Future ElectroWeak Physics at the Fermilab Tevatron Report of the *tev_2000* Study Group: Prospects for Exotic Physics

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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 $2\times10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ with an integrated luminosity in this 18 month running period of more than 100 pb^{-1}.

1. **Luminosity Upgrade of up to** $10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$. 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 $\mathcal{L} = 10^{32}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ 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} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is "TeV$\star$". In order to reach luminosities which exceed 10^{32} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ 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} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

2. **Luminosity Upgrade to** 10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. Going beyond 10^{32} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ 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} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ level is conceivable. As with the Main Injector scenarios, there are variations.

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

   (b) Bunch crossing time of 19 ns, at 10^{33} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ 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 DØUpgrades 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 $W + H \rightarrow b\bar{b}$ 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 $H \rightarrow \gamma\gamma$. 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 $q'\bar{q} \rightarrow WH$ is complementary to the LEP II/NLC process $e^+e^- \rightarrow ZH$, 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 $\sim$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 $1.3\,\mathrm{TeV}/c^2$
- axigluons in dijet mode up to $1.3\,\mathrm{TeV}/c^2$
- E_6 color triplet scalar diquarks in dijet mode up to $800\,\mathrm{GeV}/c^2$
- first generation leptoquarks up to $360\,\mathrm{GeV}/c^2$
- compositeness in $qqqq$ mode up to $2.8\,\mathrm{TeV}/c^2$
- compositeness in $qqll$ mode up to $7.4\,\mathrm{TeV}/c^2$
- excited quarks up to $1.2\,\mathrm{TeV}/c^2$
- color octet ρ_t in dijet mode up to $1.0\,\mathrm{TeV}/c^2$
- massive stable particles
  - color triplets up to $540\,\mathrm{GeV}/c^2$
  - color sextets and octets up to $600\,\mathrm{GeV}/c^2$
  - color decuplets up to $660\,\mathrm{GeV}/c^2$

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 $p_{\rm T}$ 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_{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_{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 7

Prospects for Exotic Physics at the Tevatron

7.1 Introduction

7.1.1 TeV2000 Exotics Group

This note is the first summary report of the TeV2000 Exotics Working Group, given the charge of examining the future prospects for non-SUSY exotic physics at the Tevatron. The group originated from the separate CDF and D0 efforts toward an expression of interest for Run III physics, which were united by the TeV2000 workshop at Ann Arbor in October 1994 organized by Dan Amidei and Chip Brock. Because we are a small group, we have only touched on a small fraction of the possible exotic physics we can explore at the Tevatron, and we welcome others into this collaborative CDF and D0 effort. We need as many people as possible to help us build the case for running the Tevatron with the highest luminosities and energies we can obtain. To join in this effort please send electronic mail to RHARRIS@FNALD.FNAL.GOV.

7.1.2 Motivation

Although the Standard Model is able to account for all known phenomena, it tells us nothing about the masses and mixing angles of quarks and leptons, the nature of the higgs mechanism and the value of the coupling constants. This proliferation of arbitrary parameters suggests the presence of new physics beyond the standard model. For convenience, we group the ideas for new physics into three categories. First, *extended gauge theories* which embed all or part of the standard model symmetry ($SU(3)_C \times SU(2)_L \times U(1)_Y$) within larger symmetry groups. For example grand unified theories based on the groups E_6, $SO(10)$, $SU(5)$, $SU(2)_L \times SU(2)_R$, or $SU(3)_L \times SU(3)_R$ which predict new gauge bosons (W' and Z'), leptoquarks, E_6 diquarks, axigluons, or topcolor gauge bosons. Second, *compositeness*, including models of composite quarks, leptons or higgs bosons. For example quark compositeness producing contact interactions and excited fermions, or technicolor in which the higgs boson is a composite technipion. Third, *miscellaneous phenomena*, which for now only includes massive stable particles, but we hope to study a fourth generation quark b' and also unbiased searches for mass resonances without a theoretical model.

7.1.3 Technique

Here we present the capabilities of the Tevatron collider to find or exclude models of new physics. For models with a new particle we measure our sensitivity in terms of *mass reach* for the new particle, and for compositeness scales we similarly define an energy reach. For simplicity we will define mass reach as the largest excluded mass at 95% CL, and where possible we also present discovery reach numbers which represent the observation of significant deviations ($\sim 5\sigma$ effects). Defining mass reach in terms of exclusions allows easy comparison with prior searches where these limits are almost always stated. Mass reach is presented as a function of integrated luminosity, and also as a function of CMS energy where possible.

Our estimates are based on either fast simulations or extrapolations from existing searches. Extrapolations are based on the simple principle that when background is present the cross section limit scale inversely with the square root of the luminosity and when background is not present they scale inversely with the luminosity. We assume that current CDF and D0 capabilities for detection of high P_T jets, photons, and isolated leptons will not be significantly reduced at higher luminosities or energies. This assumes that if CDF and D0 are given 100 fb^{-1} in run III, we will also have the time and money to make modest modifications to the dynamic range of electronics and trigger systems to handle very high P_T objects.

7.2 Extended Gauge Theories

7.2.1 New Gauge Bosons W' and Z'

Heavy W bosons, generically denoted as W', occur in the left-right symmetric model [1] of electroweak interactions $SU(2)_R \times SU(2)_L \times U(1)_Y$. This model reproduces the standard electroweak model and also contains new right-handed W and Z bosons: W_R and Z_{LR}. Heavy Z bosons, generically denoted as Z', also occur in any extension of the standard model that contains an extra U(1) after symmetry breaking. For example, in one model with E_6 as the grand unified gauge group [2] there exists a Z_ψ from the symmetry breaking $E_6 \rightarrow SO(10) \times U(1)_\psi$ and a Z_χ from the symmetry breaking $SO(10) \rightarrow SU(5) \times U(1)_\chi$. Finally the SU(5) symmetry breaks to recover the standard model: $SU(5) \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$. In superstring inspired E_6 models there exists a Z_η which is the linear combination $Z_\eta = \sqrt{3/8}Z_\chi + \sqrt{5/8}Z_\psi$.

$W' \rightarrow l\nu$

Searches for $W' \rightarrow l\nu$ have been conducted by both CDF in the electron and muon channels [3, 4] and by D0 in the electron channel [5]. Here we extrapolate the CDF limit in the electron channel [6]. The search assumes the decay mode $W' \rightarrow WZ$ is suppressed, and that

ν' in the decay $W' \to e\nu'$ is light, stable and non-interacting. The extrapolation assumes the background in the search region remains zero events, as it was in the CDF and D0 searches. The 95% CL upper limit on the cross section times branching ratio then scales inversely with luminosity. The theoretical W' cross section is calculated assuming standard model couplings and using $MRSD-'$ parton distributions and a K-factor to account for higher order terms [7]. Comparing the cross section upper limit to the theoretical calculation gives the results in Table 7.1 for the 95% CL lower limit on the W' mass.

Run	IA	IB	II	III
$\int \mathcal{L}dt$ (fb^{-1})	0.02	0.1	2.0	100
95% CL Limit (TeV)	0.65	0.77	0.99	1.28

Table 7.1: Current and projected CDF 95% CL lower limits on the mass of a heavy charged gauge boson from the decays $W' \to e\nu$. The limits are shown in TeV as a function of the luminosity exposure $\int \mathcal{L}dt$ for a $p\bar{p}$ center of mass energy $\sqrt{s} = 1.8$ TeV.

$W' \to$ dijets

Here we extrapolate CDF searches for new particles in the dijet mass spectrum [8]. There are significant backgrounds in the search region so the 95% CL upper limit on the cross section times branching ratio scales inversely with the square root of the luminosity. The theoretical W' cross section is calculated assuming standard model couplings and using CTEQ2L parton distributions and a K-factor to account for higher order terms [7]. As in the leptonic search, this search assumes the decay mode $W' \to WZ$ suppressed. In Fig. 7.1 we compare the current and projected CDF upper limits on cross section times branching ratio to the theoretical calculation to give the results in Table 7.2 for the 95% CL excluded regions for the W' mass. These projected limits are compared with those for other phenomena decaying to dijets in Fig. 7.2.

Run	IA	IB	II	III
$\int \mathcal{L}dt$ (fb^{-1})	0.02	0.1	2.0	100
95% CL Lower Excluded (TeV)	–	0.33	0.20	0.20
95% CL Upper Excluded (TeV)	–	0.47	0.72	0.92

Table 7.2: Current and projected CDF 95% CL limits on the mass of a heavy charged gauge boson from the decays $W' \to$ dijets. The upper and lower excluded ranges are shown in TeV as a function of the luminosity exposure $\int \mathcal{L}dt$ for a $p\bar{p}$ center of mass energy $\sqrt{s} = 1.8$ TeV.

$Z' \to ll$

Searches for $Z' \to l\nu$ have been conducted by both CDF in the electron and muon channels [9, 10] and by D0 in the electron channel [11]. Here we extrapolate the CDF limit in the electron and muon channels. The extrapolation assumes the background in the search region remains practically zero events, as it was in the CDF and D0 searches. The 95% CL upper limit on the cross section times branching ratio then scales inversely with luminosity. The theoretical Z' cross section is calculated assuming standard model couplings and using $MRSD-'$ parton distributions and a K-factor to account for higher order terms [7]. Comparing the cross section upper limit to the theoretical calculation gives the results in Table 7.3 for the 95% CL lower limit on the Z' mass.

Run	IA	IB	II	III
$\int \mathcal{L} dt$ (fb^{-1})	0.02	0.1	2.0	100
95% CL Limit (TeV) at $\sqrt{s} = 1.8$ TeV	0.55	0.68	0.9	1.2
95% CL Limit (TeV) at $\sqrt{s} = 2.0$ TeV	—	0.74	1.0	1.3

Table 7.3: Projected CDF 95% CL lower limits on the mass of a heavy neutral gauge boson from the decays $Z' \to ee, \mu\mu$. The limits are shown in TeV as a function of the luminosity exposure $\int \mathcal{L} dt$ for various $p\bar{p}$ center of mass energies.

$Z' \to$ dijets

Here we extrapolate CDF searches for new particles in the dijet mass spectrum [8]. There are significant backgrounds in the search region so the 95% CL upper limit on the cross section times branching ratio scales inversely with the square root of the luminosity. The theoretical Z' cross section is calculated assuming standard model couplings and using CTEQ2L parton distributions and a K-factor to account for higher order terms [7]. In Fig. 7.1 we compare the current and projected CDF upper limits on cross section times branching ratio to the theoretical calculation to give the results in Table 7.4 for the 95% CL excluded regions for the Z' mass. These projected limits are compared with those for other phenomena decaying to dijets in Fig. 7.2.

Run	IA	IB	II	III
$\int \mathcal{L} dt$ (fb^{-1})	0.02	0.1	2.0	100
95% CL Lower Excluded (TeV)	–	0.34	0.29	0.20
95% CL Upper Excluded (TeV)	–	0.46	0.72	0.94

Table 7.4: Current and projected CDF 95% CL lower limits on the mass of a heave charged gauge boson from the decays from the decays $W' \to$ dijets. The upper and lower excluded ranges are shown in TeV as a function of the luminosity exposure $\int \mathcal{L} dt$ for a $p\bar{p}$ center of mass energy $\sqrt{s} = 1.8$ TeV.

New Gauge Boson Summary

In Fig. 7.3 current and projected search results for new gauge bosons at Fermilab are compared with the maximum capabilities of LEP II and NLC for direct searches. Until LHC, Fermilab has no competition in direct searches for new gauge bosons. Fig. 7.3 shows that Run III has the potential to effectively double our current mass reach for new gauge bosons.

7.2.2 E_6 diquarks $\rightarrow$ dijets

Superstring theory in 10 dimensions, which holds the prospect of unifying all forces including gravity, is anomaly free if the gauge group is $E_8 \times E_8$. The compactification of the extra 6 dimensions can lead to E_6 as the grand unification group for the strong and electroweak interactions. The E_6 models in turn predict the existence of many kinds of new particles [22], including a color triplet scalar diquark $D(D^c)$ with charge $-1/3(+1/3)$ which couples to $\bar{u}\bar{d}(ud)$. Thus the discovery of a dijet mass resonance could indicate an E_6 diquark and be interpreted as evidence for a "theory of everything". Here we extrapolate CDF searches for new particles in the dijet mass spectrum [8]. There are significant backgrounds in the search region so the 95% CL upper limit on the cross section times branching ratio scales inversely with the square root of the luminosity. The theoretical E_6 diquark cross section is calculated assuming electromagnetic Yukawa couplings, mass degenerate diquarks D and D^c, and using CTEQ2L parton distributions. In Fig. 7.1 we compare the current and projected CDF upper limits on cross section times branching ratio to the theoretical calculation to give the results in Table 7.5 for the 95% CL excluded regions for the E_6 diquark mass. These projected limits are compared with those for other phenomena decaying to dijets in Fig. 7.2.

Run	IA	IB	II	III
$\int \mathcal{L}dt$ (fb^{-1})	0.02	0.1	2.0	100
95% CL Lower Excluded (TeV)	–	0.33	0.20	0.20
95% CL Upper Excluded (TeV)	–	0.46	0.57	0.78

Table 7.5: Projected CDF 95% CL limits on the mass of an E_6 diquark from decays to dijets. The upper and lower excluded ranges are shown in TeV as a function of the luminosity exposure $\int \mathcal{L}dt$ for a $p\bar{p}$ center of mass energy $\sqrt{s} = 1.8$ TeV.

7.2.3 Axigluons $\rightarrow$ dijets

Although there is now little doubt that strong interactions result from an SU(3) gauge symmetry, there remains the possibility that the unbroken color symmetry $SU(3)_C$ results from the breaking of the larger chiral color group $SU(3)_L \times SU(3)_R$ [12]. One unambiguous prediction of all chiral color models is the axigluon, a massive color-octet of axial vector gluons. Axigluons are produced and decay strongly from quark-antiquark interactions, giving very large cross section times branching ratio to dijets. There is a long history of searches for axilguons at UA1 [13] and CDF [14, 15]. Here we extrapolate CDF searches for new particles in the dijet mass spectrum [8]. There are significant backgrounds in the search region so the 95% CL upper limit on the cross section times branching ratio scales inversely with the square root of the luminosity. The theoretical axigluon cross section is calculated assuming decays to the six flavors of quarks in the standard model and using CTEQ2L parton distributions. In Fig. 7.1 we compare the current and projected CDF upper limits on cross section times branching ratio to the theoretical calculation to give the results in Table 7.6 for the 95% CL excluded regions for the axigluon mass. These projected limits are compared with those for other phenomena decaying to dijets in Fig. 7.2.

Run	IA	IB	II	III
$\int \mathcal{L}dt$ (fb^{-1})	0.02	0.1	2.0	100
95% CL Lower Limit (TeV)	0.87	1.0	1.16	$\sim$1.3

Table 7.6: Actual and projected CDF 95% CL lower limits on the mass of an axigluon from decays to dijets. The limits are shown in TeV as a function of the luminosity exposure $\int \mathcal{L}dt$ at $\sqrt{s} = 1.8$ TeV.

7.2.4 Topcolor

The large mass of the top quark suggests that the third generation may be special. Topcolor [16, 17, 18] assumes that the top mass is large mainly because of a dynamical $t\bar{t}$ condensate generated by a new strong dynamics coupling to the third generation. Here the $SU(3)_C$ of QCD is a low energy symmetry arising from the breaking of an $SU(3)_1$ coupling to the third generation and an $SU(3)_2$ coupling to the first two generations only. There are then massive color octet bosons, topgluons B, which couple largely to $b\bar{b}$ and $t\bar{t}$. An additional $U(1)$ symmetry is introduced [18] to keep the b quark light while the top quark is heavy; this leads to a new gauge boson, Z'_{TopC}, which again couples largely to $b\bar{b}$ and $t\bar{t}$. CDF has preliminary results on the search for topgluons B and Z'_{TopC} in the $b\bar{b}$ channel using b-tagged dijets [19] and we hope to extrapolate these limits soon. Searches are also underway in the $t\bar{t}$ mass distribution [20].

7.2.5 Leptoquarks

Leptoquarks, color triplet particles coupling to a lepton and quark, appear in many extensions of the standard model [21, 22]. In grand unified theories with E_6, $SO(10)$ or $SU(5)$ as the grand unified gauge group, quarks and leptons are in the same multiplet and there exist leptoquarks which connect them. In composite models some bound states of preons are leptoquarks. In technicolor some technipions are leptoquarks. Also, models with a horizontal symmetry connecting leptons and quarks contain leptoquarks.

Leptoquarks are generally assumed to link, through an unknown coupling strength, λ, quark and lepton multiplets of the same generation in order to prevent violation of bounds on rare decays of mesons and bounds on flavor changing neutral currents [21, 23]. First generation leptoquarks decay to first generation quarks and leptons, etc. Leptoquarks can be produced singly via λ or in pairs through α_s or λ. Some constraints on λ [24] restrict λ to be less than one for leptoquark masses less than 200 GeV/c^2. Ignoring leptoquark production through λ, Tevatron experiments have searched for pair production of scalar leptoquarks where the production cross section is independent of λ.

First Generation Leptoquarks

Searches for first generation scalar leptoquarks have been conducted by CDF [26] and D0 [27]. Searches for second generation scalar leptoquarks have also been conducted by CDF [28] and D0 [29]. We have made an attempt to estimate the mass reach for leptoquarks with the proposed upgrades of the Tevatron center of mass energy or luminosity. Here we employ a simulation of leptoquark detection at D0 from which we estimate a 25% detection efficiency for leptoquarks with masses between 300 and 400 GeV/c^2. The efficiency will be a little less for lighter mass leptoquarks and a little more for heavier mass leptoquarks, but the 25% will be used for all masses. The calculation of the theoretical cross section was performed by taking the pair production sub-process cross section for supersymmetric squarks in the limit of a very heavy gluino and folding it with the CTEQ lowest order parton distribution functions. This was found to be consistent with ISAJET's cross section. Here, we again assumed that λ is small compared to α_s and is ignored. In Table 7.7 we present mass thresholds for a ten event discovery of a scalar leptoquark; for a three event observation, corresponding to a 95% CL upper limit, add roughly 0.05 TeV to the numbers listed except where the three event limit is indicated by the numbers in the parentheses. The 100 fb^{-1} mass numbers at the $\sqrt{s} = 2.0$ TeV and $\sqrt{s} = 3.5$ center of mass energies were extrapolated from the other numbers. The three event, 95% C.L., limit should not be significantly different for these two numbers.

$\int \mathcal{L}dt$ (fb^{-1})	0.1	1.0	10	100
Discovery Reach (TeV) at $\sqrt{s} = 2.0$ TeV	0.175	0.235	0.325	0.360
Discovery Reach (TeV) at $\sqrt{s} = 3.5$ TeV	0.250	0.356	0.438(0.460)	0.470
Discovery Reach (TeV) at $\sqrt{s} = 4.0$ TeV	0.278	0.380	0.452(0.470)	0.486(0.490)

Table 7.7: Projected D0 10 event discovery reach for a leptoquark. The masses are shown in TeV as a function of the luminosity exposure $\int \mathcal{L}dt$ for various $p\bar{p}$ center of mass energies.

In Fig. 7.4 these projected search results for leptoquarks at Fermilab are compared with the maximum capabilities of HERA, LEP II and NLC for direct searches. Until LHC, Fermilab has little competition in direct searches for scalar leptoquarks. In addition to scalar leptoquarks, the possibility of vector leptoquarks exist. Cross sections for the pair production of vector leptoquarks are in the process of being calculated [25]. The pair production cross section for vector leptoquarks appears to be much larger than that for scalar leptoquarks. Though verified cross sections are not yet available, mass reaches of about twice those for scalar leptoquarks may be possible.

In summary, for the 1994 - 1996 run in progress at the Tevatron ($\sqrt{s} = 1.8$ TeV), the expected reach in mass is about 200 GeV/c^2 for scalar leptoquarks and perhaps 400 GeV/c^2 for vector leptoquarks. The mass reach for the most aggressive upgrade of the Tevatron for scalar leptoquarks seems to top out at about 0.5 TeV and perhaps about 1 TeV for vector leptoquarks. These limits represent a significant amount of search space, and the potential for discovery is exciting.

Second Generation Leptoquarks

Searches for second generation scalar leptoquarks have been conducted by CDF [28] and D0 [29]. The mass reach for second generation leptoquarks is expected to be similar to first generation leptoquarks.

7.3 Compositeness

Perhaps the most historically compelling model of new physics is compositeness. If quarks and leptons are composite particles we expect four fermion contact interactions [30] to modify the quark and lepton production cross sections at high transverse momentum. If quarks are composite particles excited states [31] are expected and can be searched for in the quark plus gauge boson invariant mass spectrum. Finally, technicolor provides a dynamic mechanism for electroweak symmetry breaking based on composite higgs bosons. Models of walking technicolor have not been excluded and predict color octet technirhos which decay to dijets and color singlet technirhos which decay to W or Z plus dijets.

7.3.1 Contact Interactions

$\Lambda(qqqq)$

The four quark contact interaction has been extensively searched for at the CERN SPPS collider [32] and the Tevatron [33]. The usual method has been to search for either an excess of high P_T jets or a more isotropic jet angular distribution than the QCD prediction, the most stringent limits coming from the former. D0 is searching for contact interactions in the distribution of the scalar sum of event transverse energy. All other limits presented in this note scale roughly proportionally with the logarithm of the luminosity, so for a first pass we will assume the same for the compositeness scale. We fit the last 2 published CDF compositeness limits from the high P_T jet search to a straight line in the limit vs. log luminosity plane, and obtain the results presented in table 7.8. We caution the reader that this gives a higher projected limit than indicated by preliminary CDF data in Run 1A. This data is currently fit better by QCD + compositeness with Λ = 1.5 TeV, than by QCD alone [34].

Run	IA	IB	II	III
$\int \mathcal{L}dt$ (fb^{-1})	0.02	0.1	2.0	100
95% CL Limit (TeV) at $\sqrt{s} = 1.8$ TeV	1.6	1.8	2.2	2.8

Table 7.8: Projected CDF 95% CL lower limits on the compositeness scale for a four quark contact interaction $\Lambda(qqqq)$. The limits are shown in TeV as a function of the luminosity exposure $\int \mathcal{L}dt$.

$\Lambda(qqll)$

If quarks and leptons are both composite and share constituents, then effective contact interactions arise between them at low energies [30]. The quark-lepton contact interaction has been searched for at CDF in the dielectron [35] and dimuon [9] channels. The technique is to search for an excess of high mass dileptons compared to the Drell-Yan prediction. We define a mass above which there will be essentially no Drell-Yan background– $M(0.5)$, the mass above which 0.5 events are expected. We then calculate the integrated cross section above this mass including a contact interaction. Figure 7.5 shows the effect of the compositeness interaction on the integrated cross section. We take as the 95% CL lower limit the size of this interaction that would give less then 3.2 events above this mass. Here, the lepton-quark compositeness scale ($\Lambda(qqll)$) corresponds to a left-left coupling with constructive interference with the dominant u-quark contribution to the cross section. The results are tabluated in table 7.9.

$\int \mathcal{L}dt$ fb^{-1}	σ_{DY} fb^{-1}	M(0.5) GeV	$\Lambda(qqll)$
1	0.5	660	5.1
2	0.25	712	5.4
5	0.1	780	6.1
100	0.005	980	7.4

Table 7.9: Projected CDF 95% CL lower limits on the compositeness scale for a lepton-quark contact interaction $\Lambda(qqll)$. The limits are shown in TeV as a function of the luminosity exposure $\int \mathcal{L}dt$.

7.3.2 Excited Quarks

Excited states of composite quarks, denoted q^*, have been searched for at UA2 [36], CDF [37, 8] and soon at D0 [38]. They are produced singly by quark gluon fusion and can decay to a common quark and any gauge boson (g, γ, W or Z) [31].

$q^* \to q\gamma, qW$

Here we extrapolate the CDF search [37] in the photon + jet and W + jet channels. There are almost no events in the mass region where the combined limit is set, and we assume this will remain the case so that the cross section limit will roughly scale inversely with luminosity. For the theoretical prediction we perform a lowest order calculation using CTEQ1L parton distributions and assume standard model couplings and mass degenerate diquarks u^* and d^*. In Fig. 7.6 we compare the current and projected CDF upper limits on cross section times branching ratio to the theoretical calculation to give the results in Table 7.10 for the 95% CL excluded regions for the excited quark mass.

Run	IA	IB	II	III
$\int \mathcal{L}dt$ (fb^{-1})	0.025	0.1	2.0	100
95% CL Limit (TeV) at $\sqrt{s} = 1.8$ TeV	0.54	0.64	0.82	1.08
95% CL Limit (TeV) at $\sqrt{s} = 2.0$ TeV	—	0.69	0.91	1.18
95% CL Limit (TeV) at $\sqrt{s} = 3.5$ TeV	—	1.03	1.41	1.90

Table 7.10: Actual and projected CDF 95% CL lower limits on the mass of a excited quark from the decays $q^* \to\to q\gamma, qW$. The limits are shown in TeV as a function of the luminosity exposure $\int \mathcal{L}dt$ for various $p\bar{p}$ center of mass energies.

$q^* \rightarrow qg$

Here we extrapolate CDF searches for new particles in the dijet mass spectrum [8]. There are significant backgrounds in the search region so the 95% CL upper limit on the cross section times branching ratio scales inversely with the square root of the luminosity. The theoretical q^* cross section is calculated assuming standard model couplings, mass degenerate excited quarks u^* and d^*, and uses CTEQ2L parton distributions. In Fig. 7.1 we compare the current and projected CDF upper limits on cross section times branching ratio to the theoretical calculation to give the results in Table 7.11 for the 95% CL excluded regions for the q^* mass.

Run	IA	IB	II	III
$\int \mathcal{L}dt$ (fb^{-1})	0.02	0.1	2.0	100
95% CL limit (TeV)	0.56	0.71	0.82	1.02

Table 7.11: Current and projected CDF 95% CL lower limits on the mass of an excited quark from the decays $q^* \rightarrow$ dijets. The limits are shown in TeV as a function of the luminosity exposure $\int \mathcal{L}dt$ for a $p\bar{p}$ center of mass energy $\sqrt{s} = 1.8$ TeV.

Excited Quark Summary

In Fig. 7.7 current and projected search results for excited quarks at Fermilab are compared with the maximum capabilities of HERA and NLC for direct searches. Until LHC, Fermilab has no competition in direct searches for excited quarks. Fig. 7.7 shows that a luminosity upgrade for Run III has the potential to effectively double our current mass reach for excited quarks, and an energy upgrade for run III has the potential to triple it.

7.3.3 Technicolor

The origin of electroweak symmetry breaking is arguably the last remaining puzzle of the standard model. Symmetry breaking arising from a fundamental Higgs boson is admittedly ad hoc. Instead, technicolor assumes that pairs of fundamental techniquarks are bound into a composite scalar, a technipion, which generates a dynamical symmetry breaking. The mechanism is similar to the way cooper pairs of electrons generate a superconducting phase transition in the BCS theory of superconductivity.

Color Octet Technirho $\rho_T \rightarrow$ dijets

In a recent technicolor model [39, 40] there exists a color octet technirho (ρ_T) which couples to $q\bar{q}$ and gg via a virtual intermediate gluon ($\rho_T \rightarrow g \rightarrow q\bar{q}, gg$). Here we extrapolate CDF searches for new particles in the dijet mass spectrum [8]. There are significant backgrounds in the search region so the 95% CL upper limit on the cross section times branching ratio scales inversely with the square root of the luminosity. The theoretical cross section is calculated assuming the technirho decays only to dijets (assumes all technipions are too massive to be decay products). We use CTEQ2L parton distributions. In Fig. 7.1 we compare the current and projected CDF upper limits on cross section times branching ratio to the theoretical calculation to give the results in Table 7.12 for the 95% CL excluded regions for the ρ_T mass. These projected limits are compared with those for other phenomena decaying to dijets in Fig. 7.2.

Run	IA	IB	II	III
$\int \mathcal{L} dt$ (fb^{-1})	0.02	0.1	2.0	100
95% CL Lower Excluded (TeV)	.32	0.26	0.20	0.20
95% CL Upper Excluded (TeV)	.48	0.54	0.77	0.96

Table 7.12: Current and projected CDF 95% CL limits on the mass of a color octet technirho from the decays $\rho_T \rightarrow$ dijets. The upper and lower excluded ranges are shown in TeV as a function of the luminosity exposure $\int \mathcal{L} dt$ for a $p\bar{p}$ center of mass energy $\sqrt{s} = 1.8$ TeV.

7.4 Miscellaneous Phenomena

7.4.1 Massive Stable Particles

Massive stable particles are possible features of several theories which go beyond the standard model including supersymmetry, mirror fermions, technicolor, and compositeness. CDF has conducted a search for heavy stable charged particles [41, 42] based upon their expected high transverse momenta, relatively low velocities, and muon-like penetration of matter.

The basic CDF result consisted of upper limits on the cross-section for the production of heavy stable particles as a function of their mass. To translate this into mass limits, one has to assume a theoretical cross-section appropriate to a particular theory. As an example we consider unit-charged fermionic particles which are pair-produced and belong to various color multiplets, ie. triplets, sextets, octets, and decuplets. Table 7.13 gives the expected lower mass limits as a function of integrated luminosity. It has been assumed that the cross-section limits scale inversely with the luminosity and that the relevant detector components remain as they are currently configured. In particular, a new time-of-flight system could improve these results significantly.

Run	IA	IB	II	III
$\int \mathcal{L} dt$ (fb^{-1})	0.02	0.1	2.0	100
color triplets	0.19	0.25	0.38	0.54
color sextets	0.26	0.32	0.45	0.60
color octets	0.26	0.33	0.45	0.60
color decuplets	0.33	0.39	0.52	0.66

Table 7.13: Projected CDF 95% CL lower limits on the mass of stable unit-charged particles at $\sqrt{s} = 1.8$ TeV. The limits are shown in TeV as a function of the luminosity exposure $\int \mathcal{L} dt$.

In Fig. 7.8 projected search results for massive stable particles at Fermilab are compared with the maximum capabilities of LEP II and NLC for direct searches. Until LHC, Fermilab has no competition in direct searches for these particles. Fig. 7.8 shows that Run III has the potential to effectively double our current mass reach.

7.5 Summary and Conclusions

We have investigated the exotics search potential of a superluminous Tevatron. The mass reach for many new particles at the Tevatron is summarized in figure 7.9. For excited quarks and leptoquarks we have also presented the search potential of an energy upgraded Ditevatron. In many channels the results are similar: a luminosity upgrade to 100 fb^{-1} will effectively double our current mass reach, and an energy upgrade to 4 TeV will effectively triple it. Although these results prefer an energy upgrade, they illustrate that a luminosity upgrade is the equivalent of exploring a completely new energy scale. Most new phenomena have no preferred mass scale, so doubling the mass reach with a superluminous tevatron provides an experiment with twice the discovery capability of all previous experiments in high energy physics. These prospects are quite exciting.

Bibliography

[1] For a review and original references see R. N. Mohapatra, *Unification and Supersymmetry* (Springer, New York, 1986).

[2] See F. del Aguila, M. Quiros, and F. Zwirner, Nucl. Phys. **B287**, 457 (1987) and references therein.

[3] (CDF Collaboration) F. Abe et al., Phys. Rev. Lett. **67**, 2609 (1991).

[4] (CDF Collaboration) F. Abe et al., Fermilab-PUB-94/268-E, submitted to Phys. Rev. Lett.

[5] (D0 Collaboration).

[6] (CDF Collaboration) S. Kopp and J. Wahl, CDF Note 2541, 1994.

[7] V. Barger and R. Phillips, *Collider Physics*, (Addison-Wesley, 1987), p.233 for Z' K-factor and p. 248 for W' K-factor.

[8] (CDF Collaboration) R. Harris, Fermilab-Conf-94/222-E, proceedings of the meeting of the Division of Particles and Fields, Albuquerque, New Mexico, August 2-6, 1994.

[9] (CDF Collaboration) F. Abe et al., Phys. Rev. Lett. **68**, 1462 (1992).

[10] (CDF Collaboration) F. Abe et al., Fermilab-PUB-94/198-E, submitted to Phys. Rev. Lett.

[11] (D0 Collaboration).

[12] P. Frampton and S. Glashow, Phys. Lett. **B190**, 157 (1987).

[13] (UA1 Collaboration), C. Albajar et al., Phys. Lett. **B209**, 127 (1988).

[14] (CDF Collaboration) F. Abe et al., Phys. Rev. **D41**, 1722 (1990).

[15] (CDF Collaboration) F. Abe et al., Phys. Rev. Lett. **71**, 2542 (1993).

[16] C. Hill and S. Parke, Phys. Rev. **D49**, 4454 (1994).

[17] C. Hill and X. Zang, Fermilab-PUB-94/231-T (1994).

[18] C. Hill, Fermilab-PUB-94/395-T (1994).

[19] (CDF Collab) J. Bao, J. Benlloch, and R. Harris, CDF Note 3024, or on the WWW see http://www-cdf.fnal.gov/physics/new/qcd/btag_dijet/btag_dijet.html

[20] (CDF Collab) Kirsten Tollefson, private communication.

[21] J. Hewett and S. Pakvasa, Phys. Rev. **D37**, 3165 (1988).

[22] J. Hewett and T. Rizzo, Phys. Rep. **C183**, 193 (1989).

[23] W. Buckmüller and D. Wyler, Phys. Lett. B *177*, 377 (1986).

[24] J. L. Hewett and T. G. Rizzo, Phys. Rev. D *36*, 3367 (1988).

[25] J. L. Hewett, T. G. Rizzo, S. Pakvasa, H. E. Harber, A. Pomarol, Proceedings of the Workshop on Physics at Current Accelerators and the Supercollider, Argon National Laboratory, June2-5, 1993, ANL-HEP-CP-93-52.

[26] (CDF Collaboration) F. Abe et al., Phys. Rev. **D48**, 3939 (1993).

[27] (D0 Collaboration) S. Abachi et al., Phys. Rev. Lett. **72**, 965 (1994).

[28] (CDF Collaboration) S. Park.

[29] (D0 Collaboration) D. Norman.

[30] E. Eichten, K. Lane, and M. Peskin, Phys. Rev. Lett. **50**, 811 (1983).

[31] U. Baur, I. Hinchliffe, and D. Zeppenfeld, Int. J. Mod. Phys. **A2**, 1285 (1987); U. Baur, M. Spira and P. Zerwas, Phys. Rev. **D37**, 1188 (1988).

[32] (UA2 Collaboration) J. A. Appel et al., Phys. Lett. **B160**, 349 (1985); (UA1 Collaboration) G. Arnison et al., Phys. Lett. **B172**, 461 (1986), Phys. Lett. **B177**, 244 (1986).

[33] (CDF Collaboration) F. Abe et al., Phys. Rev. Lett. **62**, 613 (1989), Phys. Rev. Lett. **62**, 3020 (1989), Phys. Rev. Lett. **68**, 1104 (1992), Phys. Rev. Lett. **69**, 2896 (1992).

[34] (CDF Collaboration) A. Bhatti, CDF Note 2457, Version 3.0.

[35] (CDF Collaboration) F. Abe et al., Phys. Rev. Lett. **67**, 2418 (1991).

[36] (UA2 Collaboration) J. Alitti et al., Nucl. Phys. **B400**, 3 (1993).

[37] (CDF Collaboration) F. Abe et al., Phys. Rev. Lett. **72**, 3004 (1994).

[38] (D0 Collaboration) Bob Madden, private communication.

[39] K. Lane and M. V. Ramana, Phys. Rev. **D44**, 2678 (1991).

[40] E. Eichten and K. Lane, Phys. Lett. **B327**, 129 (1994).

[41] (CDF Collaboration) F. Abe et al., Phys. Rev. Lett. **63**, 1447 (1989).

[42] (CDF Collaboration) F. Abe et al., Phys. Rev. **D46**, 1889 (1992).

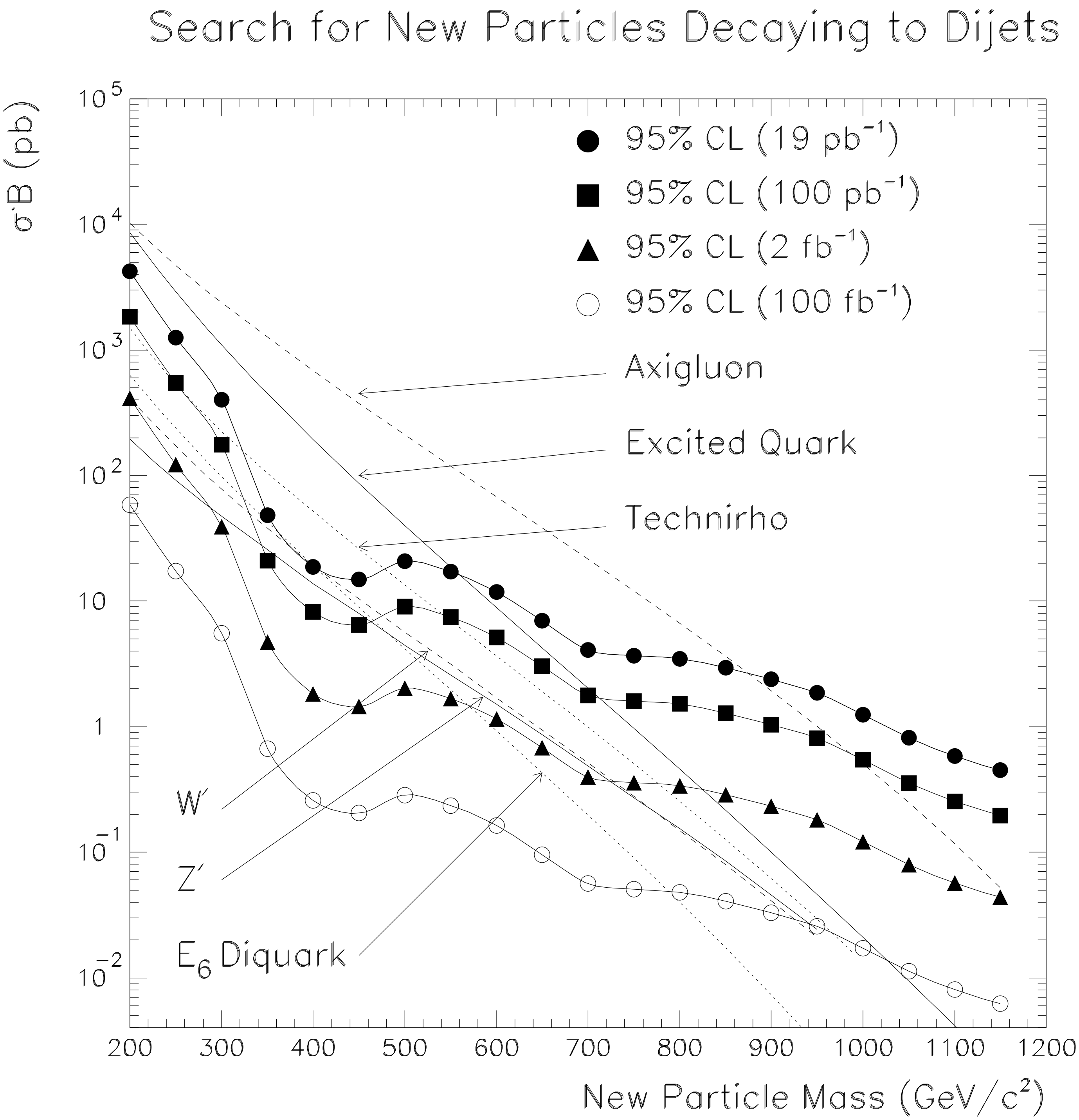

Figure 7.1: The 95% confidence level upper limit on the cross section times branching ratio for new particles decaying to dijets vs. new particle mass for an exposure of 19 pb^{-1} (closed circles) 100 pb^{-1} (squares) 2 fb^{-1} (triangles) and 100 fb^{-1} (open circles) is compared to the theoretical prediction for the cross section for axigluons, excited quarks, technirhos, new gauge bosons (W' and Z'), and E_6 diquarks.

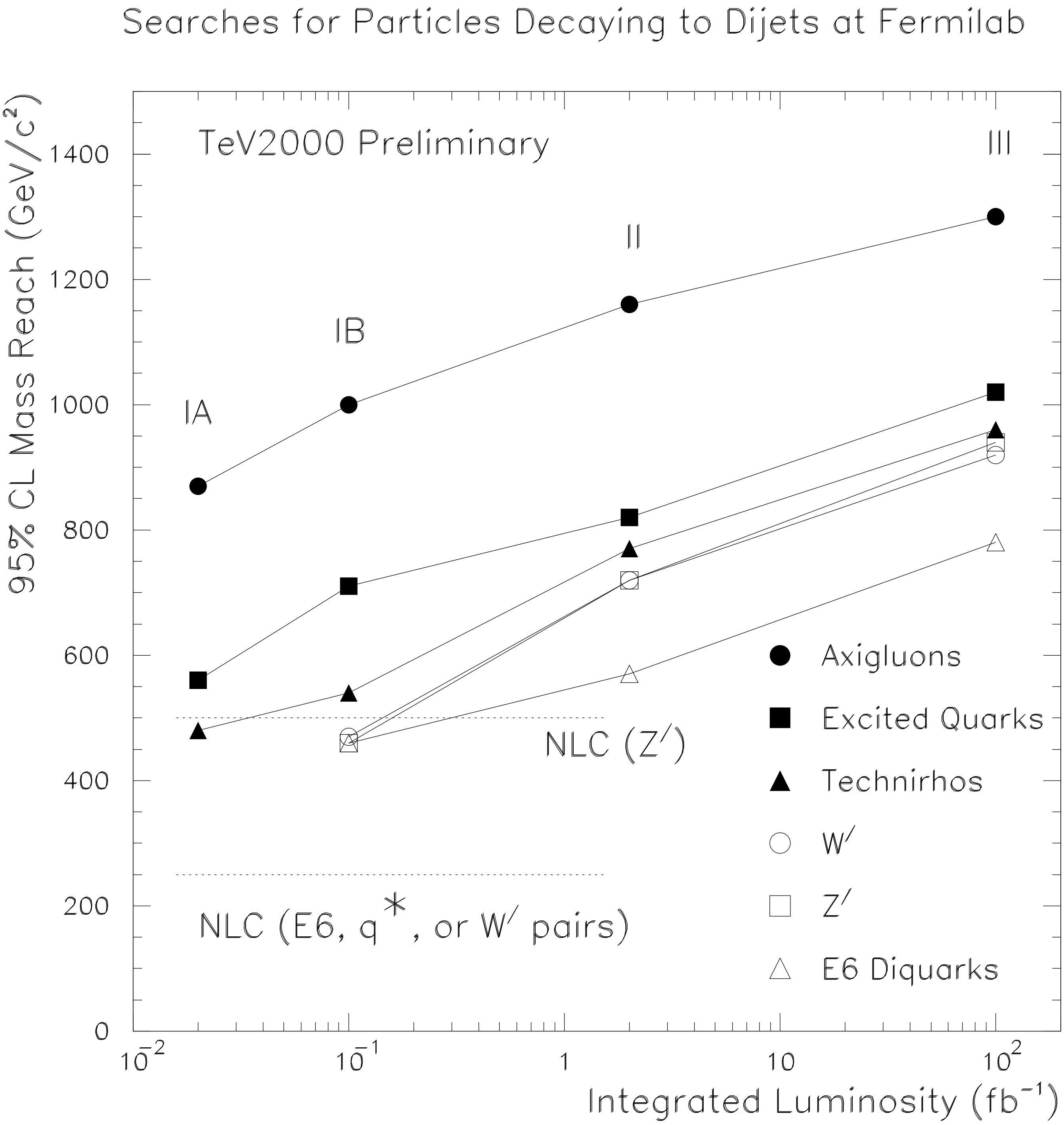

Figure 7.2: The mass reach for new particles decaying to dijets, defined as the 95% CL lower limit on the mass, is plotted vs. integrated luminosity at the Tevatron. The maximum mass reach of other accelerators is shown.

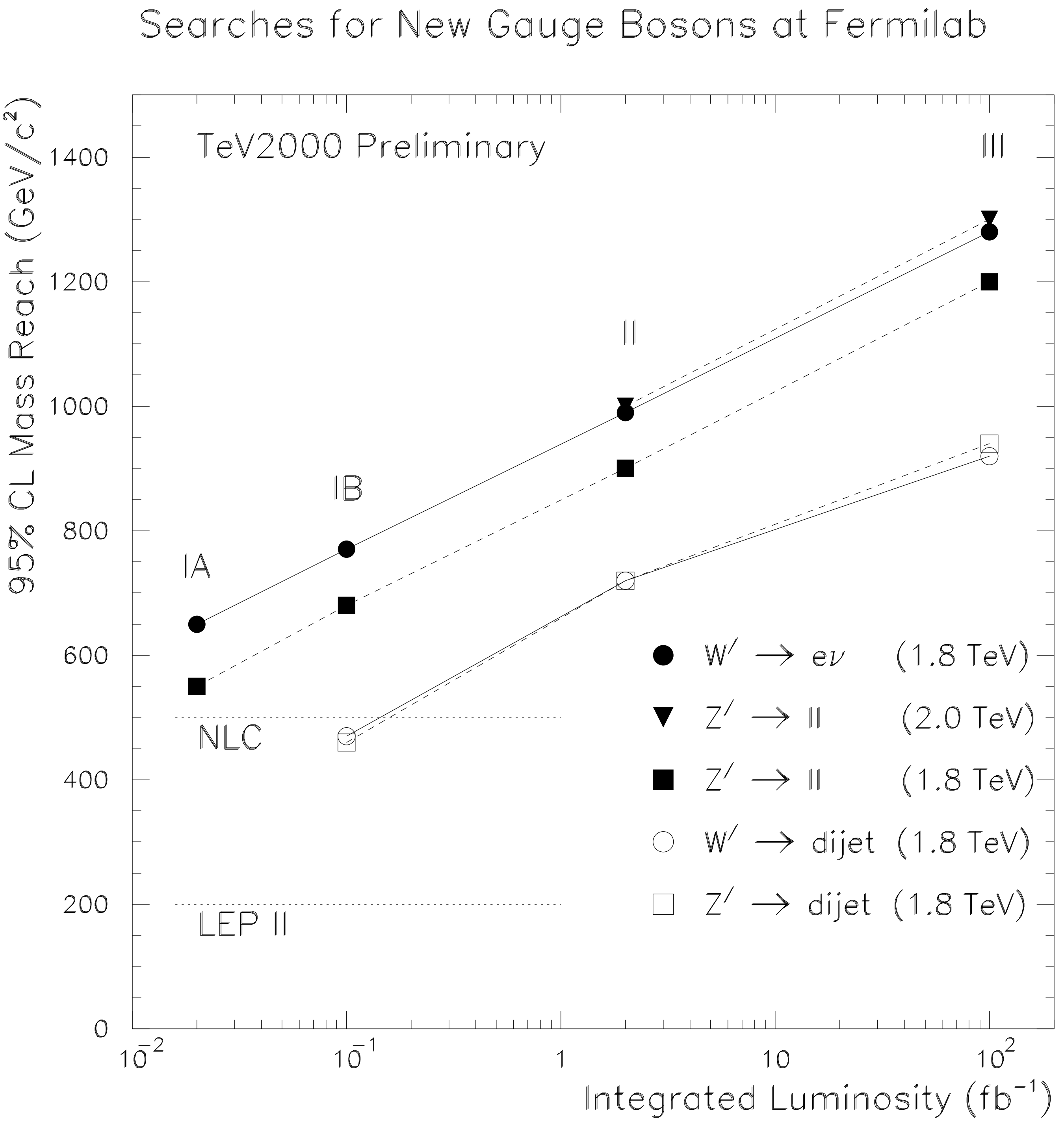

Figure 7.3: The mass reach for new gauge bosons, defined as the 95% CL lower limit on the mass, is plotted vs. integrated luminosity at the Tevatron. The maximum mass reach of other accelerators is shown.

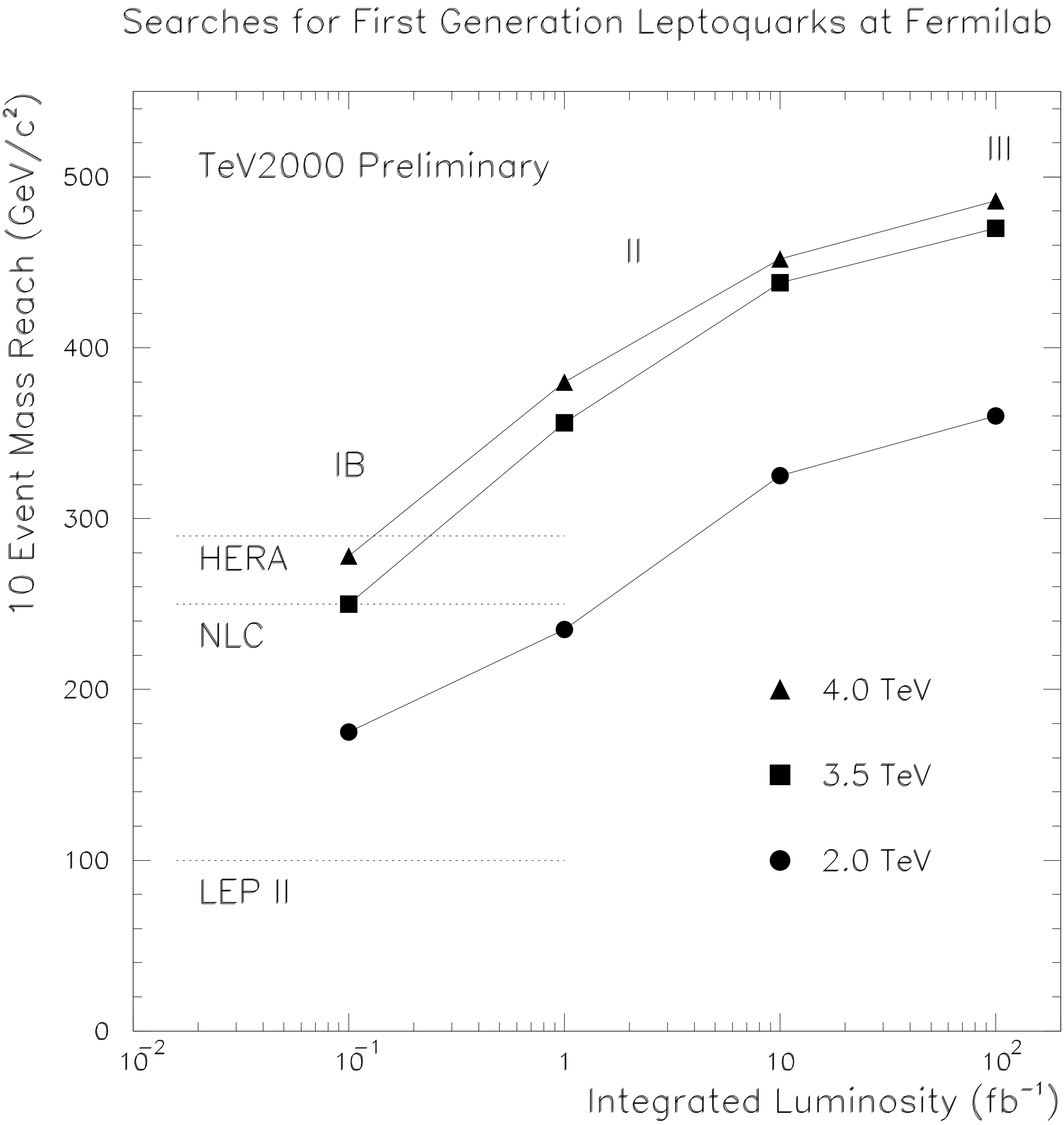

Figure 7.4: The mass reach for new particles decaying to dijets, defined as the mass at which 10 events can be observed, is plotted vs. integrated luminosity at the Tevatron. The maximum mass reach of other accelerators is shown.

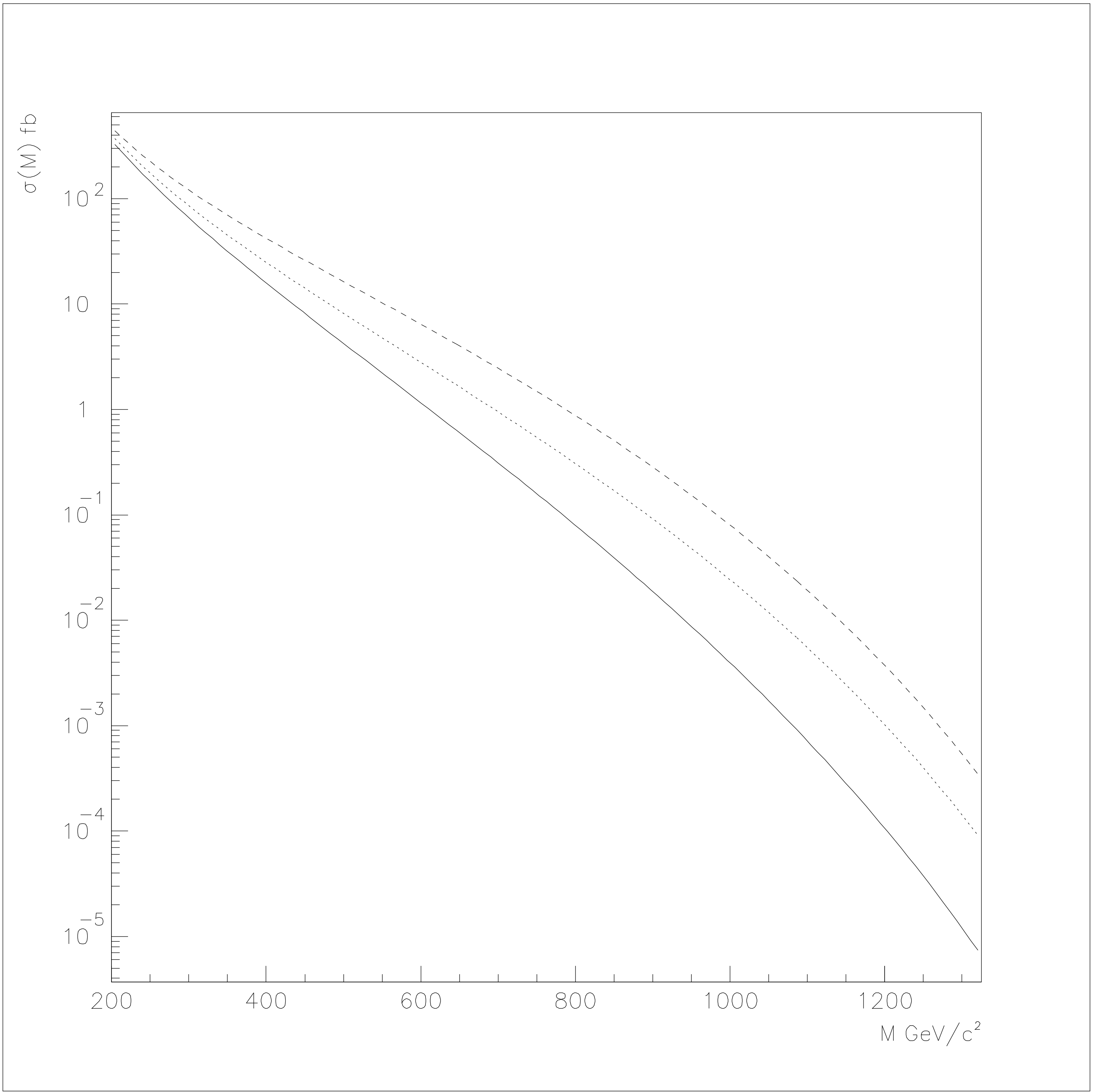

Figure 7.5: The standard model integrated Drell-Yan cross section for lepton pair production (solid line); integral cross section including a contact interaction $\Lambda(qqll) = 5$ TeV (dashed line); integral cross section including a contact interaction $\Lambda(qqll) = 7.5$ TeV (dotted line).

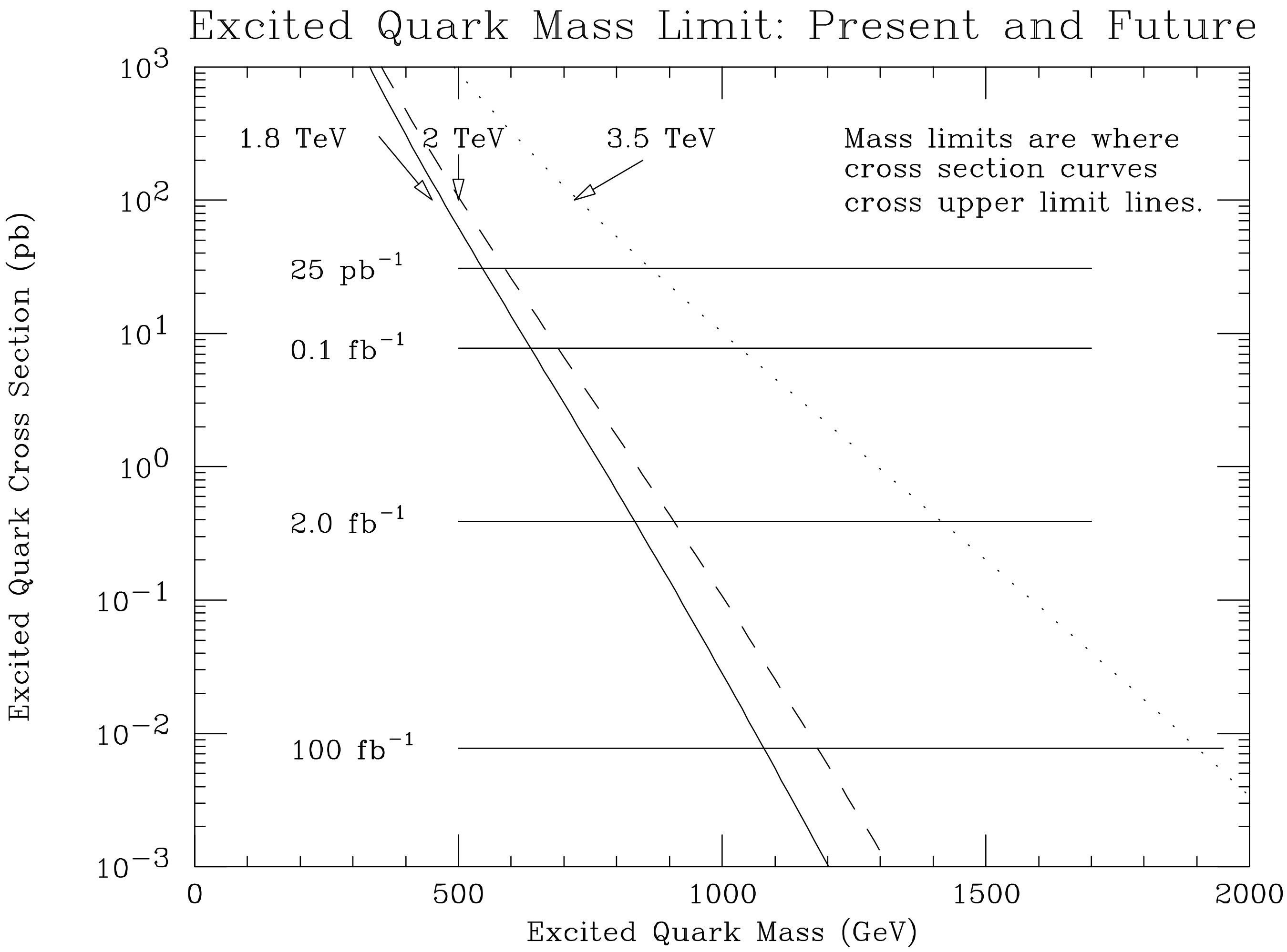

Figure 7.6: The 95% confidence level upper limit on the total cross section for excited quarks from searches in the $q\gamma$ and qW channel is shown by horizontal solid lines for exposures corresponding to the 1988-89 run + run 1A, run 1B, run II and run III. This limit is compared to the theoretical cross section for excited quarks at three CMS energies.

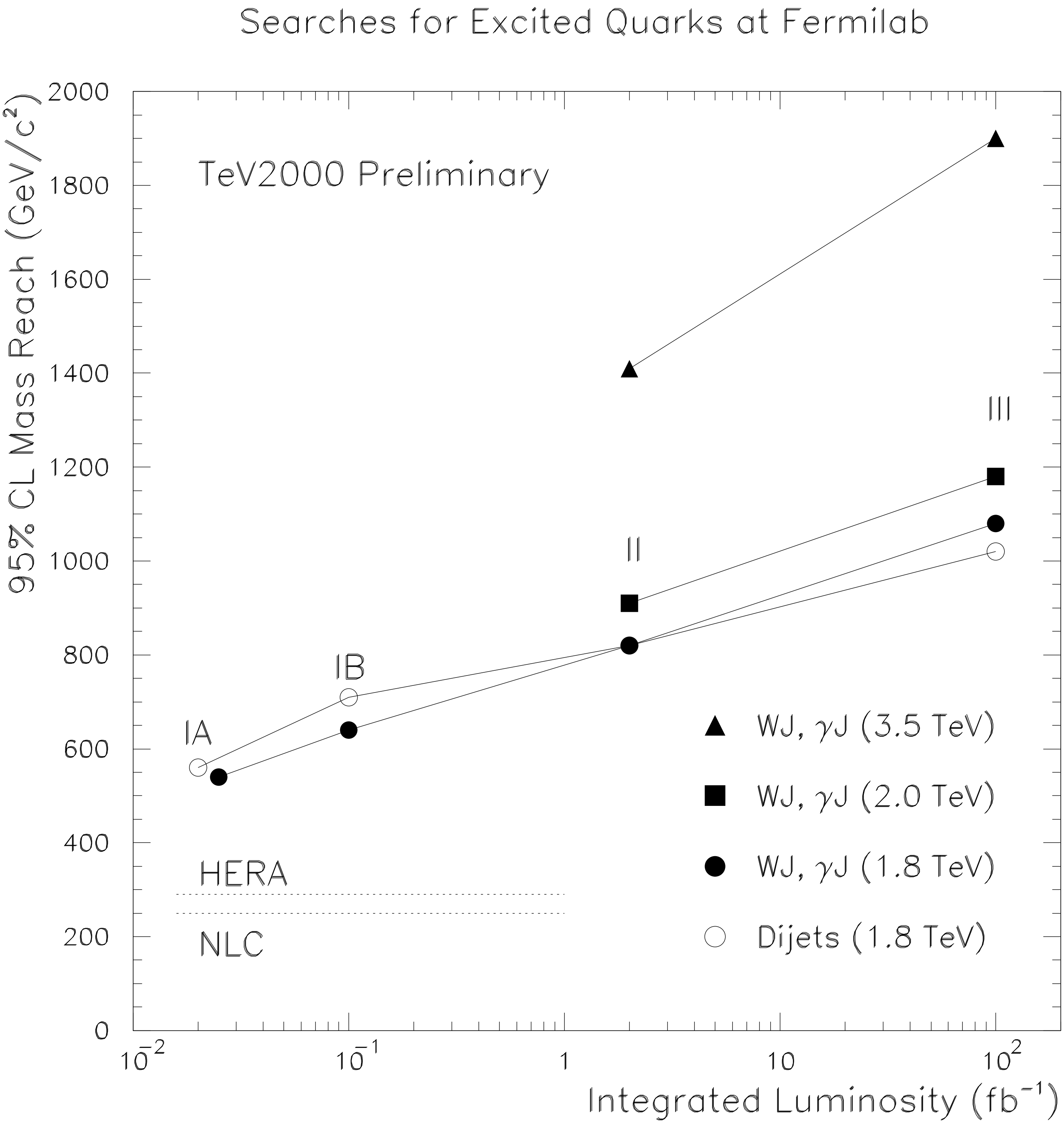

Figure 7.7: The mass reach for excited quarks, defined as the 95% CL lower limit on the mass, is plotted vs. integrated luminosity at the Tevatron. The maximum mass reach of other accelerators is shown.

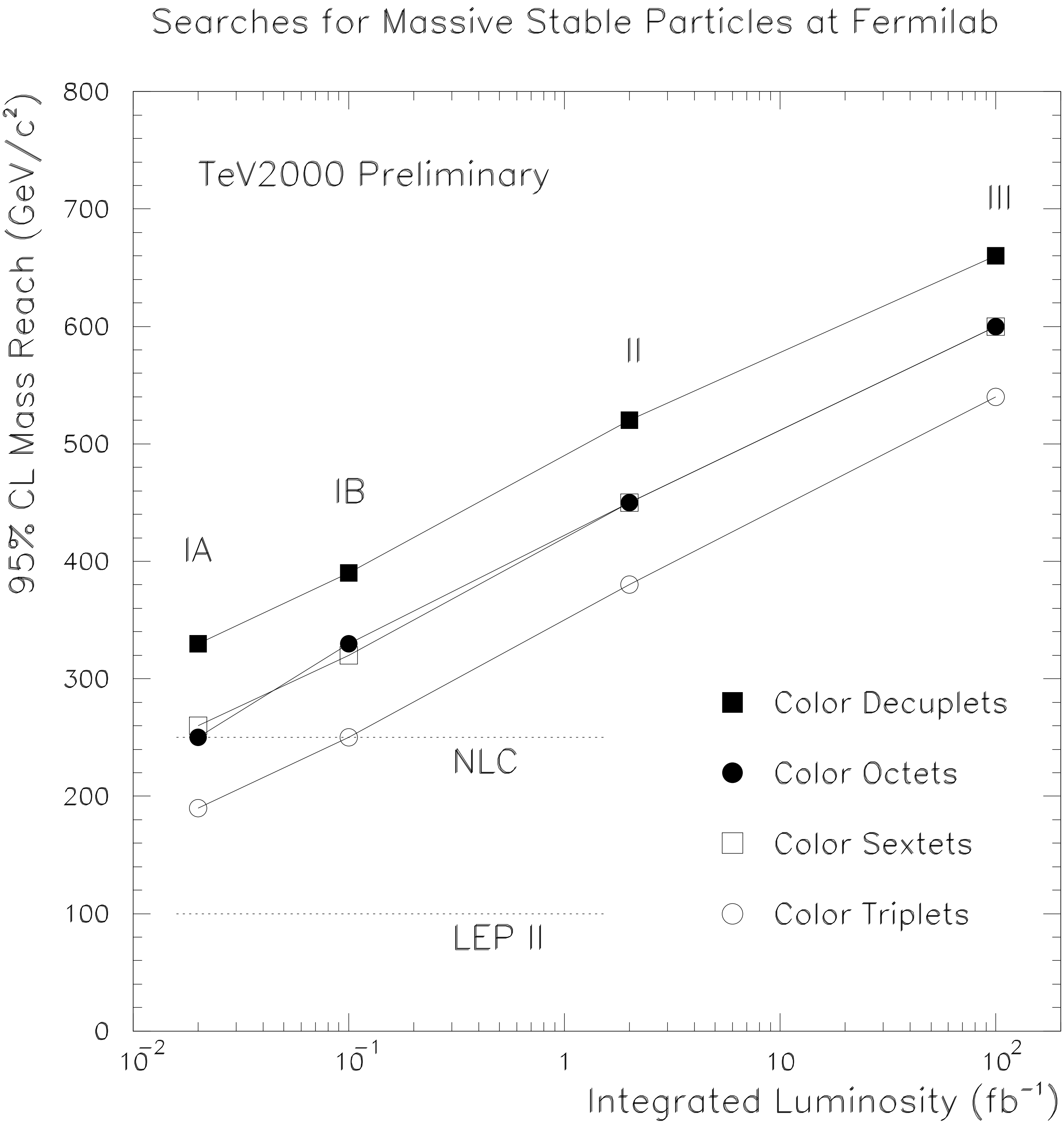

Figure 7.8: The mass reach for heavy stable particles, defined as the 95% CL lower limit on the mass, is plotted vs. integrated luminosity at the Tevatron. The maximum mass reach of other accelerators is shown.

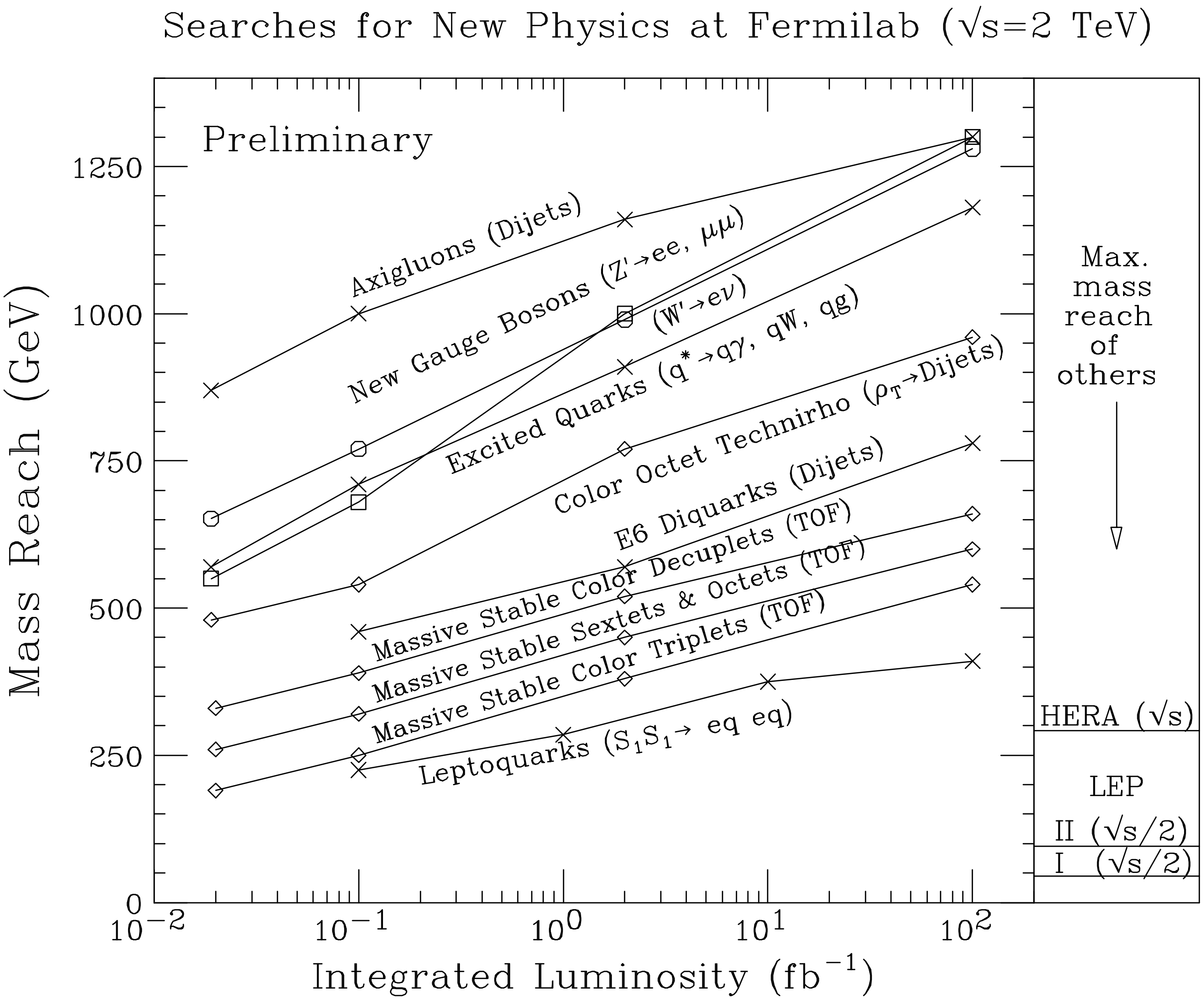

Figure 7.9: The mass reach, defined as the 95% CL lower limit on the mass, is plotted as a function of integrated luminosity at the Tevatron. The maximum mass reach of other accelerators is shown for selected processes.

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**.