass Λ_b mass	Yes, but limited statistics	depends on branching to J/Ψ	depends on 2-body branching	with SVX but limited statistics	expect 25 Mev mass resolution for both	
Rare Decays ($BR < 10^{-4}$)	need to go to higher beam intensity and/or energy		2-body modes reachable	requires vertex detector, lower pt trigger, Main-Inj. luminosity and DAQ upgrade	$10^{-5 \text{ or } -6}$ reachable without tag	10^{-7} reachable
B_s Mixing	out of reach				mainly R&D	full tagging in a few exclusive modes
CP Violation					explore self-tagging modes	

Table 4.3. Summary of B-physics Reach of Fixed Target and Collider Experiments

Both B_s mixing and CP-violation can be studied semi-inclusively using lepton decays, or using exclusive modes and lepton (and maybe kaon) tags from the other B. As an illustrative example, the observation of CP violation in ΨK_s requires of order 1000 fully reconstructed decays, tagged via a detached semi-leptonic decay, with leptons produced from charm decay cleanly rejected. If one assumes a single detached lepton as a trigger and typical efficiencies and branching ratios the required number of produced B's which decay into ΨK_s is 2×10^7. Assuming a branching ratio of 5×10^{-4} for this decay mode, one needs 4×10^{10} B's produced.

Various methods will be pursued, beginning with the simulation programs developed by CDF, D0 and BCD. In the next run, CDF will have data on the all-important question of the signal to background ratio for detached lepton vertices, allowing a comparison with the Monte-Carlo models.

DETECTOR R&D

Several on-going R&D efforts are directly applicable to the problems of high-rate B-physics experiments. These include the work of various groups (at Fermilab and elsewhere) on detector components, in particular, silicon vertex detectors, pixel devices, straw tubes, RICH counters, VLSI readout electronics and "barrel switch" event builders. As an example we discuss below the work with silicon detectors.

The use of silicon vertex detectors in hostile environments is common to all B-physics experiments and their continued development, and experience with their use in high rate environments is essential for the program at Fermilab and elsewhere. Present experiments use single-sided silicon, typically of 25 or 50 micron strip pitch, at modest rates of about 10^6 particles per second per cm^2. Recent progress includes the development of double sided detectors with various sizes and pitch using VLSI readout. This reduces the multiple-scattering, and allows for a correlation between the charge collected on the two sides, reducing ambiguities.

One issue for such detectors is the effect of radiation damage. There is limited experience at present with large integrated exposure for these devices. At least one fixed target experiment will expose its detectors to up to 10^{14} particles per cm^2 in the next run, and will have the opportunity to map out the effects in a real environment. CDF will soon have experience with the operation of a silicon detector in the collider environment. The BCD group will test a variety of detectors and readout electronics in a test beam this run.

DATA ACQUISITION AND ANALYSIS

The high statistics achievable for B-physics in hadronic interactions carries with it a price in small fractional cross-section and event complexity. This places a burden on data acquisition and analysis, and specialized event selection capability, requiring advances in these areas. Fermilab is already in the forefront with the current generation of experiments which can digitize and read out fixed target events in 1 ms to a pipeline or in 20 ms to buffers, record data at 10 MBytes/second, and reconstruct data from experiments with the order of 10,000 9-track raw data tapes. These are the current achievements. We can continue to advance these techniques and develop B event selection algorithms while doing the earlier stages of B physics research. This evolutionary approach will allow the techniques to be checked at each stage of development.

COMPUTER SIMULATION

The pursuit of B-physics with fixed target and present and future collider experiments has been studied at Snowmass and at last year's meeting at Breckenridge. These studies are continuing. To help determine the best way to study B_s mixing and CP violation, extensive simulation of triggering and filtering schemes is needed to determine their event rejection characteristics, and to determine the level of the remaining background and its effect on the measurements. The data collected in the next few years can be compared to the simulation predictions, improving the extrapolation to higher luminosities, rarer processes, and harder measurements.

CONCLUSION

We expect the heavy flavor program at Fermilab to continue to be highly productive through the 1990's, with the analysis of both very high statistics charm samples, and large samples of beauty decays. With continued simulation studies, advances in detector, electronics and computer technology, and with growing experience we expect to push to higher rates and more precise measurements of rarer processes. R&D on detectors and data-acquisition, coupled with intermediate and attainable physics goals, is the right path towards the study of CP violation in hadron collisions. This path will very likely lead to a collider detector dedicated to B-physics at Fermilab near the end of the century, when D0 or CDF have completed their physics program, or to a beauty experiment at the SSC.

QCD PHYSICS

INTRODUCTION

In the study of hadron collisions, QCD processes are, and will continue to be the baseline against which all new processes are measured. The luminosity upgrades to the Tevatron, and specifically the Main Injector will extend the studies of QCD into a substantially higher energy regime where many new phenomena may be found. In addition, new calculations and improvements in the experiments and understanding of the detectors will increase the precision of the tests of QCD. To illustrate the reach in energy gained by the upgrade, the following collider processes will be discussed along with the discovery potential in each channel: Collider jet cross section, Collider direct photons, and high p_t W's and Z's.

Presently, the state of the theory of QCD is such that it must be split into two separate "theories" - perturbative QCD and non-perturbative QCD. While it is not clear exactly where the dividing line should be placed, perturbative QCD is used to address "hard scattering" processes, such as those dominated by the Collider processes. Non-perturbative QCD covers the "soft" processes and is often needed to interpret hard scattering measurements. The current activity pushes the level of precision at which tests are being performed, both to extend our understanding of the theory as it stands, as well as to look for any unexpected phenomena. This involves using as many fundamental processes as possible, in as large a kinematic range as possible. Fermilab is well suited for such explorations.

Although an extremely large number of experiments have been and are continuing to be performed that are in the "non-perturbative" regime, the ability to interpret their results within universally accepted theoretical framework is still lacking. However, before we accept QCD as "the" theory of strong interactions, we must be able to deal with all such processes.

The Fixed Target program includes many experiments which provide QCD parameters and which probe the essence of the theory. The experiments that will be mentioned in this regard are E-744/E-770 (neutrino deep inelastic scattering), E-665 (muon deep inelastic scattering), E-605/E-772 (high mass dimuon and high p_t hadron production) and E-706 (direct photon production). Results from heavy flavor production experiments (with the exception of the the A dependence of J/ψ and Y production from E-772) are not covered here.

COLLIDER JET CROSS SECTION

The measurement of the inclusive jet cross section ($\bar{p}p \rightarrow$ jet + X) is well defined to all orders of perturbation theory. At any fixed total transverse energy, two jet production dominates the final state over all other cross sections. In particular, because of the large cross section, jet production explores the highest Q^2 available. In particular, the highest invariant mass seen at the Tevatron to date is 1 TeV. Recently, the inclusive jet cross section has been calculated to order α_s^3 by S. Ellis, Z. Kunszt and D. Soper. This calculation greatly reduces the theoretical uncertainty associated with the variation in renormalization scale associated with α_s and the evaluation of the parton distribution function.

Figure 5.1 shows as a function of jet E_t the jet cross section measured by CDF, based on an integrated luminosity of 4.2 pb^{-1}. The most outstanding features are the large range (≈ 7 orders of magnitude) over which the cross section has been measured and the highest transverse energy reached (420 GeV). The solid line, indicating the predictions of leading order QCD, appears to already provide a fairly good description of the data.

The new calculations to α_s^3 have the additional feature that the jet cross section depends on the effective radius in the η-ϕ metric used for clustering. This is because, at the theoretical level, gluon radiation can escape the jet clustering cone. This aspect of the calculation does not exist at leading order where only two partons are emitted in the final state. Figure 5.2 shows the

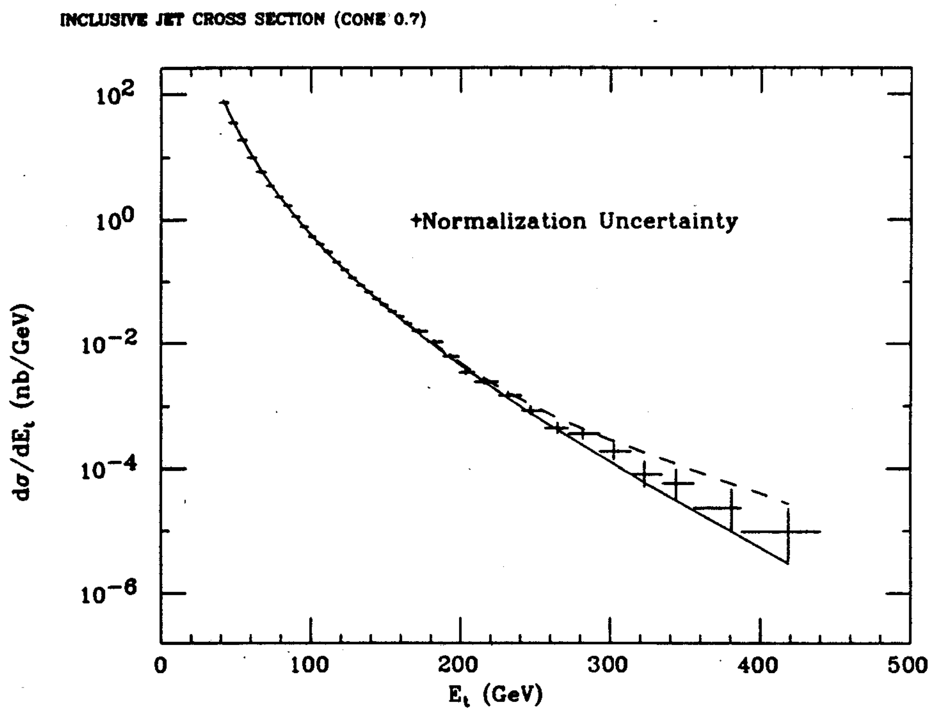

Figure 5.1. The inclusive jet cross section measured by the CDF detector. The solid line is the prediction of leading order QCD, where the curve has been normalized to the data in the region 70 $\leq E_t \leq$ 200 GeV.

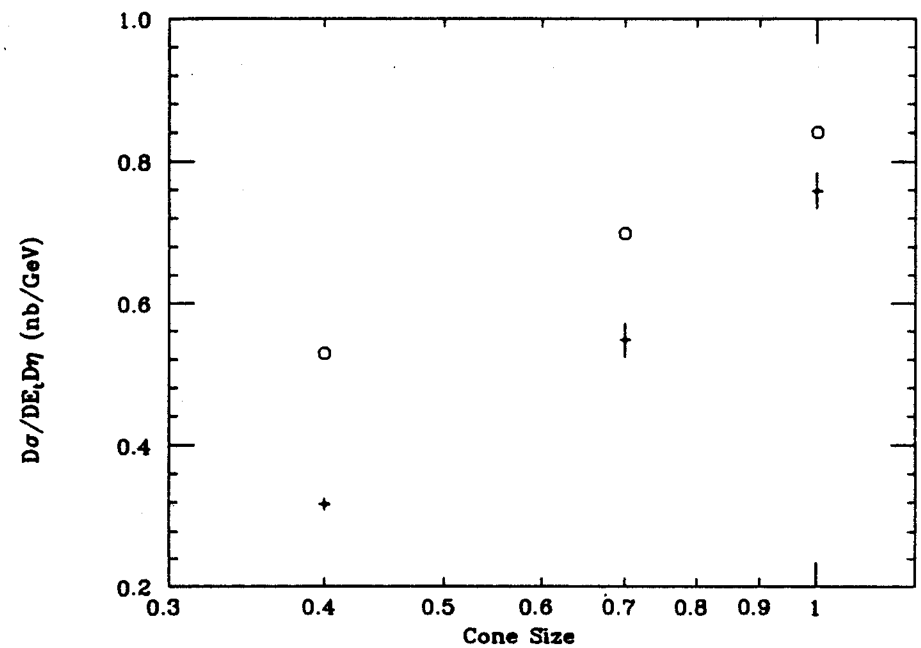

Figure 5.2. The variation in the jet cross section with the clustering cone radius at fixed transverse energy (100 GeV). The predictions are those of S. Ellis, Z. Kunszt and D. Soper, Phys. Rev. D 40 2188 (1989); U. of Oregon Preprint OITS 436 (1990).

variation in the jet cross section with cone radius at 100 GeV E_t compared to prediction. There is some expectation that the prediction would steepen with calculations performed at still higher orders.

The jet cross section can be used as a probe of effects which appear with large coupling strengths. The best known example is the effect of quark substructure on the shape of the jet E_t spectrum at the high end. If quarks were composed of smaller objects, a structure function for the quark would exist, which would modify the scattering at short distances. This effect can be parameterized by adding a contact term to the QCD Lagrangian with an effective distance scale defined by the parameter Λ^*. Figure 5.1 shows the effect of a Λ^* of 950 GeV as a dashed line. This is the current best lower limit (95 % CL), derived from CDF data.

Figure 5.3 shows the jet cross section on a linear scale, normalized to leading order QCD in the region $70 \leq E_t \leq 150$ GeV. Because of the way energy corrections are handled, in order to compare to α_s^3 calculations, no correction was used for energy out of the jet clustering cone. This effect is not in the leading order calculation, and has a size roughly indicated by the dotted line. At the high end, there appears to be a small excess of events relative to QCD. This excess for now is a curiosity. One thing this does indicate is the need for understanding the high x end of the structure functions at high Q^2.

Figure 5.4 shows the high energy end of the inclusive jet cross section, and the E_t reach for different amounts of integrated luminosity. The final arrow indicates the reach for 1000 pb^{-1}, 1 fb^{-1}. From this, it can be shown that the ultimate reach will correspond to a Λ^* of approximately 1.8 TeV. It is important to point out that in the event of no signal, this measurement plays a role in tying down the high x end of the parton distribution functions. For example, if an excess is eventually observed at the SSC, the results of a tevatron measurement at high x should provide the basis for understanding whether the excess lies in the structure functions or in some new effective interaction.

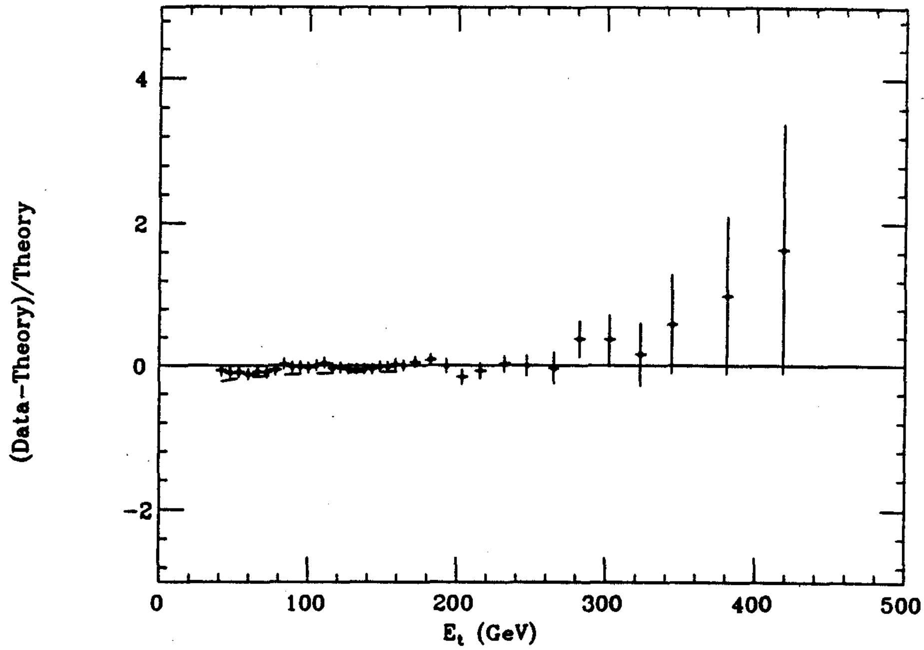

Figure 5.3. The jet cross section plotted on a linear scale, and normalized to leading order QCD in the region below 170 GeV. The excess of events at the high end varies from 2.5 to 3.5 standard deviations over the predictions, depending on structure function choice.

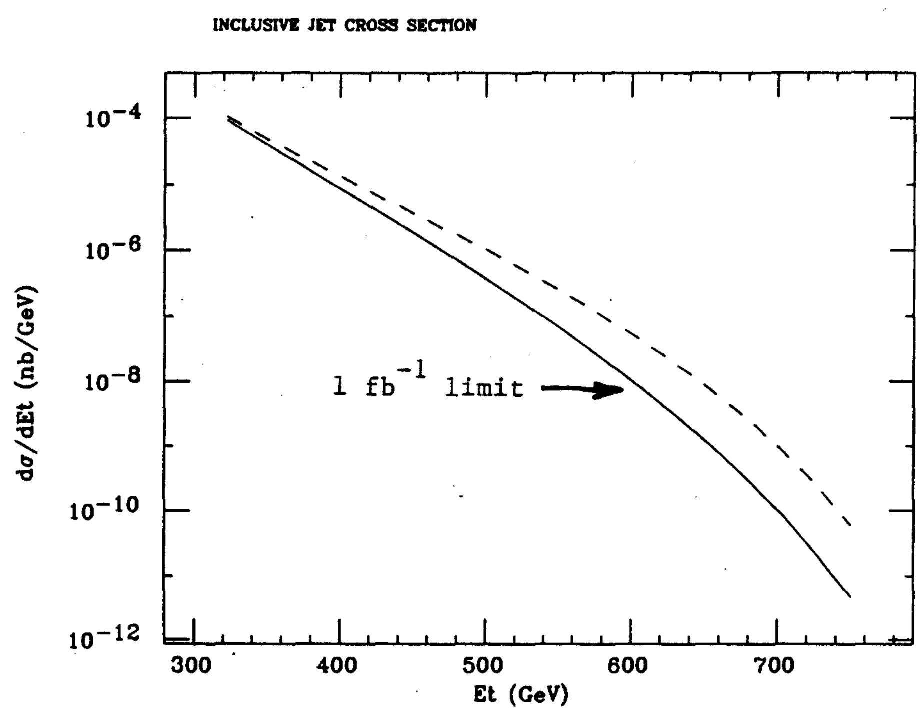

Figure 5.4. The jet cross section from leading order QCD (solid) and with the inclusion of a contact term with the characteristic energy scale of 1.8 TeV (limit of reach with injector upgrade). The highest reach with the main injector is indicated by the arrow.

The two-jet invariant mass spectrum is likewise sensitive to heavy objects produced with a strong coupling. In chiral color models, a massive octet of gluons is predicted which would lead to a broad resonance in the two-jet invariant mass spectrum above 150 GeV. This resonance, because of its strong coupling, would produce a sizable enhancement in the dijet mass spectrum above the QCD background. Figure 5.5 shows the two jet mass spectrum from approximately 25 nb^{-1} of data. The leading order QCD predictions again provide a good description of the data, allowing limits on the axigluon mass to be set at $120 \leq M_a \leq 210$ GeV for $\Gamma_A = .09\ M_A$. The most current data set includes events with invariant masses in excess of 900 GeV, allowing a substantially higher sensitivity to such objects. With 1 fb^{-1} of data, the discovery limit for axigluons should extend well above 1 TeV. This is shown in Figure 5.6 where the predicted signal is shown above a QCD background for different masses.

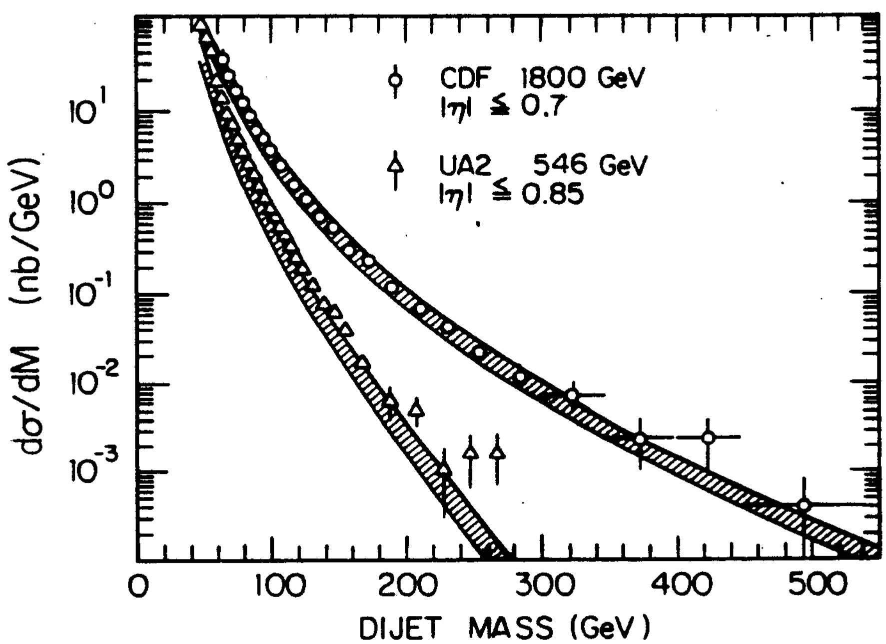

Figure 5.5. Two jet invariant mass spectrum from CDF data, along with a band representing the range of leading order QCD predictions. New CDF data exists, increasing the reach in invariant mass to above 900 GeV.

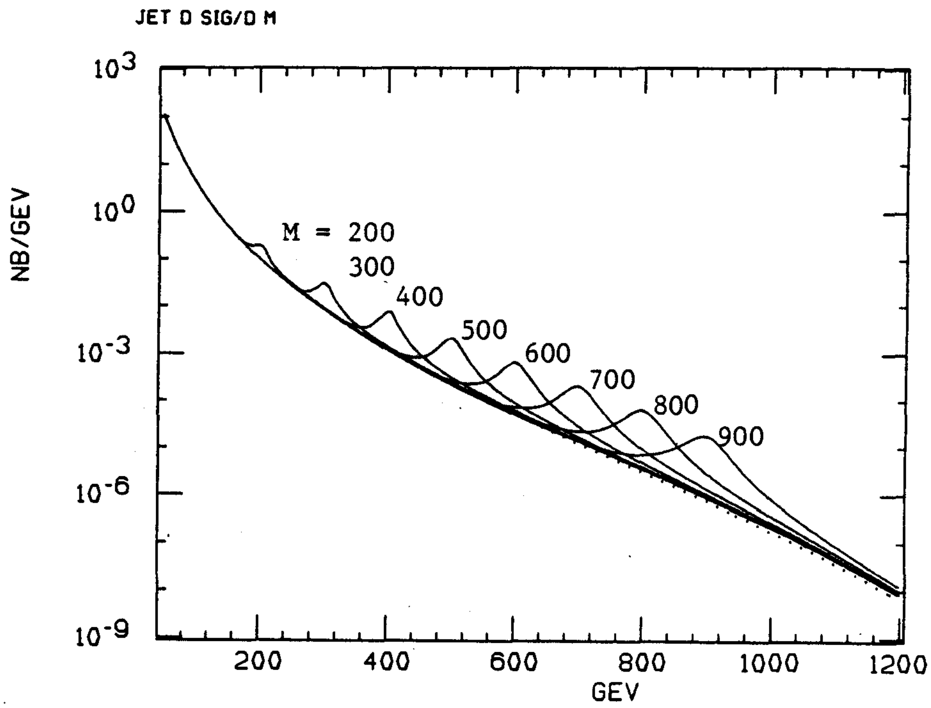

Figure 5.6. Expected cross section for the two jet invariant mass up to 1.2 TeV. Sensitivity to possible new strongly interacting particles would show up as resonances, with a sensitivity reaching 1 TeV.

COLLIDER DIRECT PHOTONS

As with jets, direct photons provide both a probe of QCD and a signature for interesting new physics processes. Figure 5.7 shows the highest E_t (300 GeV) direct photon candidate observed to date in the CDF detector. Direct photons in QCD probe the quark-gluon vertex, and are sensitive to the gluon structure function at low x. At high energies, they provide a good test of vector boson couplings ($W\gamma$) and don't involve losing rate because of a branching fraction.

Figure 5.8 shows the most recent direct photon cross section from CDF. This is compared to a leading order QCD calculation. Recent calculations exist at the next-to-leading order level, and work is in progress to make more precise comparisons to these. The reach in E_t will be up to 400 GeV for this process for a single direct photon for 1 fb^{-1}. One might expect roughly 40 W-γ events where the W decays into leptons, and 120 Z-γ events where the Z decays into leptons; this is requiring an invariant mass of 200 GeV between the boson and the direct photon.

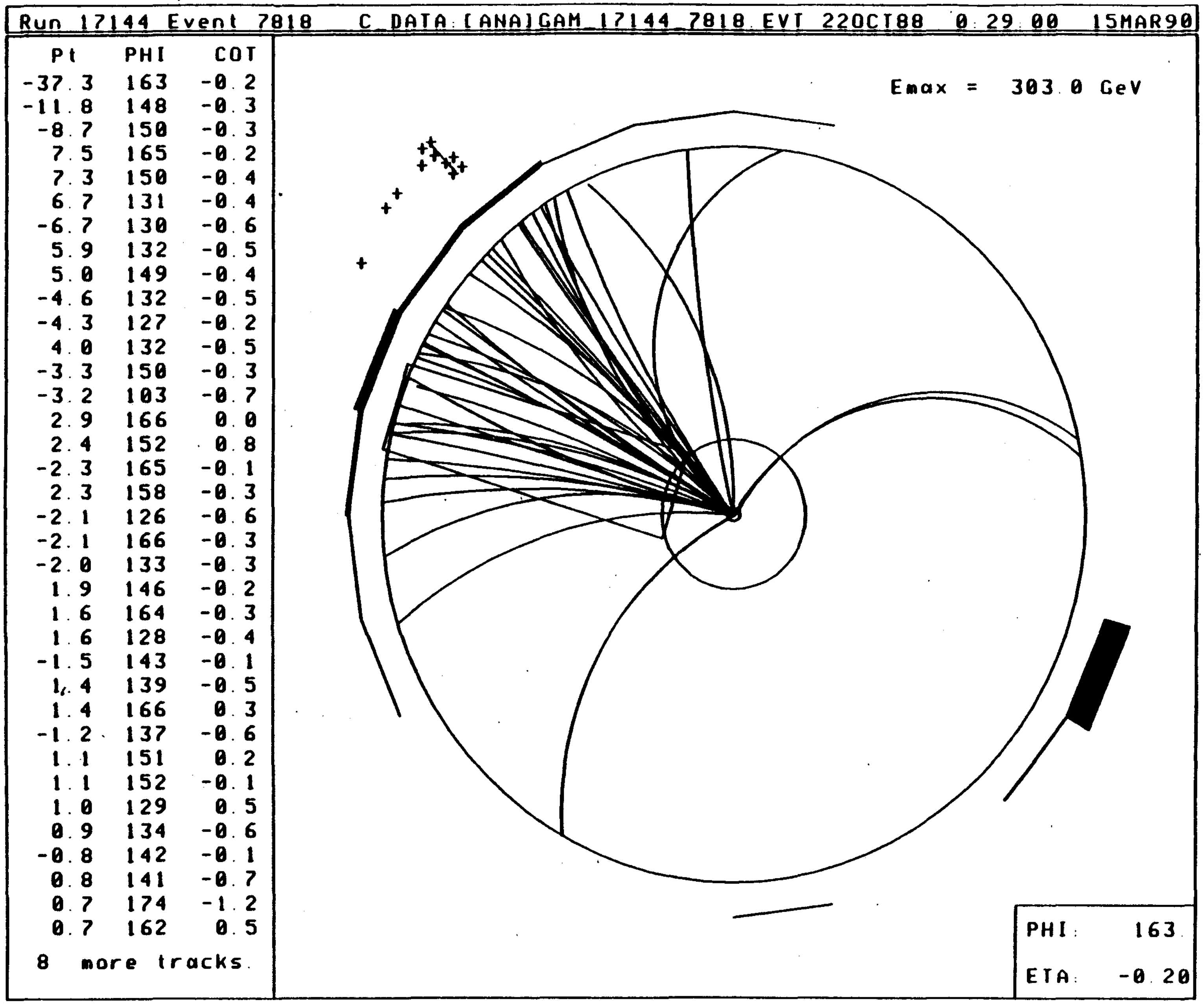

Figure 5.7. The highest E_t direct photon candidate observed in the CDF detector, having over 300 GeV transverse energy.

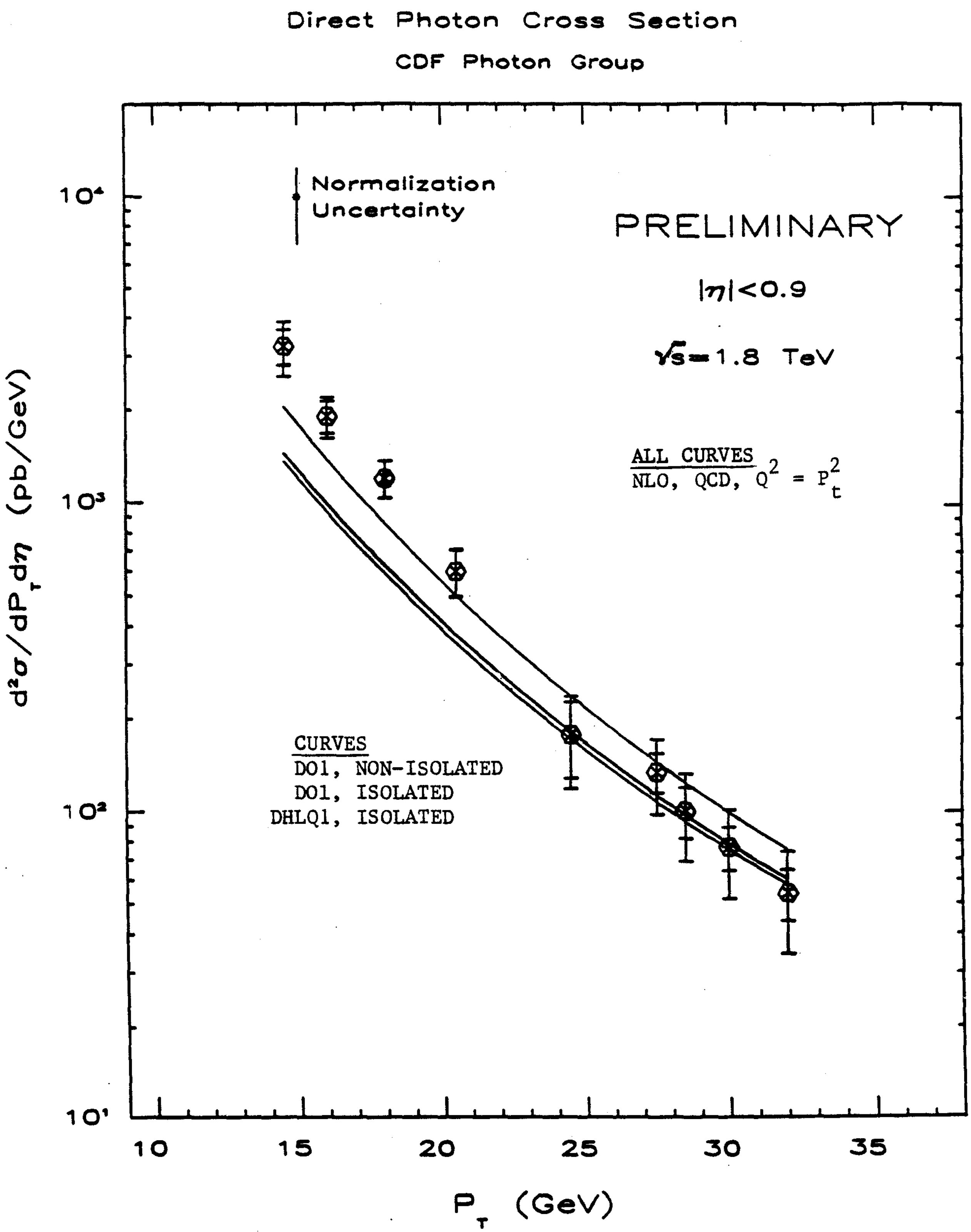

Figure 5.8. The direct photon spectrum from CDF, along with the predictions of leading order QCD.

HIGH E_t W AND Z PRODUCTION

High E_t W and Z production are analogs to direct photon production for massive gauge bosons, and form the background for other processes, such as heavy top. Other, non-standard processes, such as a techni-rho would appear as an enhancement in the p_t spectrum. Recently, calculations have been performed by P. Arnold and M.H. Reno at order α_s^3 for the p_t spectra of the W/Z. These calculations reduce the theoretical uncertainty in the cross section. Figure 5.9 shows these predictions for the cross section along with CDF data. Clearly there is a reasonable agreement between theory and experiment. With 1 fb^{-1}, the p_t reach for W's should allow a significant measurement out to 250 GeV.

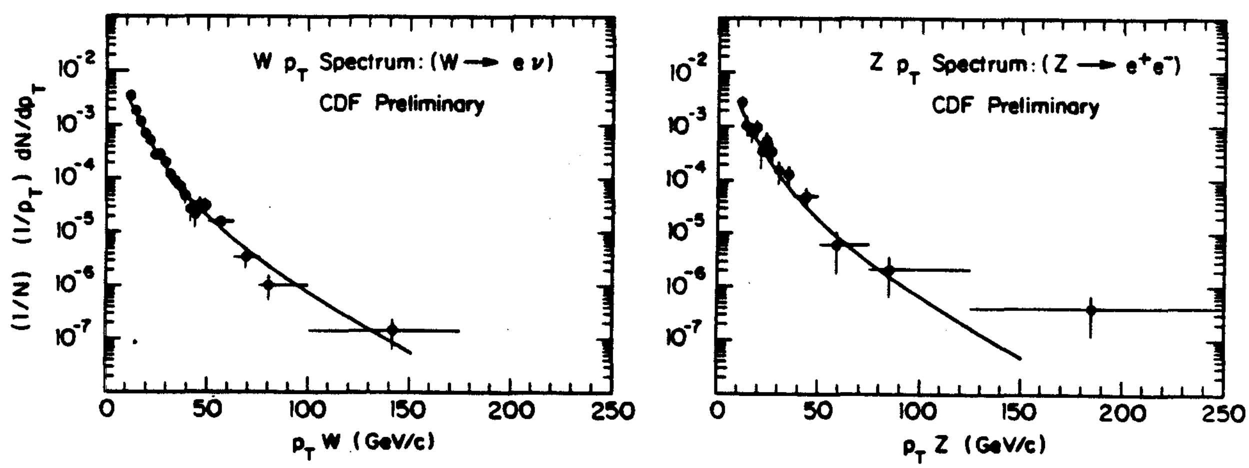

Figure 5.9. P_t distribution for W and Z production from CDF compared to the order α_s^2 predictions of P. Arnold and M.H.Reno, FERMILAB-Pub-88/168(1988).

FIXED TARGET PROBES OF QCD

Deep inelastic lepton scattering experiments have historically been used to probe the compositeness of hadrons and have yielded detailed tests of the quark parton model within the context of perturbative QCD. Precise measurements of the nucleon structure functions, analyzed within the QCD formalism have allowed the extraction of various types of parton distributions that have been used extensively within the analyses of many other physics processes. Fermilab has had a long history of muon and neutrino scattering experiments, that continues to this day.

E-744/E-770 (CCFR collaboration) are high statistics neutrino scattering experiments that took data during the 1985 and 1987 fixed target runs. The combined data sets represent the highest statistics, highest energy neutrino data in the world (the 1985 data alone are comparable in statistics with the muon experiment BCDMS). Preliminary results are expected soon on $F_2(x,Q^2)$, $xF_3(x,Q^2)$ and the Gross-Llewellyn-Smith (GLS) sum rule, in the kinematic range $0.015<x<0.65$ and $1<Q^2<200$ GeV^2. As a measure of what is possible, this data can be used to extract $\Lambda_{\bar{MS}}$ with a statistical precision of ~20-30 MeV and a systematic uncertainty of ~60-70 MeV, and the GLS sum rule can be tested to the level of 1% (which is a factor of 2 better than existing measurements), using the 1985 data only. There is twice as much data in the 1987 sample.

E-665 is a muon deep inelastic scattering experiment. Its primary goals are to study the hadronic system, as well as general A dependence effects. With an average beam energy of 490 GeV (highest in the world), it can probe new kinematic regimes ($x<10^{-3}$; $W>20$ GeV). Topics within the perturbative QCD framework include measurements of the ratio of neutron to proton structure functions at low x, as well as studies of QCD processes like gluon bremsstrahlung and photon-gluon fusion, which manifest themselves as three jet events. Topics within non-perturbative QCD include the A dependence of the muon cross-section at low x, as well as the A dependence of hadron production. Data on the A dependence of the muon cross-section have been presented at the Jan. 90 DPF meeting, and show a clear shadowing effect at low x. Further results on many other topics will be presented at the April 90 APS meeting.

Intimately related to deep inelastic lepton scattering is the Drell-Yan process, which has also had a long, and very successful history at Fermilab. E-605/E-772 represent the latest in a series of experiments that have measured high mass dimuon and dihadron production. They have extended the energy to an 800 GeV p beam and include A dependence studies. A recent comparison of the differential scaling form of the cross-section between E-605 (800 GeV) and E-288 (200,300,400 GeV) show significant scaling violations which are in good agreement with an $O(\alpha_s)$ QCD calculation. E-605 has also studied the K/π and p/π production ratios as a function of p_t. Above about 5 GeV, the ratios are nearly constant, indicating that the fragmentation process factorizes from the original partonic interaction (an assumption that is built into most Monte Carlo programs). E-772 results on the A dependence of J/ψ and Y production have shown significant suppression in heavy targets as compared to H_2. Naive perturbative arguments would expect an A^1 behavior, and thus some unexplained non-perturbative effect must also be occurring. On the other hand, the A dependence of continuum Drell-Yan production shows approximate A^1 behavior, but also indicate significant shadowing at low x_t, consistent with the shadowing observed in deep inelastic muon experiments.

Another process that tests QCD is direct photon production. In contrast to lepton scattering and Drell-Yan, direct photon experiments involve gluons at first order, through both the gluon-Compton and $q\bar{q}$ annihilation diagrams. Thus, direct photon studies are sensitive to the gluon structure function as well as to the gluon fragmentation functions. While there are still open questions (eg. choice of scale, inclusion of isolation cuts within the theory, A dependence), the current state of the experimental and theoretical techniques have advanced sufficiently that precise QCD tests may be possible. E706 is an experiment dedicated to studying direct photon production. They took data during the 1987 Fixed Target run with 530 GeV $\pi^{\pm}$ and p beams on a Be target, which allows them to study the extended kinematic range $0.2<x_t<0.5$. This range bridges that of previous direct photon fixed target and ISR experiments and is complimentary to the FNAL collider. Preliminary direct photon cross-sections from π^- Be and p Be have been presented. They are currently working on understanding the systematics of π^0 and η backgrounds within the direct photon sample, and expect to have comparisons to next-to-leading-order QCD calculations later this summer. In addition, they will be studying the correlation between the photon and the accompanying jets, which may allow more stringent comparisons to theory.

As mentioned earlier, all of this data should be understandable within the context of QCD. A working group at Snowmass 88 began a study to see if this was possible. Jorge Morfin and Wu Ki Tung have continued this work, and have successfully combined muon deep inelastic scattering results from EMC and BCDMS, neutrino deep inelastic scattering results from CDHSW and Drell-Yan results from E-288 amd E-605 to obtain a new set of parton distribution functions. They stress the importance of correctly including experimental systematic errors, and have explored the dependence of their results on such things as kinematic cuts, heavy target corrections, different data sets and initial functional forms used in the fit. Good fits were obtained to all the data examined. Comparisons to previous parton distributions show significant differences, especially at low x. Morfin and Tung emphasize the danger of using parton distributions extrapolated to regions beyond which data exists (i.e., low x). They have explored the variations allowed by current data at low x, and find significant variations. This has direct consequences for the physics analyses performed at high energy hadron colliders. They are eager to include new data when available (CCFR neutrino results, E-665 muon results, CDF W and Z production, E706 direct photons, etc.) and stress the need to push measurements to lower x.

In summary, QCD is actively being studied at Fermilab, with many different processes, in a variety of kinematic regimes, covering both perturbative and non-perturbative issues. Excellent agreement has been obtained in several comparisons to perturbative QCD calculations, while non-perturbative results lag behind in their level of understanding. The immediate future for further tests of QCD is very bright. Many experiments are just now coming out with results from data taken in previous runs. Many of these experiments will be running again (the 1990 Fixed Target run is currently underway) with improved detectors, triggers, systematics, etc. and most expect factors of 5 - 10 times the statistics of previous runs. The global analyses will continue to try to incorporate new data,

ELECTROWEAK MEASUREMENTS AND TOP PHYSICS

INTRODUCTION

The very large luminosity that will be produced with the Main Injector will provide greatly enhanced physics capabilities for the Tevatron Collider. These include sensitivity to the top quark over the entire mass range allowed in the Standard Model, precision tests of the Standard Model, and sensitivity to other heavy particles with masses approaching the 1 TeV scale.

In order to quantitatively estimate these capabilities, assumptions must be made about the performance of both the accelerator and detectors. One inverse femtobarn is taken as the integrated luminosity, corresponding to two one-year runs at design luminosity and luminosity lifetime. The average accelerator efficiency is assumed to be the same as in the 1988-89 Collider run. Corrections have also been made for detector down time and deadtime. The detector is assumed to have full lepton and jet coverage (calorimeters, tracking, and muon chambers). It is not, however, an ideal detector; inefficiencies are taken from the current CDF analyses.

SEARCH FOR THE TOP QUARK

The latest CDF result requires M_t in the minimum standard model > 89 GeV/c^2 at the 95% confidence level. There is indirect evidence from a number of sources that allows or suggests a very high top quark mass:

νN neutral currents	$\lesssim 200\ GeV/c^2$
ε'/ε (FNAL+CERN)	$\lesssim 175$ (higher for FNAL alone)
$\Gamma\ (Z \rightarrow hadrons)$ (LEP)	150-250
latest UA2 M_W	150-250

Thus, the top quark mass may well be as high as 200-250 GeV/c^2. It is very important that this entire range be covered.

In the Standard Model, top quarks with mass above 85 GeV/c^2 are produced in $t\bar{t}$ pairs with each quark decaying into a real W and a b quark. Signal to background should be acceptable both for a single lepton tag, where one W decays to $e\nu$ or $\mu\nu$ and the other decays to a $q\bar{q}$ pair, and a double lepton tag, where both W's decay into $e\nu$ or $\mu\nu$. The former provides events with a lepton, four jets, and missing P_T; the latter yields two leptons, two jets, and missing P_T. The table below gives estimates of the number of events produced and the number detected for each mode as a function of the top quark mass. The assumed detection efficiency, taken from current CDF analysis, is conservative. For large top quark mass, the dominant backgrounds contain leptons from W and Z decay. Consequently there is little gain in signal to noise by cutting hard on lepton identification criteria.

Top Quark Events Produced and Detected for 1 fb^{-1}

M_{top} (GeV)	$t\bar{t}$ pairs produced	Lepton+4 jet events detected	Dilepton events detected
100	80000	<7200	1000
140	15000	1350	200
180	3300	300	40
220	1000	90	12
260	350	30	5
300	120	10	2

The accessible mass range is determined by both the number of events produced and the expected background. For single lepton decay, the dominant source of background is QCD W + four jet production. In the absence of significant W + four jet data or a QCD calculation, we use a W + three jet calculation normalized to the CDF cross section and extrapolated to W + four jets using CDF W + n jet cross sections. The background has a rapidly falling jet E_T spectrum, in contrast to the spectrum from top decay which becomes harder as M_t increases. By selecting a jet E_T threshold which increases with M_t, a signal to noise ratio ~4 can be maintained over the entire accessible M_t range. A significant improvement in the signal to noise can be obtained by identifying one or both of the b jets in $t\bar{t}$ decay using a vertex detector. The CDF silicon vertex detector will have an impact parameter resolution of 10-15 μ, compared to the 300 μ cτ for b decay. It will provide a > 50% probability of identifying at least one of the b jets.

There are two major backgrounds for the dilepton mode. One is QCD production of Z + two jets, followed by Z decay into ee, μμ, or $\tau\tau \rightarrow \ell\ell + \nu$'s. These events are easily removed using the multi-lepton invariant mass, transverse momentum imbalance, and the collinearity of the two leptons. This leaves as the dominant background vector boson pair production, WW + 2 jets. Again by choosing a jet E_T threshold which increases with M_t, excellent signal to noise (~10:1) can be maintained over the entire accessible M_t range.

Thus there should be a significant number of detected $t\bar{t}$ events (≤ 25 ℓ+ν+4 jet events and ≤ 5 $\ell\ell$+ν's+2 jet events per detector) with good signal to noise up to M_t = 260-270 GeV/c^2. Approximately 10 single lepton and a few dilepton events are expected per detector at M_t = 300 GeV/c^2. The entire region allowed in the Standard Model is therefore covered.

If a signal is observed, the first task will be to identify it as a top quark. There are a number of characteristics which can be checked. The number of events with 0, 1, and 2 identified secondary vertices must be consistent with two b jets per event. The ratio of the number of dilepton events to single lepton events should be consistent with two W's per event. The presence of the two W's can be further confirmed with the lν transverse mass and the jet-jet invariant mass. Finally, the production cross section should agree with the QCD calculation, which has a quoted uncertainty of only ±20-30%.

Work is just beginning on optimal strategies for extracting a heavy top quark mass from the data. For the single lepton mode, one can look at the W + b jet invariant mass distribution. After applying kinematic cuts to improve the resolution, a width of 20% is obtained. This results in a statistical uncertainty in the mean mass of ~ ±5 GeV/c^2 for a 200 GeV/c^2 mass. The systematic uncertainty will present additional problems, but it can be studied with events in which both b jets are identified with the vertex detector. The remaining high E_T jets will have an invariant mass peak at the W mass. Other potentially more precise techniques are under study. These include reconstruction of both t and $\bar{t}$ using the two M_W constraints as well as $M_t = M_{\bar{t}}$. Finally, the E_T spectra of the lepton, W jets, b jets, and the missing P_T all depend on the top mass and consequently can be used as mass estimators.

For a dilepton sample, Baer et al have considered a number of mass estimators. The best of these is the lowest reconstructed top mass when the missing P_T is distributed between the two neutrinos. Their analysis indicates that the mean mass can be measured to ±10 GeV/c^2 for a 200 GeV/c^2 top quark.

One additional estimate of the mass comes from comparing the observed cross section with the QCD calculations.

The highest priority, of course, is discovering the top quark and measuring its mass. With this comes a precision test of the Standard Model by comparing the top mass to the W mass (see the Electroweak section below). In addition, if the mass is not too high there will be a large enough data sample so that a study of the properties of the top quark can begin. Assume that M_t is 150 GeV/c^2 and that 1000 single lepton and 130 dilepton events are detected. The ratio of events with one and two detected secondary vertices is sensitive to a 10% branching ratio to final states with no b quark ($t \rightarrow W+s/d$). The possibility that the Higgs sector contains more than one doublet and that the top quark can decay into a charged Higgs plus a b quark can be tested over a wide range of the parameter space. From the rate of single and double lepton events and the rate of events with very large missing E_T but no e or μ (looking for $t\bar{t} \rightarrow HbHb \rightarrow \tau\tau\nu\nu bb$), the $t \rightarrow Hb$ decay can be studied over most of the range $\tan\beta > 0.1$, where $\tan\beta$ is the ratio of the vacuum expectation values for the two Higgs doublets. The top quark decay angular distribution will provide information on the spin of the top quark. The $t\bar{t}$ invariant mass spectrum will be investigated for the presence of peaks, for example from the decay of technimesons. If there are additional hard partons in the events, they could be due to the decay of heavier objects like a third generation leptoquark into $t\tau$. Finally, there is always the totally unexpected, which might not be so unexpected since the top quark is already an oddity by virtue of its extremely large mass.

ELECTROWEAK PHYSICS

W Mass

With an integrated luminosity of 1 fb^{-1}, more than 10^6 $W \rightarrow e\nu$, $\mu\nu$ events and 10^5 $Z \rightarrow ee$, $\mu\mu$ events will be detected. The latter sample is extremely important, since it is used to study and measure many of the sources of systematic uncertainty in M_W: the detector energy scale and resolution, the P_T distribution of the W, the effect of electron energy leakage on the inferred ν P_T, the background, and the mass fitting procedure.

The M_W statistical uncertainty will be ≤ 30 MeV/c^2. The dominant systematic uncertainty may well be the imprecise knowledge of the structure functions and the resulting W rapidity distribution. Here our measurement of the W charge asymmetry will give us the important u to d ratio for our range of x and q^2. If no unexpected new sources of systematic uncertainty appear, it is likely that the W mass can be measured to ~ ±50 MeV/c^2. Such a measurement, coupled with the measurement of the top quark mass, provides a powerful test of the Standard Model at the level of electroweak radiative corrections (see figure below). If the result disagrees with the Standard Model, it is of course extremely important. If it is consistent with expectations, then the sensitivity of the measurement allows the effect of the Higgs mass to be seen. (Figure 6.1)

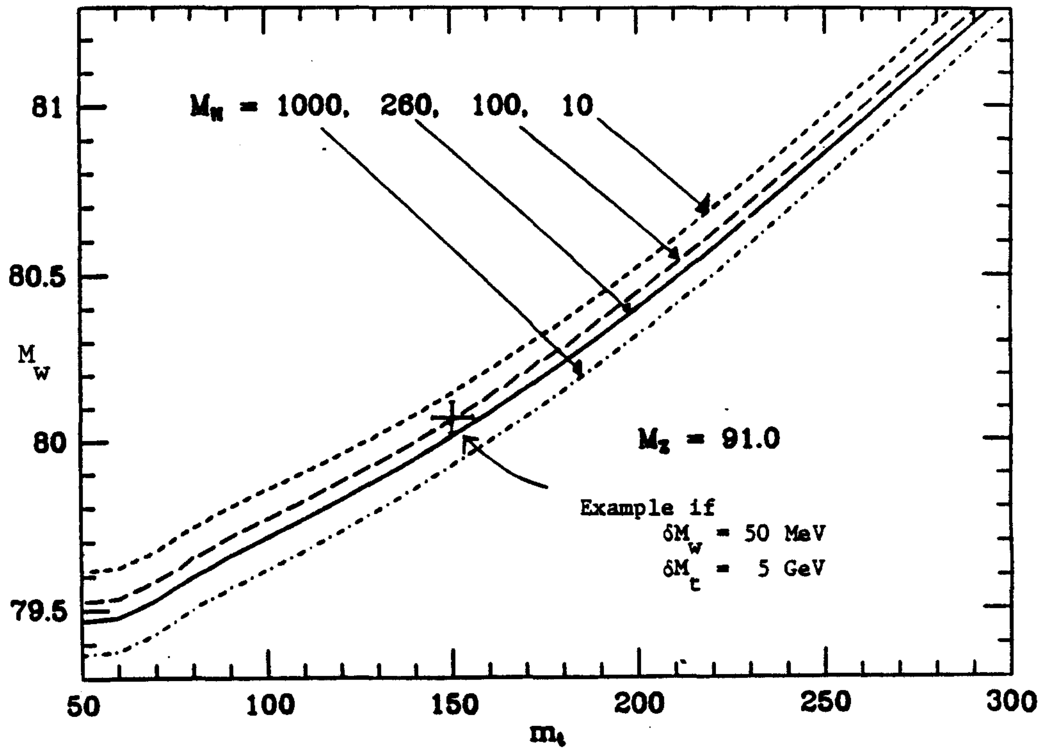

FIGURE 6.1. Effects of the masses of the top quark and Higgs boson on the W mass.

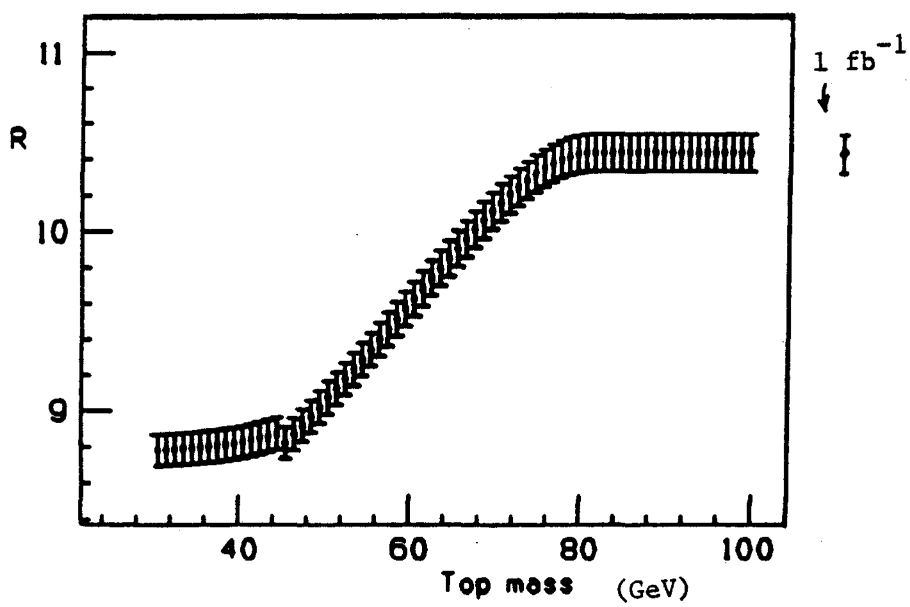

FIGURE 6.2. The ratio R of the number of $W \rightarrow \ell\nu$ events to the number of Z $\ell\ell$ events as a function of the top quark mass. The error bars show the anticip measurement uncertainty.

$Z^0 \rightarrow \ell^+\ell^-$ Charge Asymmetry

The lepton charge asymmetry in Z decay provides a measurement of $\sin^2\theta_W$. This $\sin^2\theta_W$ is not the same as that obtained in the M_W/M_Z measurement, the difference due largely to higher order electroweak diagrams containing top quark fermion loops. With the sample of 150,000 events, the statistical uncertainty in $\sin^2\theta_W$ will be 0.0007. Since this measurement is independent of the detector acceptance, requiring only charge symmetry, the dominant systematic uncertainty should come from imprecise knowledge of the proton structure functions. In the current CDF measurement, this uncertainty is ± 0.001. With the enormous numbers of jet, direct γ, W, and Z events in a 1 fb^{-1} exposure, this systematic uncertainty should become insignificant. Thus $\Delta\sin^2\theta_W \cong \pm 0.0008$ should be obtainable. Note that the initial state quarks make this measurement different from the lepton asymmetry at LEP.

The Width of the W

The ratio (R) of the number of $W \rightarrow \ell\nu$ events to the number of $Z \rightarrow \ell\ell$ events produced in $p\bar{p}$ collisions can be written as a product of three factors: the ratio of the W to Z production cross sections, the ratio of the W to Z partial widths into leptons, and the ratio of the Z to W total widths. The first two factors can be accurately predicted in the Standard Model. Thus by measuring the number of $W \rightarrow \ell\nu$ and $Z \rightarrow \ell\ell$ events, we can deduce the ratio of the W to Z total widths and, with the Z width measured in e^+e^- collisions, the width of the W. The current CDF result is $\Gamma(W) = 2.19 \pm 0.20$ GeV.

This measurement is important not only because the width, or lifetime, is a basic property of the W, but also because it allows a loophole in the top quark search to be closed. If the top mass is between $M_Z/2$ and M_W, and its decay cannot be detected (e.g., $t \rightarrow Hb \rightarrow c\bar{s}b$), it would not have been seen in the Fermilab or e^+e^- searches. However, since the $W \rightarrow t\bar{b}$ channel would still be open, $\Gamma(W)$ would increase and R would decrease. For a 1 fb^{-1} sample, the statistical uncertainty in R will be ~0.5% while the systematic uncertainty should be ~1% (dominated by the structure functions). The overall uncertainty in R is shown as the data point on the right in Figure 6.2. The curve is the theoretical expectation as a function of the top quark mass. Such a measurement would allow almost the entire range $45<M_t<80$ GeV/c^2 to be ruled out.

Vector Boson Pair Production

There will be approximately 2000 Wγ events detected with $P_T^\gamma > 10$ GeV/c and the W decaying into e or μ. This will provide a measurement of the anomalous magnetic moment of the W.

For the other boson pairs (WW, WZ, ZZ), the search must be restricted to double leptonic decays or else the signal is swamped by QCD background. Thus, there should be 125 WW events, 5 WZ events, and 1 ZZ event recorded. The WW channel is not reconstructable because of the two neutrinos, and hopefully it will have a large background from top quark decay! The numbers of WZ and ZZ events is quite small. However the experiment will be sensitive to anomalous vector boson pair production, either a failure of the diagram cancellation in the Standard Model or the presence of boson pair resonances predicted in some models.

OTHER HEAVY PARTICLES

A 1 fb^{-1} exposure will provide sensitivity to a variety of heavy objects which are extensions to the Standard Model. Heavy vector bosons (W', Z') would be seen up to a mass of ~ 1 TeV/c^2 assuming standard lepton couplings. The search for supersymmetric particles, technipions and rhos, and leptoquarks could extend up to 250-300 GeV/c^2 in mass. Quark compositeness could be seen up to a scale of 3 TeV in both inclusive jet production and Drell-Yan lepton pair production.

COMMENT ON THE DETECTORS

Both CDF and D0 will need upgrades to operate at the luminosity envisioned with the Main Injector. It is important to note, however, that most of the required modifications are already planned, since they are needed for the 1993 run when the Tevatron bunch separation will be reduced from 3.5 μsec to 0.4 μsec and the luminosity will be increased to $\sim 1\times10^{31}$.

CONCLUSIONS

The Collider physics prospects are very bright with the Main Injector. We will find the top quark and begin to study its properties, or there is a serious problem with the Standard Model. The large number of W and Z events combined with a top quark sample will allow a number of precision tests of the Standard Model. The search for new heavy particles will reach toward the 1 TeV mass scale. And perhaps most importantly, entirely unexpected phenomena might appear in a data sample which will be almost 250 times as large as the existing one. Finally, it must be kept in mind that the Tevatron Collider will play a very important role in training the generation of physicists who will be exploring even higher mass scales at the SSC. At the present time, 511 physicists are working on CDF and D0, 133 of whom are graduate students!

TO THE HORIZON

Fermilab III, the program outlined in the preceding sections, will provide the U.S. with a vibrant high energy physics program throughout the decade. It will also provide a very natural transition to the utilization of the SSC. Each of Fermilab's four physics programs will evolve, mature, and eventually cease to hold the interest of high energy physicists. When will the last stage occur? We certainly cannot foresee it by looking to the horizon of our current knowledge of elementary particles.

At this moment, the four programs are intended to provide answers to the most important questions in high energy physics. These questions, at least the ones that can be answered with the technology that is at hand or nearly at hand, include: What are the precise values of the properties of the electroweak bosons and their couplings to fermions? Does the top quark exist? If it does exist, what is its mass and are there any suggestions in its decays of something other than the minimal model? Do neutrinos have masses? Can a neutrino of one generation change into the neutrino of another generation? What is the origin of the matter-antimatter asymmetry in the universe?

We have just begun to ask the more deeply significant questions about the weak decays of charmed particles. Almost nothing is known about the weak decays of bottom particles, other than that the expected dominant b to c decay transition is, in fact, dominant. The spectroscopy of hadrons containing charmed quarks is just beginning.

Is Fermilab the best place to seek answers in the 1990's? For some of these questions, the answer is an unqualified yes. For some, the answer is it could be the best place, and for the rest the answer that Fermilab is as good as any place. This is the reason why the Fermilab program is so rich. It is rich not only in diversity, but it is rich in the opportunity to answer questions of compelling interest. The subpanel wants to know what is the future of Fermilab's programs and what will they cost in the 1990's. Let me start with the costs and then turn to the crystal ball.

THE MINIMAL BUDGET REQUIREMENTS OF FERMILAB III

The Fermilab budget request for the decade is presented in four parts: Base Operations, the Collider Program, the Fixed Target Program, and Physics. In what follows, Base Operations has been defined to be the sum of the Accelerator Division (exclusive of R&D), the Support Departments of the Research Division, the Business Services Section, the Laboratory Services Section, the G&A funded part of Technical Services Section, the Safety Section, the Directorate and last, but not least, electrical power. It also includes General Plant Projects (GPP).

The budget for Base Operations in FY 1990 is $113.1M. The expected evolution of the Base Operations budget is shown in Table 7.1. It shows an increase greater than inflation. The reason is not to be found in research, but in the new requirements placed on the Laboratory by the DOE. The cost of operations will increase because of the cost of environmental cleanup (even Fermilab has some PCB's and heavy metals), the cost of greater emphasis on safety, the cost of greater emphasis on maintaining our buildings and roads, the cost of greater emphasis on formal quality assurance programs, and the cost of documenting our response to these greater emphases. These things are sensitive issues in Washington and cannot be dismissed. It is likely that once Fermilab is in compliance with DOE orders, the annual cost of operating the Business Services Section and the Safety Section will have increased by 25%. Increased base operating costs will also appear in the programmatic parts of the Laboratory. These will need to be offset by program reductions. Some of the increase in the cost of safety lies in the expectation that the cost of the safety reviews, which we now carry out to certify that an experiment is operational, will rise. These changes in emphasis will force us to decrease the number of Fixed Target experiments.

TABLE 7.1. BASE OPERATIONS

Constant Dollar-FY90 Base Year
($M)

Base Operations Budget Profile	FY90	FY91	FY92	FY93	FY94	FY95	FY96	FY97
Facility Operations and R & D								
Accelerator Division	36.9	37.5	38.0	38.0	37.0	37.0	37.0	37.0
Research Division	12.9	13.0	14.0	14.0	14.0	14.0	14.0	14.0
Technical Support Section	6.2	6.1	6.2	6.2	6.2	6.2	6.2	6.2
Business Seveices Section	23.6	22.6	25.0	26.1	27.5	28.0	28.0	28.0
Construction Engineering	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Directorate	4.1	5.2	5.2	5.2	5.2	5.2	5.2	5.2
Laboratory Services	3.8	3.7	3.8	3.8	3.8	3.9	3.9	4.0
Safety	1.9	1.9	1.9	4.4	3.3	2.2	2.2	2.2
Inventory	1.8	1.8	1.8	1.8	1.7	1.7	1.7	1.6
Power	18.4	19.1	17.9	19.5	15.1	16.7	18.1	17.5
Sub-Total	**109.9**	**111.4**	**114.0**	**119.3**	**114.0**	**115.3**	**116.6**	**116.1**
Indirect Revenue	-5.2	-3.1	-1.8	0.0	0.0	0.0	0.0	0.0
Total	**104.7**	**108.3**	**112.2**	**119.3**	**114.0**	**115.3**	**116.6**	**116.1**
General Equipment	**4.8**	**5.5**	**6.0**	**6.0**	**6.0**	**6.0**	**6.0**	**6.0**
Construction								
General Plant Projects	3.6	3.6	4.9	5.0	4.9	4.9	4.8	4.7
Base Operations Total	**113.1**	**117.4**	**123.1**	**130.3**	**125.0**	**126.2**	**127.4**	**126.8**
Then-Year-Dollars	*113.1*	*122.3*	*133.5*	*146.6*	*145.6*	*151.7*	*158.1*	*162.5*

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The cost of electrical energy at Fermilab is roughly $20 million per year, in part because power costs in Northern Illinois are high and Fermilab receives no cheap public power. Fermilab chooses to put almost $20M into its budget in order to run the accelerator and beam lines for at least eight months a year. It should be noted that the Collider program uses less electrical energy than the Fixed Target program. This extra energy usage is in secondary beam lines and large analysis magnets. It is another one of the reasons it is necessary to decrease the number of fixed target experiments.

The cost of the Collider program includes all accelerator R&D costs, Collider detector R&D costs, and the cost of operating and improving CDF and D0. The cost of the Fixed Target program includes the cost of running the Site Operations Department and the fixed target experiment budget codes for operating and equipment. In addition, we have included in this category the budgets of the Research Facilities Department, the function of which is to provide technical facilities and personnel in direct support of Fixed Target users in constructing, operating and maintaining their detectors. The budget projection for the Collider and Fixed Target programs are shown in Tables 7.2 and 7.3 respectively.

The Physics category includes part of the Research Division, part of the Computing Division, and the Physics Section. The Computing Division bears virtually the entire cost of computing, on-line and off-line, of all experiments done at Fermilab. The cost of data acquisition systems and pool electronics, as well as their repair and service, are normally charged against the Computing Division budget. Because these costs are charged directly to experiments, however, they have been assigned to the Collider or Fixed Target programs, as appropriate, in the tables here. The central computing resources were roughly shared between the collider and fixed target programs in 1989 and these programs will be in rough equality in usage again in 1990. In time, more of the Computing Division resources will go to the Collider program. The Physics Department (Section) traditionally helps the laboratory staff with their personal contributions to experiments. Averaged over a two year cycle, its resources are roughly shared by Collider and Fixed Target programs. They are included in the Physics category

TABLE 7.2. COLLIDER PROGRAM

Constant Dollar-FY90 Base Year
($M)

Collider Program Budget Profile	FY90	FY91	FY92	FY93	FY94	FY95	FY96	FY97
Facility Operations and R & D								
Accelerator Division	3.9	3.8	9.2	7.9	5.4	3.9	4.0	4.0
Research Division	15.4	15.1	14.8	15.0	15.0	15.0	15.0	15.0
Total	**19.3**	**18.9**	**24.0**	**22.9**	**20.4**	**18.9**	**19.0**	**19.0**
Programmatic Equipment								
Research Division	**14.2**	**12.0**	**13.4**	**16.0**	**13.0**	**5.0**	**1.0**	**1.0**
Construction								
Accelerator Improvement Projects	**6.1**	**5.6**	**8.6**	**2.0**	**3.0**	**3.0**	**3.0**	**3.0**
Collider Program Total	**39.6**	**36.5**	**46.0**	**40.9**	**36.4**	**26.9**	**23.0**	**23.0**
Then-Year-Dollars	39.6	38.1	50.0	46.1	42.5	32.6	28.9	29.9

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TABLE 7.3. FIXED TARGET PROGRAM

Constant Dollar-FY90 Base Year
($M)

Fixed Target Program Budget Profile	FY90	FY91	FY92	FY93	FY94	FY95	FY96	FY97
Facility Operations and R & D								
Research Division	7.6	7.7	8.3	8.9	9.3	9.7	9.8	9.9
Computing Division	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Total	**7.9**	**8.0**	**8.6**	**9.2**	**9.6**	**10.0**	**10.1**	**10.2**
Programmatic Equipment								
Research Division	2.1	3.8	1.8	5.3	8.0	11.0	12.0	12.0
Computing Division	2.3	1.3	2.3	1.4	1.7	2.1	2.0	2.4
Total	**4.4**	**5.2**	**4.2**	**6.8**	**9.7**	**13.1**	**14.0**	**14.4**
Construction								
Accelerator Improvement Projects	**0.8**	**1.3**	**6.7**	**8.7**	**7.7**	**6.8**	**6.7**	**5.7**
Fixed Target Program Total	**13.1**	**14.6**	**19.5**	**24.6**	**27.0**	**29.9**	**30.8**	**30.3**
Then-Year-Dollars	**13.1**	**15.2**	**21.2**	**28.1**	**31.9**	**36.6**	**39.1**	**39.7**

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in the tables. The Physics category also includes the Theory Department and the Theoretical Astrophysics Department of the Research Division. The budget projections for this category are presented in Table 7.4.

Table 7.5 summarizes the budget requests for three "Line Item Construction" projects. Since these projects benefit the Collider and Fixed Target programs, no attempt to split these costs between Collider and Fixed Target was made. The Linac Upgrade Project is a three year project totaling $22.8M in construction funds. It received its initial appropriation of $4.7M in FY1990. The DOE FY1991 Congressional Budget request includes $12M for the Linac Upgrade. Fermilab's total estimated cost (TEC) for the Main Injector project is $138.6M in FY90 dollars, corresponding to $158.M in then year dollars. The TEC is being discussed by Fermilab and DOE. Following an intensive cost and schedule review of the Main Injector in January, the reviewers recommended an increase of roughly $20M. When the discussions are complete, the TEC will increase to about $170M and the TPC will increase to about $195M. In FY95 and 96, an amount equal to $8.3M is proposed for a major computer equipment acquisition. Table 7.6 summarizes the Fermilab budget projection over all categories through the fiscal year 1997.

In order to arrive at these budget figures, some assumptions had to be made about the life expectancy of the individual subprograms. Actuaries are not the object of public scorn when they compute life expectancies, but when a Laboratory Director attempts to do so, there is no way to dodge the fury of those assigned to the short end of the mortality stick. This is particularly true of the Fermilab program because of its diversity. The proposal for evolution was made by trying to keep the growth of the annual budget request to 10% over the period 1991 to 1997. To keep the plan within that constraint, some excellent things were left out. For example, this plan does not make provisions for a Tevatron Collider detector dedicated to B physics, nor does it permit the start of a major new detector for the Fixed Target program before 1994. This does not mean that they are excluded from the program. The relative allocation of funds between the Collider and Fixed Target programs after FY1991 has not been reviewed in detail by the Laboratory. Ultimately the relative allocation will be guided by advice from the Fermilab Physics Advisory Committee.

TABLE 7.4. PHYSICS AND COMPUTING

Constant Dollar-FY90 Base Year
($M)

Physics and Computing		FY90	FY91	FY92	FY93	FY94	FY95	FY96	FY97
Facility Operations and R & D									
Research Division		1.7	1.6	1.6	1.6	1.6	1.8	1.8	1.9
Computing Division		16.0	15.8	17.5	18.0	18.0	18.0	18.0	18.0
Physics Section		5.8	5.9	6.1	6.2	6.3	6.3	6.3	6.3
	Total	**23.5**	**23.3**	**25.2**	**25.8**	**25.9**	**26.1**	**26.1**	**26.2**
Programmatic Equipment									
Computing Division		5.3	6.0	4.9	5.7	5.2	5.2	5.0	5.0
Physics Section		1.3	1.2	1.3	1.3	1.4	1.3	1.4	1.3
	Total	**6.6**	**7.3**	**6.2**	**7.0**	**6.6**	**6.5**	**6.4**	**6.4**
Physics Program Total		**30.1**	**30.6**	**31.4**	**32.9**	**32.5**	**32.6**	**32.5**	**32.6**
Then-Year-Dollars		**30.1**	**31.9**	**34.0**	**36.9**	**37.7**	**39.1**	**40.2**	**41.5**

TABLE 7.5. LINE ITEM PROJECTS

Constant Dollar-FY90 Base Year
($M)

Line Item Projects Budget Profile	FY90	FY91	FY92	FY93	FY94	FY95	FY96	FY97
Linac Upgrade	4.6	11.5	5.6	0.0	0.0	0.0	0.0	0.0
Main Injector	0.0	0.0	41.6	60.0	34.1	0.0	0.0	0.0
Computer Upgrade	0.0	0.0	0.0	0.0	0.0	4.2	4.0	0.0
Total	4.6	11.5	47.3	60.0	34.1	4.2	4.0	0.0
Then-Year-Dollars	4.6	12.0	52.2	70.0	42.1	5.0	5.0	0.0

TABLE 7.6. BUDGET SUMMARY FOR FY90 THROUGH FY97

Constant Dollar-FY90 Base Year
($M)

Categorical Summary	FY90	FY91	FY92	FY93	FY94	FY95	FY96	FY97
Facility Operations and R & D	155.4	158.5	170.0	177.2	169.9	170.3	171.8	171.5
Total Equipment	30.0	29.9	29.7	35.8	35.3	34.8	31.5	27.7
Construction	15.1	22.1	67.4	75.6	49.7	14.7	14.5	13.4
TOTAL	200.5	210.5	267.2	288.6	254.9	219.8	217.8	212.7
Then-Year-Dollars	200.5	219.5	290.9	327.7	299.9	264.9	271.2	273.5

Administrative Unit Summary	FY90	FY91	FY92	FY93	FY94	FY95	FY96	FY97
Base Operations	113.1	117.4	123.1	130.3	125.0	126.2	127.4	126.8
Collider Program	39.6	36.5	46.0	40.9	36.4	26.9	23.0	23.0
Fixed Target Program	13.1	14.6	19.5	24.6	27.0	29.9	30.8	30.3
Physics And Computing	30.1	30.6	31.4	32.9	32.5	32.6	32.5	32.6
Linac Upgrade	4.6	11.5	5.6	0.0	0.0	0.0	0.0	0.0
Main Injector	0.0	0.0	41.6	60.0	34.1	0.0	0.0	0.0
Computer Upgrade	0.0	0.0	0.0	0.0	0.0	4.2	4.0	0.0
TOTAL	200.5	210.5	267.2	288.6	254.9	219.8	217.8	212.7
Then-Year-Dollars	200.5	219.5	290.9	327.7	299.9	264.9	271.2	273.5

Budget Office 3/18/90

THE EVOLUTION OF FERMILAB III

The Fermilab program does not fall neatly into Fixed Target and Collider programs, except in the case of the procrustean budget categories. To make things easier to understand, the charm and beauty experiments were not included in either category but were given their own. The 800 GeV Fixed Target program, excluding charm and beauty experiments, is further divided into two programs: CP Violation and Weak Decays, and Parton Distributions and Hard Collisions.

CP VIOLATION AND WEAK DECAYS

Table 7.7 gives the current list of approved experiments in this category. E-731, an experiment that completed data taking in 1988, will soon report CP violation parameters in the neutral K system that are more accurate than any previously reported. E-773 will make the most accurate measurement of the phase difference of the two charged pion amplitude and the two neutral pion amplitude. E-799 will search for rare neutral K decays and decays such as $K_L^o \rightarrow \pi^o e^+ e^-$ will be observed! E-773 will finish in 1991 and E-799 in 1993. Today, there may be only an upper limit for the magnitude of ε'/ε and a value for it, as opposed to an upper limit, may not have been definitively measured by 1993. The proponents of these experiments, augmented by additional physicists from four other experiments, have submitted a letter of intent to continue these experiments with the Main Injector after 1995. It is their belief that this approach is the next step in that series of measurements.

TABLE 7.7. - APPROVED CP VIOLATION AND RARE DECAYS EXPERIMENTS

E-731 (Winstein)*	A Precision Measurement of ε'/ε
E-761 (Vorobyov)	Hyperon Radiative Decays (9/43)
E-773 (Gollin)	Phase Difference Between η_{oo} and η_{+-} (5/17)
E-774 (Crisler)	Electron Beam Dump Particle Search (4/9)
E-799 (Wah/Yamanaka)	Search for $KL \rightarrow \pi^0 e^+ e^-$ (5/21)

* Completed in 1988

Note: Numbers in parentheses denote total number of institutions and physicists, respectively.

PARTON DISTRIBUTIONS AND HARD COLLISIONS

This category includes a few experiments that do not fit neatly in any single category. A list of these experiments is given in Table 7.8. All of these experiments will finish in 1991 when the current Fixed Target run ends. E-704, which uses a polarized proton beam and a polarized proton target, plans to measure a large number of inclusive cross sections. E-706 is able to measure inclusive cross sections for direct γ's up to a p_t of 8 GeV. E-683 uses a photon in the initial state and detects jets in the final state. All three experiments have some sensitivity to the proton's gluon structure function. Letters of intent for followup experiments in 1993 have been received for all three experiments. In the future, the biggest advances in our understanding of hard collisions will probably be made with Collider detectors. An exception is the measurement of inclusive cross sections for the scattering of polarized protons since this experiment has no Collider counterpart.

TABLE 7.8. APPROVED PARTON DISTRIBUTIONS AND HARD COLLISIONS EXPERIMENTS

E-683 (Corcoran)	Photoproduction of Jets (11 / 44)
E-704 (Yokosawa)	Experiments with Polarized Beam (18 / 83)
E-706 (Slattery)	Direct Photon Production (10 / 77)
E-665 (Geesaman)	Muon Scattering with Hadron Detection (13 / 82)
E-782 (Kitagaki)	Muon Scattering with Tohoku Bubble Chamber (8 / 26)
E-733 (Brock)*	Neutrino Interactions (Lab. C Detector)
E-744 (Merritt)*	Neutrino Interactions (Lab. E Detector)

* Completed in 1988

Note: Numbers in parentheses denote total number of institutions and physicists, respectively.

The μ scattering experiment, E-665, was designed to measure F_2 and quark fragmentation and it will be complete in 1991. A letter of intent for a followup has been submitted. Many of the proponents of this work are drawn from the Nuclear Physics and Medium Energy Physics communities. This may be a growing trend. The data taking for ν scattering experiments E-733 and E-744 was completed in 1988. These experiments were designed to measure $\sin^2\theta_W$ and structure functions. One of these experiments, E-744, has in excess of 10^6 ν and $\bar{\nu}$ events, the largest sample of such events ever recorded. The analysis of the data has encouraged some of the proponents of both experiments to plan a future common experiment. A letter of intent for such an experiment in the 1995-97 time frame has been received. It proposes a sample of ν events that will be at least an order of magnitude greater than the data accumulated in 1987-8. The intense neutrino beam needed to achieve this goal can only be generated by the Main Injector. While such an experiment may also run at UNK, it is still worth doing at Fermilab.

There is one experiment that fits in none of the categories, so it has its own category: Static Properties of Elementary Particles. This category contains E-800, a precision measurement of hyperon magnetic moments. This experiment, which will end in 1991, is the most recent in a series of superb experiments that began in 1972 with E-8.

Nearly all of the experiments in this category of Parton Distributions and Hard Collision Experiments use large sophisticated spectrometers that were built incrementally over the last eight to ten years. The Chicago Cyclotron magnet used in E-665 is the same iron yoke used by Enrico Fermi more than forty years ago. Any additional experiments that receive approval for running in 1993 will use existing detectors with modest improvements. Because of the funding level, the number of experiments that receive approval to run in 1993 can be expected to be smaller than the number that will run in 1991.

The SSCL request of one additional beam for detector development and testing can be satisfied in 1993. There is no request from the SSCL for use of Fermilab Fixed Target beams after 1993. Nonetheless, any such requests could be accommodated more readily after 1995 when the Main Injector is in operation. Leaving aside requests from the SSCL for test beams, Fermilab will be forced to decommission beams, but can only expect to achieve <u>small</u> operating savings thereby. Unfortunately, these savings will be counterbalanced by the increase in the cost of doing business as alluded to earlier. The list of approved detector tests is given in Table 7.9. All of these tests have been scheduled and will be completed during the 1990-91 Fixed Target run.

TABLE 7.9. APPROVED DETECTOR TESTS

E-790 (Sciulli)	ZEUS Calorimeter Module Tests (8 / 28)
E-795 (Pripstein)	Warm Liquid Calorimetry (6 / 16)
E-797 (Gustafson / Thun)	SSC R&D (Fine-grained EM Calorimeter) (1 / 6)
E-798 (Cushman / Rusack)	SSC Detector Tests (Synchrotron Radiation) (2 / 4)
E-807 (Teige)	Calorimeter R&D (Tetra-Bromo-Ethane) (1 / 7)

Note: Numbers in parentheses denote total number of institutions and physicists, respectively.

CHARM AND BEAUTY EXPERIMENTS

The set of charm and beauty experiments is the largest set devoted to any single topic at Fermilab. The list of these experiments is given in Table 7.10. The charm experiments have the goal of either accumulating samples of 10^5 charm decays (E-687, E-690, and E-791) or large samples of very rare charm decays (E-789). Many of them also plan to detect B decays. The ultimate goals of beauty physics include: the search for rare B decays, the measurement of neutral B mixing, and the observation of CP violation in the B system. While five of the eight Fixed Target charm and beauty experiments will be completed at the end of the 1991 run, these experiments have submitted letters of intent for 1993. The remainder will be completed by the end of 1993.

Work reported in papers from the Breckenridge Workshop showed that some of these experiments could reach > 10^6 fully reconstructed charm decays (by 1995). If that is the case, the best could continue with improvements to acquire these larger samples of charm and modest samples of B's. By 1993 there may be fewer than five fixed target charm and beauty experiments. Again, there is a hope that mergers of teams with a common interest will occur and that this will lead to even stronger experiments.

TABLE 7.10. APPROVED CHARM AND BEAUTY EXPERIMENTS

E-672 (Zieminski)	High Mass Dimuons and High P_t Jets (7 / 30)
E-687 (Butler)	Photoproduction of Charm and Beauty (12 / 92)
E-690 (Knapp)	Hadronic Production of Charm and Beauty (5 / 28)
E-760 (Cester)	Charmonium States (7 / 72)
E-771 (Cox)	Beauty Production by Protons (20 / 94)
E-775 (Shochet / Tollestrup)*	CDF - Silicon Microvertex Detector
E-781 (Russ)	Large-X Baryon Spectrometer (8 /43)
E-789 (Kaplan / Peng)	Production and Decay of B-Quark Mesons and Baryons (6 / 26)
E-791 (Appel / Purohit)	Hadronic Production of Beauty and Charm Particles (10 / 60)

* This part of CDF is listed here for completeness

Note: Numbers in parentheses denote total number of institutions and physicists, respectively.

The continuing CDF collaboration, E-775, will have its first experience with a silicon microstrip detector during the 1991-92 Collider run. This collaboration is prepared to welcome an infusion of talent that might want to work with a 25 microbarn cross section rather than a 25 nanobarn cross section. Such an infusion would help to speed the development of the technology needed to make B detection practical at a hadron collider. The request to add a silicon microstrip detector to the D0 detector will almost certainly be presented to the Laboratory if CDF demonstrates the feasibility of the identification of charm and beauty with this technique.

Intermediate between CDF and the Fixed Target experiments is E-784, BCD. Its goal is to become a Collider experiment, although it has only been approved for R&D. It is addressing many of the most difficult problems of technology that must be solved if a large number of B's are to be detected and analyzed in hadron collisions.

At this time, one can say with certainty that none of the approved experiments will reach the distant goals of mixing and CP violation in their current form. However, these experiments are developing the technology that will lead to the next step, and that step will develop the technology for the next step. If enough of the steps are successful and the results are applicable to collider detectors, a major fraction of the participants can be expected to coalesce around a collider detector dedicated to B physics. If this detector is built for use at Fermilab, it would replace either CDF or D0. The development of technology to take one of these steps may not occur, or it may take too long. If that happens then this approach will lose out to the e^+ - e^- B factories. Given the importance of CP Violation and the fact that good physics is done at every step, the effort is certainly worth while.

Major funding for the construction of such a detector could not start until the upgrades of CDF and D0 were nearing completion. Since funds for this detector were not included in the minimal budget requirements, a significant but unknown increment would be needed starting in 1995.

TWO TEV COLLIDER PHYSICS

CDF and D0 are clearly the flagships of Fermilab III's voyage to the region beyond the electroweak scale. They will define the horizon. In order to see as far as the Tevatron and its higher luminosity will permit, significant improvements will continue to be made to CDF and D0 through 1995. The cost estimates for these upgrades that were prepared by the CDF and D0 collaborations were included in the budget tables. Improvements to the Tevatron will continue until a luminosity of greater than $5x10^{31}cm^{-2}sec^{-1}$ is reached and a center of mass energy of 2.2 TeV is reached. The expectation is that this goal will be achieved around 1996.

CDF and D0 will continue data taking until about 1998, roughly a few years before the SSC turns on. Ever larger numbers of the senior members of these collaborations will shift their attention to the SSC after 1994. The remaining senior physicists, the postdoctoral fellows and students will continue on with many of the Fermilab staff and discover the top, measure its mass, measure M_W/M_Z very accurately, and do lots more.

The population parameters of these collaborations are shown in Table 7.11, along with the two small completed collider experiments. It will still be possible to schedule low luminosity runs for small collider experiments, although it will be done at the expense of the 800 GeV Fixed Target program.

TABLE 7.11. APPROVED COLLIDER EXPERIMENTS

E-740 (Grannis)	D0 Detector (23 / 187)
E-741 / 775 (Shochet / Tollestrup)	Collider Detector at Fermilab (20 / 326)

Note: Numbers in parentheses denote total number of institutions and physicists, respectively.

120 GEV FIXED TARGET PHYSICS

Physics research with the 120 GeV Main Injector beam can be a truly impressive program because the Main Injector is a very impressive machine. One of the best kept secrets is that the 400 MeV Linac and 8 GeV, 15 Hz, Booster are also very impressive machines.

Around 1995 or 1996, the program of neutral K experiments that has done so well at 800 GeV will move to the more intense neutral K beams that can be provided by the Main Injector. The timing will depend on funding. A letter of intent to carry out such a program of experiments has been submitted.

Letters of intent for two ν experiments that intend to use the very intense neutrino beam that can be created by the Main Injector have been received. Such a facility could be mounted by 1996 if funding came rapidly. When the budget tables were prepared, the cost estimates for these experiments and their beam lines were included.

These three efforts, which are listed in Table 7.12, are only letters of intent. Neither the Fermilab PAC nor the Fermilab management has scrutinized these letters to determine whether the experiments are feasible or affordable. They are certainly directed at interesting and fundamental topics. These letters will be reviewed carefully in the coming year. Should Fermilab receive full proposals and approve such experiments, the start of their construction would not begin until after the Main Injector is approved.

TABLE 7.12. LETTERS OF INTENT FOR 120 GeV FIXED-TARGET EXPERIMENT

P-803 (Reay)	$\nu_\mu - \nu_\tau$ Oscillation
P-804 (Winstein)	Kaon Physics at Main Injector
P-805 (Gajewski)	Long Baseline ν Oscillation

If dollars are one important resource, then people must be another. The Fermilab program has a large amount of diversity because there are large numbers of physicists with diverse ideas. Tables 7.13 and 7.14 provide information on the population statistics for Fermilab for the experiments still taking data.

A number of startling facts can be gleaned from these tables. First, the number of students, 341, working at Fermilab is very large. It must be a very big part of the the entire U. S. high energy physics graduate student population. These students will, in five or six years, become the senior postdoctoral and junior faculty that will make the SSC experiments successful. Students choose to work on exciting, forefront experiments, provided that the experiments have a realistic prospect of taking data in a timely way. If Fermilab experiments are stretched out for years because of funding, the graduate students will leave the field for others which allow the completion of a dissertation in a reasonable length of time. Today, Fermilab is a place for graduate students. Seven years ago during the Great Midwest Physics Draught, Fermilab was not the place and numbers of students were much smaller. If the next seven years are the promised fat years, then the SSCL will be assured an experienced and enthusiastic team of scientists. If 1991 is the start of another seven lean years, the prospects for utilization of the SSCL by young U. S. physicists in the 21st century are grim.

The number of physicists that use Fermilab is also very large. Of these, 25% are from abroad. The largest contingents are from Italy and Japan. A significant number of Latin American physicists also work at Fermilab. These colleagues are also very important to the health of high energy physics research.

TABLE 7.13. PARTICIPANTS IN THE FIXED-TARGET EXPERIMENTS

Expt.	Physicist	Student	Total
E665	54	28	82
E672	26	4	30
E683	29	16	45
E687	64	28	92
E690	20	8	28
E704/581	70	13	83
E706	38	39	77
E761	37	6	43
E760	53	19	72
E771	73	21	94
E773	14	3	17
E774	9	0	9
E781	41	2	43
E782	24	2	26
E789	22	4	26
E791	48	12	60
E799	17	4	21
E800	6	7	13
Total	580	208	**788**

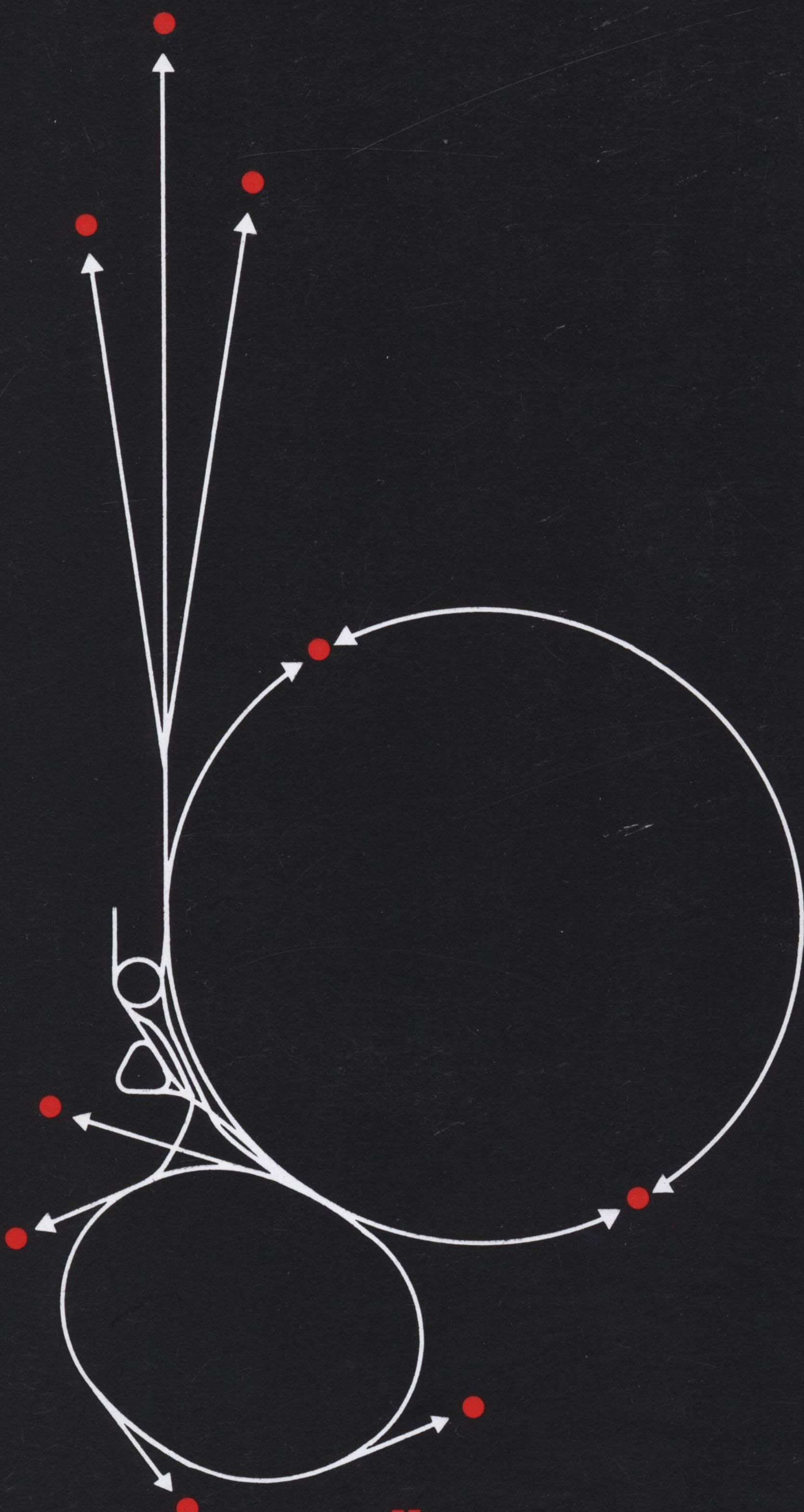
TABLE 7.14. PARTICIPANTS IN THE COLLIDER PROGRAM

Experiment	Physicist	Student	Total
E-740	160	27	187
E-741/775	220	106	326
Total	378	133	511

NEW DIRECTIONS FOR FERMILAB

On October 1988, when the then Secretary of Energy announced that Texas was the winner of the SSC sweepstakes, Fermilab's long-range plan disappeared. Since then, Fermilab has dedicated itself to creating a credible ten year plan. Fermilab, like the U.S. high energy physics community, has to succeed in the 1990's if it is to succeed in the following decade. While the year 2000 is far away in time, we are giving some thought to new directions that Fermilab could explore to keep it vital in the 21st century. At present, the most notable effort is Fermilab's participation in the Solenoidal Detector Collaboration. Thirty-five staff physicists have proposed to spend 20% or more of their time working on the letter of intent. The Laboratory is supporting this effort and will give it greater support in the future.

Two long range planning committees are considering other directions of research that would be new for Fermilab. One committee is evaluating whether Fermilab should enter experimental astrophysics and the other is considering whether Fermilab can contribute to e^+e^- linear collider R&D. It is not clear that these efforts will lead to support from the DOE. It is clear that there is extremely interesting physics and accelerator development that could be done by Fermilab. We have developed, perhaps unnoticed by the rest of the world, some extremely strong capabilities that will allow us to contribute in areas where we have not previously contributed. In the meantime, we will do forefront physics at the highest energies in the 1990's. None of these things, even the Large Solenoid Detector, are so well defined that one can say for certain that they will be part of Fermilab IV. One can say, however, that there will be a vital and active Fermilab beyond the year 2000.



Fermi National Accelerator Laboratory

Batavia, Illinois

Operated by University Research Association, Inc.
Under the contract with the United States Department of Energy

This booklet contains summaries of presentations prepared for the HEPAP Subpanel on the U. S. High Energy Physics Research Program for the 1990's

by:

John Peoples, Jr.	Introduction and 'To The Horizon'
Gerald Dugan	Tevatron Luminosity
Stephen Holmes	Main Injector
William J. Spalding	Charm and Beauty Physics
John Huth and Harry Melanson	QCD Physics
Melvin Shochet	Electroweak and Top Physics

Acknowledgement is made of all those whose efforts are summarized by these presenters. Special thanks are also due to Dan Amidei, Jeffrey Appel, Jerome Biltgen, Gregory Bock, Charles Brown, Joel Butler, Eugene Fisk, Brenna Flaugher, Peter Garbincius, Glenn Goderre, Michael Gold, Michael Harrison, David Herrup, Joey Huston, Simon Kwan, Paul Lebrun, Michelangelo Mangano, John Marriner, Thornton Murphy, Stephen Parke, Steve Peggs, Robert Plunkett, N. W. Reay, Heidi Schellman, B. Shiung, Kenneth Stanfield, Linda Stutte, Paul Tipton, Alvin Tollestrup, Y. Wah, and Taiji Yamanouchi. Preparation of this booklet benefited greatly from Sue Grommes, Jean Lemke, Pat Oleck, and Marilyn Smith.