Future ElectroWeak Physics at the Fermilab Tevatron Report of the *tev_2000* Study Group: Polarized Protons at the Tevatron

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Chapter 1

Foreword

In particle physics, the "High Energy Frontier" defines, at any time, a set of problems of great theoretical interest and a set of future facilities of grand reach and scope. Meanwhile, the hands–on reality of High Energy Physics proceeds in the facilities of the present, with all of the unexpected twists and turns of scientific progress. The recent observation of the massive top quark at the Fermilab Tevatron reminds us that discovery and opportunity don't mark time, and that a vital experimental program should be prepared to respond to matters arising. Although there are, as always, new facilities in our future, that future is not so immediate, and we now have the opportunity to evaluate an unexpectedly rich new physics program at the Fermilab Tevatron, an existing facility with proven capability...

This document is the report of a working group established to evaluate the potential of an extended high p_T physics program at the Tevatron Collider. We have found that, in addition to a complete program of top quark physics, there is an rich catalog of topical measurements and important discovery potential in many areas. Much of this Tevatron physics potential, such as the top quark program, and significant sensitivity to light Higgs and low energy SUSY, has not been carefully evaluated until now.

The report is organized as follows. This **Foreword** describes the process which led to our organization and guided our work. A second chapter titled **Physics Conclusions and Recommendations** contains an "Executive Summary" of results from each of the physics working groups plus more general recommendations on the pursuit of an extended Tevatron program. There follow seven chapters which catalog the results in each of the physics subtopics. Finally, an **Afterword** contains some views of where this work figures into the broader scheme of things at Fermilab and more generally in High Energy Physics. To those interested in the detailed physics studies, the individual chapters should be important and stimulating. To those with general interests, the Foreword, Conclusions, and Afterword were written to stand alone as a readable document.

1.1 The Potential for Tevatron Evolution

Ideas for upgrades to the Fermilab Tevatron began to surface almost immediately after the SSC cancellation. The most fully developed ideas at this point include improvements to luminosity, and the physics thrust of this study is directed toward this prospect. Since the options and their parameters have been in flux, we briefly review them here. We note that in the running period just completed (the "1B" run) the peak luminosity was approximately 2×10^{31}cm^{-2}s^{-1} with an integrated luminosity in this 18 month running period of more than 100 pb^{-1}.

1. **Luminosity Upgrade of up to** 10^{32}cm^{-2}s^{-1}. This is the classic Main Injector scenario with 36 proton and antiproton bunches, 395 ns between crossings, and 3 interactions per crossing at two collision points. Further study has led to two variations on this theme:

   (a) The classic scenario, but with $\mathcal{L} = 10^{32}$ cm^{-2}s^{-1} and 99 proton and antiproton bunches, leading to 132 ns between crossings and 1 interaction per crossing with two interaction regions. Detector upgrades have been designed to be compatible with this future variation.

   (b) An expansion of the antiproton capability which should provide even higher luminosity. The recent name for a Run II which would equal or surpass 2×10^{32} cm^{-2}s^{-1} is "TeV$\star$". In order to reach luminosities which exceed 10^{32} cm^{-2}s^{-1} a separate, permanent magnet storage ring of 8 GeV would be built inside the Main Injector tunnel to serve as a "Recycler" for unspent antiprotons. In this variation, the number of overlapping interactions would rise to 6/2 per crossing at 396/132 ns.

   The current plan for the beginning of the Main Injector collider run, Run II, is the "classic" scenario. It should be noted that there are now upgrade plans for CDF and DØ which very recently have been directed toward 2×10^{32} cm^{-2}s^{-1}.

2. **Luminosity Upgrade to** 10^{33} cm^{-2}s^{-1}. Going beyond 10^{32} cm^{-2}s^{-1} has become a subject of considerable interest. The Main Injector and Recycler add significant capacity to the Collider Complex, and it seems that with additional low cost accelerator improvements the 10^{33} cm^{-2}s^{-1} level is conceivable. As with the Main Injector scenarios, there are variations.

   (a) Bunch crossing time of 132 ns, at 10^{33} cm^{-2}s^{-1} which gives rise to 9 interactions per crossing with two interaction regions.

   (b) Bunch crossing time of 19 ns, at 10^{33} cm^{-2}s^{-1} which gives rise to 1.3 interactions per crossing with two interaction regions.

   This "superluminous" Tevatron upgrade has been dubbed "TeV33".

In addition to luminosity upgrades, other ideas being discussed for the Fermilab site include center of mass energy upgrades to 4 TeV (the "DiTevatron"), for $p\bar{p}$ or pp; an ultra–high energy pp or $p\bar{p}$ collider; a high energy e^+e^- linear collider, polarized p-unpolarized $\bar{p}$ collider; and a muon collider.

1.2 The *tev_2000* Effort

The *tev_2000* "workshop" was a grass–roots effort motivated by the richness of the physics at the Tevatron, the lack of an organized study of the Tevatron long range potential, and the notion that facilities planning for U.S. HEP in these times would do well to include a study of "what we could do with what we've got". It started with a two day meeting at the University of Michigan on October 21^{st} and 22^{nd} of 1994 to form an *ad hoc* partnership between CDF, DØ, and the theoretical community. More than 100 physicists attended and divided into seven working groups to begin the exploration of the physics. This "extended workshop" continued throughout the winter, spring, and summer of 1995 on many U.S. campuses and at Fermilab. During this period, work within the Fermilab Accelerator Division reached the point of designing a $\bar{p}$ Recycler ring for the Main Injector project, and the high luminosity Tevatron was poised to move from a concept to an engineering design phase. We believe the physics case is now at a similar level of maturity.

The goals of the *tev_2000* effort were:

- To quantify the scientific case for high p_{T} and electroweak physics accessible with high luminosity at the Tevatron.
- To document this case as a foundation for further literature.

We have accomplished both goals with the completion of this report. The physics program that we have found is broad and has compelling programmatic components as well as significant discovery potential.

The subsequent chapters in this report describe in detail the first results in the following general areas:

Chapter 3: Top Physics

Chapter 4: Intermediate Vector Bosons, W's, Z's, and γ's

Chapter 5: Light Higgs Bosons

Chapter 6: Supersymmetry

Chapter 7: Exotics and Searches

Chapter 8: Physics Potential of a Polarized p–Unpolarized $\bar{p}$ Tevatron

Chapter 9: Detector Challenges

The physics studies all use a common set of assumptions regarding luminosity performance at the Tevatron. It was decided that we would first revisit the physics accessible in the classic Main Injector scenario, and then extrapolate to both modest and extreme improvements in the luminosity. The extrapolated scenarios would presumably come in different calendar periods, but the workshop chose to ignore the vagaries of calendar and to concentrate on the physics. The parameters of the strawman scenarios are:

- **Run II**
  - $p\overline{p}$ with 1TeV $\times$ 1TeV.
  - $\mathcal{L} \leq 10^{32}$ cm^{-2}s^{-1} with either 395 ns bunch spacing and 3 interactions/crossing or 132 ns bunch spacing and 1 interaction/crossing.
  - $\int \mathcal{L}\, dt = 2$ fb^{-1}.
  - Proposed CDF and DØ Run II upgrades.
- **Run II–"stretch"**
  - $p\overline{p}$ with 1TeV $\times$ 1TeV.
  - $\mathcal{L}$ increasing **beyond** 10^{32} cm^{-2}s^{-1} with either 395 ns or 132 ns bunch spacing. Interactions/crossing scale from values above.
  - $\int \mathcal{L}\, dt \sim 10$ fb^{-1}.
  - Multiple years of running, possibly overlapping with LHC.
  - Incremental CDF and DØ Run II upgrades, as required.
- **High Luminosity Running**
  - $p\overline{p}$ with 1TeV $\times$ 1TeV.
  - $\mathcal{L} = 10^{33}$ cm^{-2}s^{-1} with 9 interactions/crossing and 132 ns bunch spacing.
  - $\int \mathcal{L}\, dt = 100$ fb^{-1}. We consider this upper limit to establish the asymptotic level of statistical precision in each physics study.
  - "Reasonable" CDF and DØ Run II detector extrapolations.

We assume that it will be possible to maintain detector performance levels of the CDF and D∅Upgrades by appropriate evolution of technologies. This allows us to use standing simulations for the physics studies. Since these simulations have been tuned to existing detectors in a well studied environment, we believe that our results have a degree of credibility beyond what is usually found in proposals of this type. We have considered detector issues in a general way in Chapter 9, and we find no "show stoppers". In a few critical cases we have also explicitly evaluated the effect of high luminosity conditions, for instance the impact of 9 overlapping interactions on the SUSY sensitivity, and on mass resolution in the Higgs search, and we have found the effects in these cases to be small. But we readily acknowledge that such issues require more work, and we hope that this report will stimulate further inquiry.

Our results on the physics potential of an extended Tevatron program are summarized in Chapter 2, and described in detail in Chapters 3 through 9. Where possible, we have compared with LEPII, NLC, and the LHC. We emphasize that this is the *first* look at a post–SSC Tevatron and that these results should be considered preliminary. Experience with the Collider suggests that the ultimate physics menu which would develop with tens of fb^{-1} will be richer than what is indicated by this initial study.

Chapter 2

Physics Conclusions and General Recommendations

This chapter summarizes the results from each of the working groups and draws general conclusions. The results of the workshop indicate a rich and competitive physics program for a superluminous Tevatron.

2.1 Conclusions of the Physics Groups

2.1.1 Top Physics

A detector with high–rate capability comparable to that of the CDF or DØ upgrades will identify approximately 500 b tagged (i.e. identified) top quark events per fb^{-1} in the $\ell+$ jets mode. This is 2 to 5 times the yield in this mode for equivalent luminosity at an NLC. With integrated luminosities in excess of 10 fb^{-1} it will be possible to:

- Measure a top quark mass to a precision of $2\,\mathrm{GeV}/c^2$ per experiment.
- Measure the $t\bar{t}$ production cross section to 6%.
- Measure the top quark branching fraction to b quarks in association with W with precision exceeding 2%.
- Measure the ratio of dilepton to single lepton decay rates to better than 5%, yielding the partial width to non-W final states with a precision of 6%.
- Probe for $t\bar{t}$ resonances out to masses of roughly 1 TeV/c^2.
- Probe the Wtb couplings by measuring branching fractions to W helicity states with statistical precisions of a few percent.
- Isolate electroweak single top production via t-channel W-gluon fusion $\mathrm{qg} \rightarrow \mathrm{t\bar{b}q'}$ and s-channel W^* production $\mathrm{q'\bar{q}} \rightarrow \mathrm{t\bar{b}}$, and use these production modes to:

- Measure the cross sections to $\sim 10\%$.
- Measure the partial width $\Gamma(t \to Wb)$ to $\sim 12\%$.
- Measure the CKM matrix element V_{tb} with a precision of 6%.
- Search for anomalous couplings and CP violation effects.

- Probe for the rare decay $t \to c + \gamma$ with sensitivity of 10^{-4}.
- Probe for the rare decay $t \to Z + c$ with sensitivity of 10^{-3}.

The program of accessible top quark physics at the Tevatron is certainly larger than this list and it is not inconceivable that a 180 GeV/c^2 fermion may have surprises in store. This is therefore *not* the menu of all measurements, but instead a survey of *sensitivity levels* for the ultimate broad program of top physics at the Tevatron.

2.1.2 Intermediate Vector Boson Physics

With very large integrated luminosities at the Tevatron, the electroweak sector of the SM can be probed in great detail. Our preliminary studies arrive at the following conclusions:

- With 10 fb^{-1} it should be possible to measure the mass of the W boson with a precision of at least 30 MeV/c^2, and 20 MeV/c^2 may well be within reach. This is about a factor of 2 better than what one expects for LEP II. With a precision of 20 MeV/c^2 (30 MeV/c^2) for the W mass, and 2 GeV/c^2 for the top quark mass, the Higgs boson mass can be predicted with an uncertainty of about 40% (50%) of itself. This prediction may be very useful for direct Higgs searches at the Tevatron, LHC, or NLC, and comparison with the results of a direct search will constitute an essential set of tests of the SM.

- The W width can be measured with an uncertainty of about 15 MeV. This is an improvement of almost one order of magnitude of the current uncertainty. At LEP II Γ_W can only be measured with a precision of a few hundred MeV.

- The W charge asymmetry will be a very powerful tool in constraining the parton distribution functions. In many processes the error in the parton distribution functions currently constitutes a major source of uncertainty. The forward backward asymmetry, A_{FB} in Z boson decays provides a useful cross check on the Higgs boson mass extracted from the W mass measurement.

- With 10 fb^{-1}, the WWV and $Z\gamma V$, $V = \gamma$, Z, vertices can be determined with a precision of $\mathcal{O}(10^{-1})$ and $\mathcal{O}(10^{-2} - 10^{-3})$, respectively, at the Tevatron. The expected accuracy for the WWV couplings is comparable or better than that of LEP II. However, since the methods used to extract limits on anomalous couplings at the two colliders are different, data from the Tevatron and LEP II yield complementary information. Tevatron experiments will be able to place limits on the $Z\gamma V$ couplings which are up to a factor 100 better than those which can be achieved at LEP II. At the LHC, with

100 fb^{-1}, it will be possible to place limits on anomalous WWV and $Z\gamma V$ couplings which are a factor 3 to 100 better than those one can expect for the Tevatron with 10 fb^{-1}.

- The Tevatron offers a unique chance to search for the SM "radiation zero" in $W\gamma$ production, which provides an additional test of the gauge theory nature of the SM. At the LHC, due to the large qg luminosity, QCD corrections obscure the dip in the photon lepton rapidity difference distribution which is caused by the radiation zero. This is not the case at Tevatron energies. Currently, the experimental results are statistically limited. With integrated luminosities of 2 fb^{-1} or more, it should be possible to conclusively establish the existence of the radiation zero.

- With an integrated luminosity of 10 fb^{-1}, limits on the branching ratios of rare W decays of $\mathcal{O}(10^{-5})$ to $\mathcal{O}(10^{-7})$ can be obtained. W decays into two pseudoscalar mesons offer an opportunity to probe meson decay form factors at a very high momentum transfer where these form factors have not been tested so far.

- The Tevatron offers a unique opportunity to search for CP violation in W boson production and decay since it collides protons and antiprotons, i.e. the initial state is a CP eigenstate. The extremely large number of W boson events expected at a superluminous Tevatron will make it possible to search for small CP-violating contributions to W boson production, at the level of $\mathcal{O}(10^{-3} - 10^{-4})$.

- An integrated luminosity of 10 fb^{-1}, will produce a sufficient number of $W\gamma\gamma$, $Z\gamma\gamma$ and $WW\gamma$ events to extract direct information on the quartic gauge boson couplings.

2.1.3 Light Higgs Physics

A light intermediate-mass scalar in the mass region 80 GeV/c^2 $< m_H <$ 130 GeV/c^2 is predicted by minimal supersymmetric models, and current precision electroweak data also show a slight preference for a low mass Higgs. This study confirms recent theoretical speculation that there is a **luminosity threshold for the detection of a light Standard Model Higgs boson at the Tevatron**, and suggests that this threshold varies from 5 to 25 fb^{-1} as m_H varies from 60 to 120 GeV/c^2.

- The process $q'\bar{q} \to WH$, with $H \to b\bar{b}$, is the best single mode for the detection of a light Higgs boson at the Tevatron, and leads to the luminosity thresholds stated above. The analysis relies heavily on the understanding of b tagging, the "W + flavor" backgrounds, and mass fitting with jets, and is therefore a natural complement and extension of the top physics program.

- The process $\bar{p}p \to (W,Z)H$, with $H \to \tau^+\tau^-$ and $(W,Z) \to jj$, is difficult at the Tevatron due to the large $(Z \to \tau^+\tau^-)jj$ background, but may add to the overall significance of the observation. Other channels, such as ZH with $Z \to \nu\bar{\nu}$ and $H \to b\bar{b}$, have not been investigated, and should be. A set of combined channels may have better significance than our single studied channel of WH with $H \to b\bar{b}$, and this should also be investigated.

- We have studied the potential of the $W + H \to b\bar{b}$ measurement at the LHC, assuming equivalent detection efficiencies, etc and find that it is difficult there because of large top backgrounds. It may be that the intermediate mass region is accessible at the LHC only via the rare decay mode $H \to \gamma\gamma$. Since the branching fraction to $\gamma\gamma$ varies with the choice of SUSY parameters, the LHC cannot prove that the light Higgs boson of SUSY does not exist if it is not found there.

- The process $q'\bar{q} \to WH$ is complementary to the LEP II/NLC process $e^+e^- \to ZH$, since it involves the coupling of the Higgs boson to different weak bosons. The ratio of these couplings can vary in multi-Higgs models with multiplets other than doublets (e. g., Higgs triplets).

Although further study is needed, the opportunity to detect a light Higgs boson at the Fermilab Tevatron appears to be real.

2.1.4 Supersymmetric Physics

For the next decade, the Tevatron will continue to be the highest energy accelerator in the world. We must exploit this opportunity to not only study the top quark, but to search for the signature of one of the most tantalizing new physics theories proposed beyond the Standard Model - supersymmetry (SUSY).

There are many arguments why SUSY provides an elegant extension to the Standard Model. SUSY solves the gauge hierarchy problem, unifies the SM coupling constants, provides a candidate for cold dark matter, solves the Higgs mass fine tuning problem and is naturally decoupled from Standard Model particles. The experimental consequence of these arguments for the existence of supersymmetry at the weak scale is the presence of 32 new particles in the mass range ~100 to 1000 GeV/c^2. It is not surprising that none of these particles have been discovered yet, since most current limits from supersymmetric particle searches are below this range.

With a detector similar to the upgraded DØ/CDF detectors and an integrated luminosity of order 20-25 fb^{-1}, the Tevatron will be able to significantly probe a large fraction of the expected SUSY mass range for the first time. It should be noted that the light Higgs (h) search is also an important concomitant search, since SUSY predicts it to be lighter than about 130 GeV/c^2.

Using the SUSY model based on the particle spectrum of the MSSM (a SUSY partner for each SM particle with two Higgs doublets) combined with grand unification (based on supergravity) and R parity, our preliminary conclusions are:

- We will be able to search for charginos with masses up to 250 GeV/c^2. The mass reach depends on the choice of the unknown SUSY parameters. Therefore, even though the Tevatron can find a chargino with a 250 GeV/c^2 mass, it cannot completely rule out all charginos below this mass.

- We will be sensitive to gluinos with masses up to about 400 GeV/c^2, depending on the SUSY parameters. Note, that the Tevatron can find gluinos with masses below about 300 GeV/c^2 for any choice of parameter.

- The Tevatron can search for light supersymmetric top quarks in various decay modes up to about 180 GeV/c^2 mass.
- The SUSY searches at TeV33 are complementary to those at LEP-II and NLC. For example, if LEP-II found a 90-GeV chargino, we expect the gluino mass to be in the range 270-360 GeV/c^2, which will be accesible at TeV33 (but not LEP-II). A preliminary study on the determination of the gluino mass at TeV33 shows that a 300-GeV/c^2 gluino mass could be measured with a resolution of about 20 GeV/c^2. TeV33 is also competitive to NLC in the gluino/squark searches.

The Tevatron enjoys an unique window of opportunity to discover the first evidence for a highly motivated theory beyond the Standard Model. The increased luminosity available at TeV33 is necessary to exploit this opportunity during the next decade.

2.1.5 Exotic Physics

An integrated luminosity approaching 100 fb^{-1} at the Tevatron greatly extends the present mass reach for exotic objects. Specifically, a data set of 100 fb^{-1} is sensitive to:

- W' and Z' up to 1.3 TeV/c^2
- axigluons in dijet mode up to 1.3 TeV/c^2
- E_6 color triplet scalar diquarks in dijet mode up to 800 GeV/c^2
- first generation leptoquarks up to 360 GeV/c^2
- compositeness in $qqqq$ mode up to 2.8 TeV/c^2
- compositeness in $qqll$ mode up to 7.4 TeV/c^2
- excited quarks up to 1.2 TeV/c^2
- color octet ρ_t in dijet mode up to 1.0 TeV/c^2
- massive stable particles
  - color triplets up to 540 GeV/c^2
  - color sextets and octets up to 600 GeV/c^2
  - color decuplets up to 660 GeV/c^2

Without any theoretical prejudice of the mass of new particles, a superluminous Tevatron effectively *doubles* the current discovery potential.

2.1.6 Physics with Polarized Protons

The electroweak physics benefits of polarizing the proton beam have received only a zeroth–order look.

- It may be feasible to polarize the proton beam, transversely and longitudinally in the Tevatron at high luminosity. The cost is not unreasonable, but the effect on relative performance is an issue.
- Polarizing the proton beam may result in a non–negligible improvement of the signal to noise background ratio for certain measurements, in particular where there are competing QCD and electroweak processes.
- Until a solution to the anticipated reduction in luminosity is found, the arguments in favor of polarizing one beam are not compelling enough to warrant a decision to proceed at this time. This intensity loss may not be the final story, and so it is recommended that continued accelerator R&D be done to address this question. Likewise, the physics opportunities in this one polarized beam scenario should continue to be explored.
- If it were possible to polarize both the proton and the antiproton beams, then the above background arguments signficantly improve and distinct physics opportunities might arise.

2.1.7 Detector Challenges

The high luminosity environment at the Tevatron will present a challenge to detectors, and more detailed work is required. Our initial impressions are as follows:

- Tracking and vertex-tagging seem to be feasible in a high–rate environment, based on current CDF experience and simulations of both the DØ and CDF upgrade designs. Efficiencies $> 50\%$ and mistag probability of $< 1\%$ are sufficient for the most interesting physics. Maintaining this performance in the presence of many interactions per crossing remains an issue for further study.
- Calorimeter energy resolution and coverage similar to the upgraded CDF and DØ detectors should be adequate. The effects of pileup on the calorimetric performance, and especially electron identification and $\not{E}_{\mathrm{T}}$ have been studied in a preliminary way using real minimum bias data in simple simulations. This work suggests that electron isolation efficiencies are only slightly degraded. On the matter of $\not{E}_{\mathrm{T}}$, we see that the degradation of primary vertex resolution may be a significant effect, but overall, for situations in which the $\not{E}_{\mathrm{T}}$ distribution is flat, there seems to be only a marginal effect. There are no results as yet for steeply falling distributions.
- Muon detection performance similar to the upgraded CDF and DØ detectors should be adequate. The muon momentum measurement will continue to be dominated by the central magnetic tracking. Backgrounds will likely become a more serious problem for muon triggering and analysis.

- Given reasonable assumptions regarding future bandwidths, a first pass at a trigger list suggests that the high p_T processes of interest can be accommodated. However, the assumptions of 50 kHz/$5-10$ kHz/$100-200$ Hz for L1/L2/L3 outputs are aggressive goals relative to current CDF and DØ capabilities. The question of how the trigger rejection degrades in a high luminosity environment also needs study.

- Offline processing is always a surprise in what can be accomplished. Assuming 500 MIPS-sec per event reconstruction capability, similar to the current time, a near real–time farm would need 200 workstations of 500 MIPS each. This is not inconceivable on the timescale required.

2.2 Recommendations

As previously noted, we believe that this work is not complete. We have shown that a future path of increasing luminosity at the Tevatron will lead to a full program of measurements in Top, IVB, Higgs, SUSY, and Exotic physics. Our general conclusions, as of December 1995, are these:

2.2.1 Recommendations to Fermilab

1. Fermilab will be the top quark factory for many years. As with other heavy quarks, the top quark may be entering the first of many decades of serious scrutiny. Those planning the physics program should recognize this major scientific opportunity.

2. Our study confirms recent theoretical speculation that there is a luminosity threshold for the detection of a light Higgs boson at the Tevatron, and suggests that this threshold may be at the 5-25 fb^{-1} level. The most promising single detection technique relies on detailed understanding of b tagging and the "W + flavor" backgrounds, and is therefore a natural complement and extension of the top physics program. We recommend that:

   (a) the presence of the detection threshold and its value be confirmed in more detailed simulation, including b tagging in the presence of multiple interactions.

   (b) a Tevatron strategy for crossing the luminosity threshold be developed and implemented.

3. The Tevatron program can either discover SUSY or significantly constrain a large fraction of current theoretical prejudice. The actual sensitivity and discovery potential for supersymmetric states at the Tevatron deserves significantly more study.

4. High instantaneous luminosity conditions need to be understood better with perhaps both simulation and actual detector research and development. This is especially true for the top and Higgs studies. Will it handicap the current detectors? If so, how? We urge the Laboratory to initiate an active program to investigate these questions and to engage the high energy physics community in the effort. We believe the effort will benefit from computing, R&D, and possibly test beam resources.

5. There may be significant luminosity capability beyond the "classic" Main Injector scenario during Run II. If such incremental increases in peak luminosity cannot be handled by the detectors, could this capability be channeled into a significant increase in the useful longevity of $> 10^{32}$ stores? After all, *integrated* luminosity is the key.

6. The physics overall is tantalizing, and we believe that simply waiting for the LHC is unwise. The Laboratory and the experimental collaborations should make every effort to maximize the physics return of the Tevatron. This implies the need for **an overall plan for the long term Tevatron Program** including the accelerator, the detectors, and physics simulation.

2.2.2 Recommendations beyond Fermilab

Compared to the reach of the SSC or the LHC, the high $p_{\rm T}$ physics program at the Tevatron has sometimes been casually judged to be at an end. During the SSC era, this judgement devalued all future planning for the FNAL complex, and as the LHC era looms, this sentiment might be heard again. Meanwhile, the Tevatron has uncovered a new fermion with a mass at the weak scale, and new ideas about the Tevatron luminosity enable a compelling menu of top quark and discovery–level high $p_{\rm T}$ physics — a complete Physics Program. This research was not even contemplated a year ago as applicable to Fermilab.

A productive Fermilab facing a planned LHC is an interesting example of the tension between present and future in the age of Big Science, and the importance for balance between long range commitments and data driven progress. This issue is addressed in Chapter 10.

Chapter 8

Physics with a Polarized Proton Beam at the Tevatron

8.1 Introduction

At the Tevatron Collider we would expect to have one polarized proton beam colliding with an unpolarized antiproton beam. Having one beam polarized longitudinally essentially restricts us to investigating parity violating phenomena, unless efforts are made to extract spin information from other particles in the final state[1, 2]. Similarly, having one beam polarized transversely often leaves us focusing on higher twist effects. Parity violation is manifest in the weak interactions, and much of the new physics being proposed, like supersymmetry, is replete with parity violating interactions. The chiral couplings of the weak bosons, combined with the different phenomenology found in the polarized parton densities for the up and down quarks, enhances our ability to understand how the proton spin is distributed among its constituents. Generally speaking, polarization should also find use in studying the couplings that govern particle interactions, provided there is no large loss in luminosity for the polarized proton beam as compared to the unpolarized case. For some cases where the signal events are invariant under parity and the corresponding background is parity violating, polarization may also provide a means to affect the background without ruining the signal.

In the following we consider the longitudinal and transverse polarization cases separately. The single-spin quantities of interest are the longitudinal asymmetry A_L and the transverse asymmetry A_N. Defining a particular cross section measured with the two different helicity states of the beam as σ_R (for the right-handed proton) and σ_L (for the left-handed proton), the longitudinal asymmetry is given by

$$A_L = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}.$$

The transverse asymmetry is defined analogously,

$$A_N = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow},$$

where $\sigma_\uparrow$ and $\sigma_\downarrow$ correspond to cross sections for opposite directions of transverse spin for the beam. These asymmetries may also be discussed with regard to differential cross sections.

8.2 Longitudinal Polarization

8.2.1 Inclusive High P_T Processes

The production of jets, direct photons, Drell-Yan pairs, or in general any purely QED or QCD based process, is expected to result in $A_L = 0$ because the strong and electromagnetic interactions are parity conserving. This is a rather fundamental prediction of QED and QCD, so any large deviations observed from this behavior would be very hard to explain. (Small deviations at the percent level are expected since these final states can also be produced through intermediate W and Z bosons which harbor parity violating behavior.) This is especially true for production at large P_T, where large means $> 50 - 100$ GeV; this region is governed by perturbative QCD, and any deviations from $A_L = 0$ could not be attributed to non-perturbative effects which always result in uncertainties in QCD predictions at small P_T. For example, measuring the jet inclusive cross section ($\frac{d^2\sigma}{dP_T d\eta}$) in the P_T region 50 to 100 GeV could be done with limited luminosity, because the unpolarized cross sections in this region are between 1 and 100 nb/GeV for rapidities less than 3. This measurement by itself constitutes a very fundamental test of the theory of strong interactions. In addition to measuring the total inclusive cross section, more differential two jet cross sections can be measured: For example, one can measure the angular distribution $d\sigma/d\cos\theta^*$, where θ^* is the scattering angle in the center of mass; a more differential measurement, more sensitive to higher order QCD corrections, is the triple differential dijet cross section, $d^3\sigma/dE_T d\eta_1 d\eta_2$, where E_T is the transverse energy of the leading jet and η_1, η_2 are the rapidities of the two jets. This latter cross section covers a Bjorken x-range between 0.005 and 0.7. Both the CDF and DØ experiments are currently measuring this cross section to extract parton distributions, especially for gluons at low x.

Analogous to the above jet cross sections, the cross sections can be measured for direct photons. Another example is the inclusive b-quark production cross section. The b-quark cross section has now been measured by both CDF and DØ with different techniques, and the agreement between perturbative QCD predictions and the data has significantly improved. All these cross sections are being measured rather accurately at this moment by both experiments with a total integrated luminosity of about 15 pb^{-1}. The asymmetry in such cross sections could be measured to the same precision with a similar integrated luminosity; however, accumulating such statistics with Main Injector luminosities would only take a small fraction of the running time.

2.2 W and Z Boson Production.

From the production of W and Z bosons, nonzero asymmetries are expected because the weak interaction does not conserve parity. Here we concentrate on W boson production[5].

Measuring the cross section for inclusive W boson production in a polarized collider, especially for the W^+ and W^- bosons separately, provides a measurement of the polarized quark distributions. Measuring the rapidity dependence of the lepton resulting from the decay of the produced $W^{\pm}$ bosons, which is currently called the charge asymmetry measurement, gives similar accurate information about the ratio of polarized u and d quark densities.

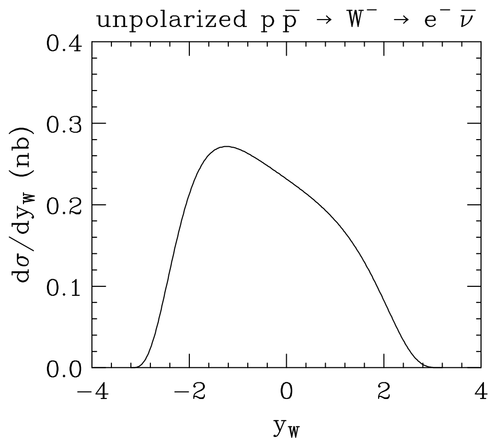

Fig. 1a. The rapidity distribution for the production of W^- bosons in unpolarized $p\bar{p}$ collisions at $\sqrt{s}$ =2 TeV.

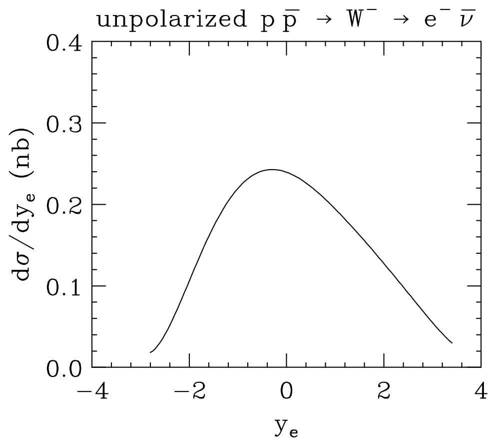

Fig. 1b. The rapidity distribution for the leptons obtained from the decays $W^- \to e^-\bar{\nu}$ from Fig. 1a.

In Figs. 1a and 1b the rapidity dependence for the unpolarized production of W^- bosons is presented both for the W^- boson and the lepton from the decay $W^- \to e^-\bar{\nu}$. The W^- boson (e^-) rapidity is symbolized by y_W (y_e). Figs. 2a and 2b show the differential cross sections in rapidity for W^- boson production using two different choices for the polarized parton densities of Nadolsky[3]. Present data still allow significant variation in fitting the polarized parton densities. In Figs. 3a and 3b a kinematic cut has been applied restriciting the transverse momentum of the lepton to be greater than 25 GeV; this constraint shifts the lepton asymmetry curve closer to that of the W boson and provides a better distinction between the two different choices for the polarized parton densities. Asymmetries around 30% are clearly possible, providing a means for determining better fits and in particular distintuishing between various models that describe the polarized parton densities at large x[4]. The reduction in the event rate due to the cut is 69%, but keep in mind that this study has yet to be optimized. The overall W boson cross section varies with proton spin, but since the polarized parton distributions have a different x-dependence than the unpolarized ones, the P_T^W distribution and the jet multiplicity distributions change accordingly.

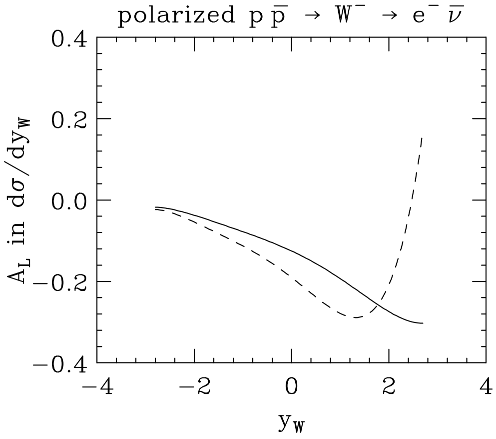

Fig. 2a. The longitudinal asymmetry A_L using the differential rapidity distribution for the W^- boson produced in polarized $p\bar{p}$ collisions at $\sqrt{s}$ =2 TeV. The solid (dashed) curve uses Set 1 (Set 2) distributions from [3].

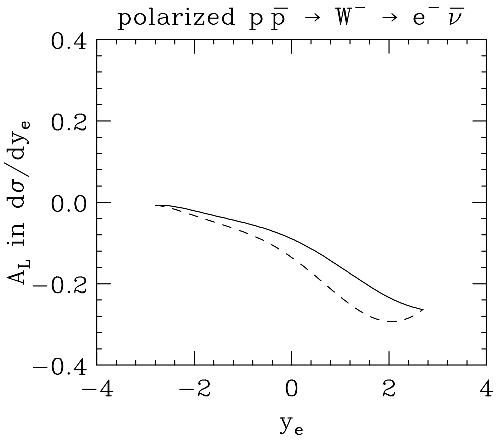

Fig. 2b. The longitudinal asymmetry A_L using the differential rapidity distribution for the lepton from $W^- \to e^-\bar{\nu}$ of Fig. 2a

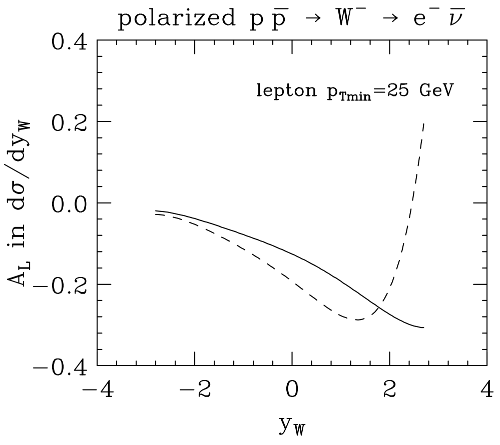

Fig. 3a. The longitudinal asymmetry A_L using the differential rapidity distribution for the W^- boson produced in polarized $p\bar{p}$ collisions at $\sqrt{s}$ =2 TeV. Here the lepton is constrained to have P_T >25 GeV. The solid (dashed) curve uses Set 1 (Set 2) distributions from [3].

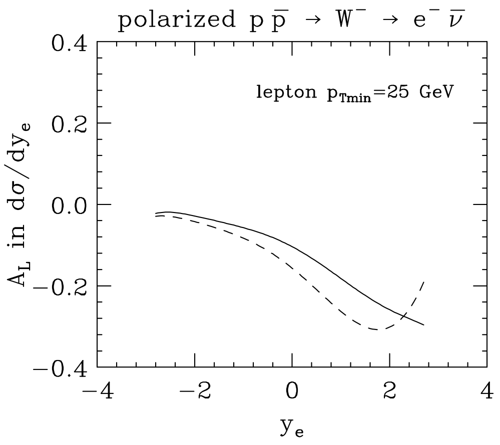

Fig. 3b. The longitudinal asymmetry A_L using the differential rapidity distribution for the lepton from $W^- \to e^-\bar{\nu}$ of Fig. 3a.

Much of the controversy regarding the polarized parton densities centers around how the proton spin is shared between the sea quarks and the gluons. Though only the proton beam is polarized, it should be possible to get a handle on the strange quark polarization by considering W+jet production via $g + s \to W^- + c$, where by tagging the charm quark with the associated W^- produced, one obtains a measure of the strange quark polarization.

With control over the beam polarization, it is possible to modify event rates. For one particular channel, W + 2 jets $\to e + \nu$ + 2 jets, the change in cross section has been estimated[6] by using polarized parton distributions citeglenn,polpar. The following table shows the change in the cross section for W^+ and W^- bosons in going from an unpolarized beam to a right-handed or left-handed polarized beam. (The subscripts R and L used for protons and quarks in this chapter respectively denote right-handed and left-handed helicities for those particles.)

W + 2 jet Production	
process	σ (pb)
without 2 jet mass cut:	
$p_R\bar{p} \to W^- \, 2j$	50.56±.58
$p_L\bar{p} \to W^- \, 2j$	41.36±.52
$p_L\bar{p} \to W^+ \, 2j$	65.46±.78
$p_R\bar{p} \to W^+ \, 2j$	26.84±.28
$p\bar{p} \to W^\pm \, 2j$	45.30±.50
with 2 jet mass cut (70-90 GeV):	
$p_R\bar{p} \to W^- \, 2j$	7.324±.070
$p_L\bar{p} \to W^- \, 2j$	5.910±.056
$p_L\bar{p} \to W^+ \, 2j$	9.404±.092
$p_R\bar{p} \to W^+ \, 2j$	3.874±.034
$p\bar{p} \to W^\pm \, 2j$	6.514±.060
with 2 jet mass cut and $\sqrt{\hat{s}} > 340$ GeV:	
$p_R\bar{p} \to W^- \, 2j$	0.348±.004
$p_L\bar{p} \to W^- \, 2j$	0.308±.004
$p_L\bar{p} \to W^+ \, 2j$	0.520±.004
$p_R\bar{p} \to W^+ \, 2j$	0.144±.004
$p\bar{p} \to W^\pm \, 2j$	0.358±.002

Table 1. QCD background cross-sections for $p\bar{p} \to W^\pm + 2$ jets at $\sqrt{s}$ =2 TeV, for various proton polarizations and kinematic cuts. The unpolarized cases were calculated separately using CTEQ2 parton distribution functions.

There is a significant change in the W^+ boson cross section expected. This in itself is an interesting measurement. Nonetheless, in most searches for new particles (*e.g.*, top quarks or SUSY partners) being used at the moment, W boson production is a serious background. Polarization makes it feasible to "control" the background to some level, which may help in determining its magnitude. One current example would be the reduction of the $W + 4$ jets background in top quark studies (see the next section).

Single helicity asymmetries also enter in the study of couplings, *e.g.*, the anomalous couplings involved in $W\gamma$ production[6], the contact interactions in direct photon or diboson production, or technicolor physics[8]. It is necessary, however, that the machine luminosity and the variation in event rates due to changes in beam polarization be large enough to make the helicity asymmetries observable.

2.3 Studying the $t\bar{t}$ Signal.

An important mode for studying $t\bar{t}$ events is where $t \to$ jets and $\bar{t} \to l^- +$ jets (or likewise $\bar{t} \to$ jets and $t \to l^+ +$ jets). The most serious background for studying the t and $\bar{t}$ quarks in this channel is due to $W + 4$ jets. Though there are differences, for the purpose of this discussion we pretend that the $W + 4$ jets rate is affected by the beam polarization in the same way that the $W + 2$ jets rate is shown to vary in Table 1.

Indeed, polarized beams create reduced backgrounds

(a)when we tag the l^+ from t decay using p_R or

(b)when we tag the l^- from $\bar{t}$ decay using p_L.

One reason to make this lepton identifcation would be to study separately the t and $\bar{t}$ quarks. Though the background in both cases looks better than the unpolarized situation when we identify lepton charge, case (a) provides a better background reduction of about 26.8/45.3=59%, given the kinematics and polarized parton densities used.

The dominant mode for top quark production at the Tevatron via $q + \bar{q} \to g \to t + \bar{t}$ is a purely QCD process and QCD is parity invariant. The QCD $gq\bar{q}$ vertex is vector-like and does conserve helicity for massless initial quarks. This means that the helicity of the initial quark must be opposite that of the initial antiquark; there are no annihilating $q_L\bar{q}_L$ or $q_R\bar{q}_R$ states, independent of p and $\bar{p}$ polarizations. So, the initial state $q_L\bar{q}_L + q_R\bar{q}_R$ contribution is zero, whether or not the beams are polarized.

Consequently, there should not be any reduction in the top quark event rate simply because the proton beam is polarized. One way to see this is that no matter what helicity quark we pull out of the polarized proton, the probability is 50% for finding the matching antiquark spin in the unpolarized antiproton. This is exacltly the same situation as with both beams unpolarized. Therefore, there is no reduction in signal.

One can also see this by examining the math. We'll just examine the up quark contributions for simplicity, but the other quark contributions enter the same way. We use the notation where $f^{(+)}$ is the parton density for getting a parton with spin aligned with that of the proton and where $f^{(-)}$ is the parton density for getting a parton with spin anti-aligned with that of the proton; the unpolarized density is $f = f^{(+)} + f^{(-)}$. The cross section for $u + \bar{u}$ annihilation when colliding a right-handed proton with an unpolarized antiproton is

$$\begin{aligned} d\sigma(p_R + \bar{p} \to X) &= f^{(+)}_{u/p} * f_{\bar{u}/\bar{p}} d\hat{\sigma}(u_R + \bar{u} \to X) + f^{(-)}_{u/p} * f_{\bar{u}/\bar{p}} d\hat{\sigma}(u_L + \bar{u} \to X) \\ d\sigma(p_R + \bar{p} \to X) &= (f^{(+)}_{u/p} + f^{(-)}_{u/p}) * f_{\bar{u}/\bar{p}} d\hat{\sigma}(u + \bar{u} \to X) \end{aligned}$$

where you should note in the last line that parity invariance of the QCD subprocess was invoked to equate the polarized parton subprocess with the unpolarized parton subprocess:

$$d\hat{\sigma}(u_R + \bar{u} \to X) = d\hat{\sigma}(u_L + \bar{u} \to X) = d\hat{\sigma}(u + \bar{u} \to X).$$

Substituting for the sum of the polarized densities,

$$d\sigma(p_R + \bar{p} \to X) = f_{u/p} * f_{\bar{u}/\bar{p}} d\hat{\sigma}(u + \bar{u} \to X),$$

which represents the unpolarized production rate.

The result is that there is no significant loss in the $q + \bar{q} \to t + \bar{t}$ signal with polarization on one proton beam, but we have been able to exert control over the background (see previous section).

As for the effect on the significance, it does depend a bit on perspective. Taking the significance for studying $t\bar{t}$ pairs at an unpolarized collider without lepton identification as the standard, we can examine the relative change in significance resulting from lepton identification and beam polarization.

Choice 1: No lepton identification and no polarization is our standard,

$$S/\sqrt{B} \propto (1)/\sqrt{1} = 1.$$

When applying lepton identification, let us focus on the case where $\bar{t} \to$ jets and $t \to l^{+}$+jets). Note that both the signal and background event rates drop by a factor of $\frac{1}{2}$ since half of the time the decays go to l^{+} and the other half of the time the decays go to l^{-}.

Choice 2: Lepton identification and no polarization changes the significance by

$$S/\sqrt{B} \propto (1/2)/\sqrt{1/2} = 0.71.$$

Proton polarization does not affect the signal, but from Table 1 the backgound gets reduced by about 40%.

Choice 3: Lepton identification with a polarized beam changes the significance by

$$S/\sqrt{B} \propto (1/2)/\sqrt{1/2 * 0.6} = 0.91.$$

Though the polarization does not affect the production of top quarks, the considerations on the decay with lepton identification make a difference. Indeed, it is difficult to get a factor of two drop in background from the single polarized proton beam, particularly in light of the incomplete beam polarization, spin distribution of parton densities, etc.; and yes, the square root in the denominator does not help. Nevertheless, if there is a desire to separately distinguish top quark decays from antitop quark decays with lepton identification, polarization is beneficial, albeit not with a big factor here (0.71 vs. 0.91).

There are also kinematic cuts that hit the background harder than the signal. The W emission will be guided by the single-beam polarization, while the top quark production is less affected. This requires a detailed study.

Continuing with this idea, it is apparent that polarizing the antiproton would be exceptional help. We want the case where the proton and antiproton have opposite helicities because with identical hadron polarizations, all $q\bar{q}$ annihilation is suppressed, including the signal. Again, let's look at $t \to bl^{+}\nu$ decays; a similar discussion applies to $\bar{t} \to \bar{b}l^{-}\bar{\nu}$ decays.

Now, with the proton and antiproton carrying the opposite helicity, we may control the background by making the proton right-handed and looking at $t \to bl^{+}\nu$ decays. Say, in an ideal kinematic limit (*e.g.*, the momentum fraction of the up quark from the proton is large so that the up quark helicity is predominatly right-handed[9]), few W+jet events could be produced where the W^{+} is emitted off the up quarks from the proton; the W^{+} would come from the left-handed sea u quarks in the antiproton (note the antiproton is left-handed in this example) combining with the right-handed $\bar{d}$ quarks of the proton, also a sea contribution.

With the background vanishing to a sea contribution (plus a spin suppressed valence contribution), what happens to the top quark rate? Well, the parton level cross section is

$$\begin{aligned} d\hat{\sigma}(u_R\bar{u}_L \to X) &= d\hat{\sigma}(u_L\bar{u}_R \to X) \qquad \text{(by QCD parity invariance)} \\ &= 2 * d\hat{\sigma}(u + \bar{u} \to X), \end{aligned}$$

that is, the top quark production rate has increased by about a factor of two compared to the unpolarized production rate. This is because by forcing the initial quarks into opposite helicity states, we don't have to average over all of the non-annihilating $u_R + \bar{u}_R$ and $u_L + \bar{u}_L$ states that dilute the production rate by 50%. Including the factor of 1/2 reduction for picking only the positive lepton decays, the signal event number does not change compared to the total unpolarized event number (assuming there isn't too much luminosity loss due to polarizing the beam).

This provides another choice,

Choice 4: Lepton identification with TWO polarized beams

$$S/\sqrt{B} \propto (1)/\sqrt{\text{small number}}.$$

Of course, reality won't give us the full factor of two for the signal, but with the signal rate relatively unchanged and the background dropping at a better rate than in the case where only the proton beam is polarized, we definitely have a better significance.

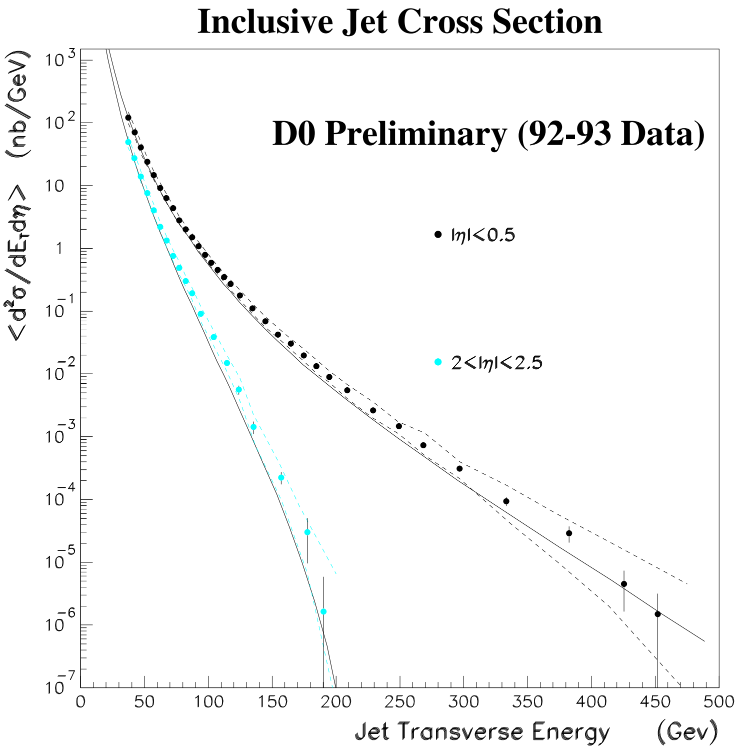

Fig. 4. Jet cross section plotted against transverse energy.

8.2.2 Asymmetries at One Loop

Though parity conservation yields $A_L = 0$ for single particle inclusive processes at the tree level, it is possible to get nonzero asymmetries by observing more than one particle in the final state. In particular, Pire and Ralston[?] and Carlitz and Willey[14] demonstrate nonzero asymmetries that appear at the one loop level in the production of dilepton pairs. These dileptons may be produced by a Drell-Yan mechanism or through decays *e.g.* of J/ψ.

The longitudinal asymmetry arises from the vector product $\mathbf{s} \cdot \mathbf{q}^+ \times \mathbf{q}^-$, which is odd under time reversal. ($\mathbf{s}$ is the pin vector, $\mathbf{q}^+$ is the μ^+ momentum and $\mathbf{q}^-$ is the μ^- momentum.) Consequently, imaginary parts of the one loop amplitude in the lepton pair production provide for the nonzero asymmetry. The parton level asymmetry corresponding to A_L is computed by Carlitz and Willey and found to $10-30\%$ for $\tau = -t/(\mathbf{q}^+ + \mathbf{q}^-)^2 < 10$. Ideally, by using on different kinematics, it should be possible to focus on subprocesses with either the quarks or gluons in the initial state. Through this asymmetry, it becomes possible to collect information on the helicity distributions.

These ideas can be applied to other processes also, like open heavy quark production, dijet production and γ+jet production.

8.2.3 Transverse Polarization

Measuring inclusive spin effects at the Tevatron Collider would provide a new probe of the strong interaction. One could explore the contribution of the valence quarks, sea quarks and gluons to the hadrons' spin. Since higher twists should not contribute at TeV energies, one could also test the prediction of perturbative QCD for a vanishing one-spin transverse asymmetry ($A_N = 0$) in high-P_T inclusive production. The study of the P_T dependence of one-spin asymmetries might reveal the transition from the nonperturbative phase of QCD ($A_N \neq 0$) to the perturbative part ($A_N = 0$). Measuring one-spin asymmetries in the process

$$p + \bar{p} \rightarrow \text{jet} + \text{anything}$$

seems especially interesting. The DØ and CDF detectors could easily measure, with high accuracy, the one-spin asymmetry in jet production at E_T of 100 to 200 GeV. The unpolarized data in Fig. 4 show that jets are easily measured in this E_T region. The prediction $A_N = 0$ could definitively be tested with high precision; this PQCD prediction should certainly be valid at $\sqrt{s}$ =2 TeV and E_T =100 GeV.

To be able to measure an asymmetry A_N in the case of transverse polarization (with only the proton beam polarized) one needs to define one more polarization direction in either the initial or final state. Since this is not possible in the initial state, the only possibility is the final state. For example, reconstructing τ-leptons in the final state might give a final state spin direction. Currently, this has not been achieved, but with the upgraded detectors this could be possible. Another possibility is to reconstruct the polarization of a jet by measuring the leading two charged particles in a jet. This has been suggested by J.Collins, S. F. Heppelmann, G.Ladinsky [10] and should in principle be possible in CDF and with the upgraded DØ detector. This is an area where a lot of work is needed to make this feasible.

In the case where no final state polarization direction is given, cross sections measured with and without transverse polarization should be identical. Deviations are possible only due to higher twist contributions and/or from imaginary parts of the contributing amplitudes. So, any measured deviations would be a direct sign of such contributions which are otherwise difficult to isolate.

8.3 Summary

Obviously, the fact that only the proton beam is polarized limits the physics capabilities of a potential collider program with polarized beams, especially in light of a possible polarization program at RHIC, where both beams would be polarized. The big advantage of a polarized collider program at Fermilab would be the detectors:

- Detectors are doing high P_T physics and will be upgraded to run at the higher luminosities. This is in contrast to the RHIC detectors which have to be adapted at a fairly large expense.

- Detectors have been used for an extensive amount of time and their systematics are very well understood.

A possible disadvantage of running in polarized mode at Fermilab is the reduction in luminosity by about a factor of six compared to unpolarized running. This is mainly limited by the output of the polarized source, which is currently 1.6 mA[11]. It is conceivable that this output could be increased in the next few years, but at this point it is not guaranteed.

The presently planned polarized collider program has proton polarization only; polarized antiprotons have been studied[12], but there is still no clear way to produce an intense highly polarized antiproton source suitable for the Tevatron. This is unfortunate since having the polarized antiproton beam would make a significant difference; polarizing the proton beam right-handed and the antiproton beam left-handed not only could have provided a strong suppression of the W^+ background to top pair production, but it also could have increased the $t\bar{t}$ signal rate. This would have provided a much cleaner environment for studying top quarks at the Tevatron.

We feel that at this time it is not possible to make a clear statement whether a polarized collider program, with proton polarization only, can be justified given that the cost of such a project is roughly estimated at $25M. On the other hand, we feel that not all the physics potential of such a facility with the existing detectors has been fully explored. We plan to pursue this further.

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Chapter 10

Afterword

D. Amidei and *R. Brock*

In the past year, a convincing case has emerged for an extended evolution of the Fermilab collider. Why did we go through this exercise when there are other opportunities in the world for future accelerators?

Two recent and familiar examples of surprises in High Energy Physics illustrate a feature of research which deserves protection when future plans are considered. These surprises, which dominate much active work in our field, are the long lifetime of B hadrons and the extremely large mass of the top quark. The efforts which eventually led to these understandings didn't come from strategic leaps, but rather from the accumulation of experimental results and techniques over time. No accelerators were proposed, planned, or constructed to make these discoveries. Instead, hints and leads, accompanied by new detector technologies, were followed over many years to eventual discovery and understanding. This is an "evolutionary path" to scientific progress. The continued importance of results from CESR (the Cornell Electron Synchrotron Ring) is one of the excellent examples of the success of the evolutionary approach in facility planning, and reminds us that continued investment and the establishment of *depth* with promising platforms ensures progress.

Particularly applicable to our concerns in the 1990's are the following four points regarding the evolutionary path for High Energy Physics:

1. The bottom quark and top quark stories referred to above represent the usual path toward scientific breakthrough. "Throwing long" is a strategy which has a place as a component of a broad, stable physics program. However, it cannot dominate a program in difficult times.

2. As much as anything in science can come with a guarantee, success and surprise seem repeatedly to be the eventual outcomes of the evolutionary approach in high energy physics.

3. This sort of success doesn't happen accidentally. Rather, the guarantee is underwritten by the mounting of topical experiments which attract the brightest scientists, coupled

with the means to do those experiments in a timely way. We call this **Following the Physics**, as decidedly distinct from "waiting for the physics".

4. The Fermilab program outlined here is a paradigm example of Evolutionary Physics at its best and it is feasible now.

Like other sciences, in High Energy Physics there are periodic and sometimes dramatic advances in understanding. What's perhaps unique about our field is that these changes occur primarily through massive efforts, each requiring many years and large sums of money. This means that an historical perspective is necessary to see incremental progress. If we pause and view the present from the standpoint of 10 to 15 years ago, our current understanding of elementary particle physics would have looked unpredictably unfamiliar. Sensible planning would take into account that such unpredictability is a part of doing well planned scientific experiments and therefore would build in our ability to make a similar statement about a new physics landscape 15 years from now. We need to prepare and defend a plan which combines the proper mix of sensible short term extrapolation, far–future opportunities, and faith in scientific unpredictability which is borne of a broad perspective. This report forms the beginning of such a plan by describing a set of significant experiments all within the context of a feasible collider program. That 100 physicists began this exercise and that 70% of them are authors of the individual detailed chapters is evidence of the excitement of the science and the commitment of the Tevatron community.

If resources are limited, and there is no expectation that this will not be the case for years, we should pay attention to the hints which exist and **Follow the Physics**. While the precise locations of surprises can't be predicted, we are fortunate that the various general areas are woven together in an increasingly correlated tapestry. The general threads are:

- **Top and Electroweak physics, combining direct measurements and indirect constraints from many different experiments.**
  If the Standard Model is correct, the generation of mass is related to at least two important length scales: the mass of the W and Z, of $\approx$ 100 GeV/c^2. and the vacuum expectation value of $\approx$ 246 GeV/c^2. That the top quark mass is nearly twice the former, and not far from the latter is probably a hint about the top quark which should not be ignored. Many measurements are possible to probe these scales.

- **Symmetry Breaking**
  Inherent within the Standard Model are explicit predictions, but also a set of underlying assumptions regarding the symmetry breaking mechanism. One of these predictions is the existence of a Higgs boson of indeterminate mass, playing the role of the quasiparticle of a possible phase transition. Other related but different schemes, also encompass Standard Model predictions but are more general. Supersymmetry is a leading example of such an extension. A component of any electroweak "prospecting" will include emphasis on these anticipated themes.

- **Generational Mixing among quarks and among leptons.**
  Among the oddest of field–theoretic consequences is the apparent quantum mechanical mixing of fundamental fermions of grossly differing mass scales which seems to be operative only in

the quark sector. Why? The opportunities for studying this phenomenon in the bottom system and perhaps the top system have been well–documented. Further, the astrophysical motivations for continued investigation of this phenomenon in the lepton sector are similarly well–documented.

- **CP violation in the strange, bottom, and top(?) systems.**
  Large–scale CP violation in the bottom system is expected as in the strange system. What about their $I_3 = 1/2$ partners, charm and top? While probably related to fermion mixing, this question stands alone as an experimental question, independent of models.

- **Spectroscopy and Rare Decays in the strange, charm, bottom, and top systems.**
  From the strange and charm to the bottom and now top systems, the "onia" of baryonic and mesonic spectroscopies and rare decays are always of interest. The study of the bottom sector will be with us for decades. With the top quark, we have the first quark which will not hadronize, but remains bare...it will not likely form hadronic matter, like a lepton. This second top quark hint may provide important clues to new physics.

- **Hadronic Structure in both high and low p_{T} regimes.**
  We tend to become excited about the extremes of the electroweak world. Could this be, in part, related to our familiarity with a perturbative and straightforward diagrammatic language? Experimentally accessible but much less well–understood, is the passage from the perturbative regime into the actual binding regimes. The structure of hadrons and the many–body aspects of gluon and low–x physics may become clearer with continued focus. Of course, the high p_T extreme is always of great interest, with higher statistical precision leading to probes of higher mass scales.

- **The Zoo**
  This is the part of elementary particle physics which is always revolutionary, and inherently unpredictable. The unusual seems to happen on a periodic basis, albeit at a timescale which is long. Because of that, we become complacent and tend toward a self–assured posture that we know what to expect. But reflection over the past 40 years of this field reminds one of the "who ordered *that*...!" aspects of digging deeper. The muon, partons and scaling, weak neutral currents, CP violation, the tau, the strange quark, the huge top quark mass, and the bottom quark lifetime were all largely unanticipated. They were brought to prominence and shown to be true only by experimental skill and theoretical imagination.

This is a list of broad themes, but it does surround what most would acknowledge to be the important general areas of elementary particle research. As befitting for the National High Energy Physics Laboratory:

the Fermilab complex is guaranteed to impact each of these areas.

From the collider to the fixed target area to the neutrino oscillation program, this facility offers significant short term gains and long term promise. Fermilab will allow us to weave a tight pattern in the physics tapestry presented above by following the physics as it develops within a vigorous and comprehensive program. That this evolutionary path is *completely* within the scope and control of the U. S. program is crucial to the maintenance of the flexibity and autonomy which is befitting our history and traditional commitment to this field.

We have outlined here a program of research specifically for the Tevatron collider at Fermilab. It is rich in guaranteed physics (top, IVB), surprising in its reach to the next level (SUSY, Higgs, exotics), fertile in the different configurations which are feasible, stimulating to continued R&D in accelerator and detector technologies, and stable as a platform for the far future of high energy physics (ultra–high energy pp, or $p\bar{p}$, an e^+e^- linear collider, or a μ–collider). Much work still remains to be done, but we hope that those who have not considered the evolutionary opportunities at the Fermilab complex will begin to look deeper with us. We urge our colleagues, the Fermilab management, the Department of Energy, the National Science Foundation, and members of Congress to take seriously a Physics Program for the United States which builds on the significant investment of millions of dollars and thousands of physicist–years to continue to **Follow the Physics**.