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Run III: Continued Running of the Tevatron Collider Beyond 2011

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Executive Summary

We propose a Tevatron Run III Program that would extend the operations of the Tevatron Collider Program for three years from the end of 2011 through 2014, with the major goal of providing greater than 3σ evidence for the low mass Standard Model Higgs Boson in its dominant decay channel, $b\bar{b}$. Failure to detect evidence for a Higgs signal at the end of Run III will provide conclusive proof of physics beyond the Standard Model. Such a Tevatron Run III can be done in parallel with simultaneous running of NOνA up to 71% of the requested 700 kW power, with small and low-cost modifications to the Main Injector/Recycler complex.

In addition to providing at least a 3σ evidence of the Higgs Boson in the low mass range, should it exist, the purpose of Run III is to: (1) more than double the currently existing data sets of both collaborations up to a total integrated (analyzed) luminosity of 16 fb^{-1}; (2) extend the program to the estimated end-point of the useful operational span of the current detectors without a significant upgrade cycle; (3) provide Fermilab with an additional outflow of exciting, rich and new results, and continued training of students and RA's, during the transition to the Intensity Frontier.

We urge consideration of creative solutions to give this program a high profile, to seek national and international support for this effort, and to aggressively support this program to ensure its success. This program has the possibility of a profound discovery unraveling the mystery of electroweak symmetry breaking and beyond.

1 Introduction

The most important issue facing modern High Energy Physics is the origin of electroweak symmetry breaking and any associated new physics at the electroweak scale. Other issues, such as “the origin of flavor”, “the origin of mass patterns and mixing angles”, “dark matter and dark energy”, “is string theory the theory of everything?” are contingent on how electroweak symmetry breaking occurs. We cannot ascertain what the scientific handles on these latter problems are until we understand whether nature deploys an elementary Higgs boson, whether nature is supersymmetric, whether there are new strong forces, etc. Our entire philosophy of nature turns on the unknown physics at the electroweak scale. Moreover, the Standard Model itself points to a low mass for the Higgs boson, the simplest hypothetical agent of the origin of mass. Standard model fits constrain the Higgs boson to lie in the range 114 GeV $< M_h <$ 145 GeV at 95% CL [1].

We are only now beginning, with the Fermilab Tevatron, to reveal this layer of nature. It is important to realize that, while the Tevatron has the mass reach of the electroweak scale, it is now arriving at the required integrated luminosities to discover new objects produced by the electroweak scale interactions, such as the Higgs boson. This program is running spectacularly well and is beginning to probe possible realms of new physics. At some point the LHC will supersede the capabilities of the Tevatron to probe the low mass range, but Until the end of 2014 the Tevatron Collider has a unique capability to search for and to find the low mass Higgs boson and other new physics at the electroweak scale.

Fermilab, the U.S. High Energy Physics Program, and the International High Energy Physics Program, are at a critical cross-roads. The LHC is now commissioned for an initial run at $\sqrt{s} = 7$ TeV, extending for up to twenty-one months. This run will be at the energy of 3.5 TeV per beam and is expected to generate 1 fb^{-1} of integrated luminosity. The LHC plans to shut down after this initial run for a period of a year to eighteen months and resume at or near design energy in calendar year 2013. The initial run should begin to demonstrate the potency of the LHC physics capabilities, and will provide confidence that the program can achieve its design goals. In terms of physics reach, data from the initial LHC run, apart from very high mass objects, is roughly comparable to the Tevatron. The LHC reach is limited in modes initiated by quark-anti-quark annihilation and in particular it is not at all competitive with the Tevatron in the $h \to b\bar{b}$ mode in the initial run. The window before the LHC can definitively address new physics at the energy frontier presents opportunities for the Tevatron to continue its systematic multichannel program addressing the search for the Higgs as well as other precision measurements in the Standard Model.

The Fermilab Tevatron Collider has now provided about 8 fb^{-1} per experiment of analyzable data, and is running extremely well. The Tevatron is now arriving at the threshold of sensitivity to electroweak symmetry breaking effects and may be seeing the first hints of new physics. The low mass $q\bar{q} \rightarrow W/Z + (h \rightarrow b\bar{b})$ sensitivity is such that it may begin to provide observational evidence of the Standard Model Higgs. There is also an assortment of tantalizing excesses seen in various other modes. These may be the first hints of new physics, expected to be revealed at the electroweak scale.

As currently envisioned, the Tevatron Collider is expected to run through the end of FY 2011, nominally yielding about 10 fb^{-1} of analyzable luminosity per experiment. At that time, Fermilab plans to discontinue the Tevatron Collider program. The rationale for terminating the Tevatron is that Fermilab is planning on migrating to the "Intensity Frontier." This is a program that will involve the commissioning of the NOνA detector in FY2011 at 300 kW of beam power, and an upgrade to 700 kW in 2012. Subsequent plans envision construction of a new tunnel for the LBNE beam and other initiatives, including Mu2e and g-2. These are intermediary to the eventual design and construction of Project-X, which supports higher luminosity neutrino experiments, next generation muon experiments, ultra-rare kaon physics and an eventual Neutrino Factory and Muon Collider. Together these will constitute a powerful and exciting program in experimental physics, potentially leading the U.S. HEP program back to the energy frontier.

The terminating of the Tevatron effort in 2011, however, is not based upon another program that has demonstrated equality or superiority in physics results. The LHC will not be able to surpass the Tevatron in key electroweak modes, such as the low mass Higgs search, until much later (see section 4.4). In fact, many authors believe that the fundamental $h \rightarrow b\bar{b}$ mode cannot be probed at the LHC, or at least not until a detailed understanding of jet substructure has evolved, permitting extraction of this signal in high E_T jets, expected no sooner than with an integrated LHC luminosity of order 30 fb^{-1} [2]. From this perspective, the Tevatron could remain preeminent for at least three years beyond the current intended date of foreclosure, in 2011.

The Tevatron Collider has been the flagship in the U.S. HEP program for the past 25 years. It is currently at its peak, prodicing ~ 50 PhD's and ~ 100 scientific publications per year. We believe that Project-X, which represents a significant infra-structure investment at Fermilab, will become the future flagship program. Fermilab is beginning now to undergo an "adiabatic" transition to the new Project-X era in tandem with Run III by operating NOνA concurrently with the Tevatron, and phase in the other initiatives through 2014 when Run-III would conclude. We believe the Tevatron offers a cost-effective interim program that strongly reinforces the transition era to Project-X. The planning cycle of the FY 2012 budget makes it urgent to decide the issue to provide for continued Tevatron operation at this time.

As stated, one of the key issues is to ensure that the commitment to NOνA is relatively unaffected by a Tevatron Run III. NOνA is an approved program and must go forward, with an ultimate power of order 700 kW. In the present note we will show that the existing complex (with minimal expenditure and no serious down-time) is capable of delivering 71% of the beam power needs to NOνA while simultaneously operating the Tevatron. When the Tevatron is finally decommissioned these modifications may be able to deliver significantly higher beam power to NOνA alone. We further note that the collider detectors will sustain continued operation with modest maintenance. Manpower and personnel commitment depend critically on the vision and posture of the lab to continue the Tevatron Collider for an extended period of time.

At stake is the potential for significant discovery that could represent confirmation of the Higgs boson or a break-down of the Standard Model. Running the Tevatron for 16 fb^{-1} of analyzable data could provide greater than 3σ evidence of the Higgs in the full SM expected range. Experience has shown that new signals often evolve faster than the statistical rate, "$\propto \sqrt{N}$," as more data accrues and a better understanding of complex signal and background issues emerges. In addition, the various anomalies at the few-sigma level in the current data sample, which may be the first hints of new physics, can be resolved with 16 fb^{-1} of data.

Without direct observation of the $h \to b\bar{b}$ signal it is not possible to reach a definite conclusion about the Higgs mechanism of electroweak symmetry breaking. The Tevatron is likely to be the only way to achieve this in the foreseeable future. A 3-σ exclusion of a low-mass Higgs would also be revolutionary, and would have a profound effect on both theory and the planning of future energy frontier colliders.

2 Fermilab Accelerator Complex Capabilities

The Tevatron Collider is currently operating at its peak performance:

- The average yearly–integrated luminosity exceeds 2 fb^{-1}.

- The average weekly–integrated luminosity exceeds 50 pb^{-1}.
- The average peak luminosity is over 300 $\mu\mathrm{b}^{-1}$/second.
- The Tevatron provides over 130 hours per week in colliding beam physics.

Assuming this level of future performance with a one-month shutdown in 2010 and 2 months shutdowns each subsequent year, it will be possible to obtain a delivered luminosity of 19 fb^{-1} (delivered integrated luminosity) by the end of FY2014.

2.1 Maintenance Issues

The Tevatron Collider complex has sometimes been referred to as an "aging machine," implying that continued operations would be *a priori* fragile. This is simply not the case for the Fermilab collider complex. Tevatron performance parameters continue to climb. The store hours per week have risen dramatically over the years, from 70 hours per week in Run I to over 130 hours per week in Run II. While every machine of this complexity needs constant maintenance, the overall outlook on maintenance and availability of spare components for the Tevatron, Main Injector, Recycler, and Antiproton Source has remained unchanged for the past three years. One of the major components of the Fermilab antiproton production capability is the Recycler and its electron cooling.

2.2 Role of the Recycler in the Tevatron Collider

Since the Tevatron is a proton-antiproton collider its luminosity is limited by antiproton beam brightness. The spectacular performance of the Tevatron Collider is the culmination of many years of investment into the Main Injector, Recycler, and Run II upgrades that substantially increased the antiproton beam brightness.

The Recycler functions as a third stage storage ring for antiprotons that reduces the burden of rapid stacking with stochastic cooling in the Antiproton Source. Electron cooling in the Recycler, which was considered by many as risky when it was first proposed, condenses the antiproton beam to unparalleled beam brightness. Without the Recycler and electron cooling, it is estimated that the yearly–integrated luminosity would be less than half of its current level.

2.3 Planned Accelerator Upgrades for NOνA

Current plans for the end of the collider run include decommissioning of electron cooling and conversion of the Recycler to a proton accumulator for the Main Injector. The conversion of the Recycler is a part of a suite of upgrades to the accelerator complex in support of the neutrino program. The upgrades can be summarized as follows (with details in Table 1):

- With the use of the Recycler as a proton accumulator and upgrades to the Main Injector magnet power, the Main Injector cycle time can be decreased from 2.2 to 1.33 seconds. The cycle time reduction provides a 1.65× increase in 120 GeV beam power.
- The Recycler can accommodate an additional Booster batch, improving on current Main Injector slip stacking operations. The extra batch provides a 1.11× increase in the 120 GeV beam power.
- Once the collider run is terminated, the two antiproton production batches per Main Injector cycle can be allocated to the neutrino program yielding another factor of 1.2× increase in 120 GeV beam power.

With these changes, the maximum Main Injector 120 GeV beam power will be 700kW, more than twice the current 320kW level depicted in Table 1.

2.4 Proposal: Simultaneous NOνA and Tevatron Collider Operation

It should be noted that the current maximum flux provided by the Fermilab Proton Source is 11×10^{16} protons/hour. To run NOνA at 700kW, the Proton Source would have to provide 14×10^{16} protons/hour. Therefore it is assumed in this section that all the protons that the Proton Source can produce will be used for NOνA and the Collider program. As noted earlier, once the Recycler is recommissioned for the NOνA program, it will be impossible to run Tevatron Collider operations without a severe drop in collider luminosity.

However, by keeping the Recycler dedicated to the collider program for a longer period, it would be possible to run both NOνA and the collider simultaneously.

By taking advantage of the NOνA upgrades to the Main Injector, it is possible with little or no additional cost to provide a substantial increase in Main Injector 120 GeV beam power over the present 320 kW level. This is achieved by:

Table 1: Proton Flux Allocation for 120 GeV Neutrino and Antiproton Production.

	NUMI I	NOνA	This proposal	units
Booster Cycle Rate	5.00	9.00	5.89	Hz
NOνA/NuMI Booster Batches	9	12	10	
NOνA/NuMI Booster Batch Intensity	4.30	4.30	5.10	$\times 10^{12}$
Antiproton Booster Batches	2	NA	1	
Antiproton Booster Batch Intensity	4.60	NA	5.50	$\times 10^{12}$
Main Injector Fill Period	0.67	0.00	0.67	sec
Main Injector Ramp Period	1.53	1.33	1.20	sec
Main Injector Cycle Time	2.20	1.33	1.87	sec
Main Injector Efficiency	95%	95%	95%	
Main Injector 120 GeV Intensity	45.51	49.02	53.68	$\times 10^{12}$
Main Injector Loss Rate	1.39	2.48	1.94	kW
Antiproton Used in the Recycler	Yes	NA	Yes	
Antiproton Cycles Interleaved	No	NA	Yes	
Antiproton Cycle Time	2.2	NA	3.73	sec
Booster Flux	7.84	13.93	10.90	$\times 10^{16}$/hour
Antiproton 120 GeV Proton Flux	1.43	NA	1.01	$\times 10^{16}$/hour
NOνA/NuMI Beam Power	320	700	500	kW

- Upgrades to the Main Injector magnet power system, shorter flattop dwell times, and elimination of deceleration energy ramp parabolas will permit a faster Main Injector energy ramp yielding a 1.18× increase in beam power.

- Allocation of all of the currently available proton source flux (11×10^{16} protons/hour) to the NOνA and Collider programs by increasing the proton source batch intensity by 18% is assumed.

- Interleaving the antiproton production pulses to every other Main Injector ramp cycle, which will increase neutrino flux by a factor of 1.11×. The interleaving of antiproton production pulses reduces the proton flux on the antiproton production target, seemingly causing a drop in the antiproton accumulation rate. However, the antiproton source stochastic cooling becomes more efficient with the longer antiproton cycle time as a result of interleaving. Since the antiproton source uses only 10% of the proton source flux, the proton source batch intensity for antiproton production can be increased substantially with a negligible effect on the total proton flux. The net reduction in antiproton stacking rate would be only 12%.

- The reduction of 12% in antiproton production rate would create a corresponding reduction in collider luminosity. The reduction in luminosity can be compensated by increasing the number of protons at collisions, changing the Tevatron betatron tunes The circuits for the time change are already in place. The concept has been thoroughly worked out.

With the changes outlined above, the 120 GeV beam power available to NOνA would be 500kW, which is 71% of the 700kW goal. Again it should be noted that these steps would require no additional cost beyond what is already allocated for NOνA and does not require the Proton source to provide more flux than it currently is delivering.

2.4.1 Main Injector Cycle Time

The NOνA upgrades to the Main injector include the installation of a new quad bus power supply and two additional RF stations. This brings the cycle time to 1.33 seconds. To decrease from 1.33 seconds to 1.2 seconds, 0.13 seconds is eliminated by shortening the dwell times and deceleration parabola's. The 1.33 second ramp includes a 0.08 second 8 GeV dwell time, a 0.05 second flattop dwell time, and two deceleration parabola's of 0.1 secs each resulting in 0.23 extra seconds (using only half of the parabola time). Adequate time remains for power supply regulation during these shortened dwell periods. Due to substantial RF bucket area at 120 GeV, flattop bunch rotation can be started during acceleration. Deceleration parabolae can be reduced or eliminated.

2.4.2 Slip Stacking Efficiency

The Booster longitudinal and transverse emittances do not grow linearly with intensity. The Booster longitudinal emittance is dominated by instabilities, however the Booster longitudinal dampers maintain the longitudinal emittance at a relatively constant level over a wide range of intensity. The slip stacking loss in the Main Injector is from DC beam not captured in the in the RF bucket. There are no instabilities in the Main Injector at these beam currents. Ample RF overhead power exists to comepnsate for transient beam loading . Therefore, the slip stacking efficiency should remain constant with intensity over the proposed range of operation. In any case it would be prudent to investigate the lost DC beam due to slip-stacking and recoup this 5% beam loss due to slip stacking for any operational scenario.

2.4.3 Booster Beam Intensity

The Booster can currently accelerate 5.3×10^{12} protons/batch with 93% efficiency. The efficiency for 4.3×10^{12} protons/batch, used in routine operations, is on the order of 94%. To run 11×10^{16} protons/hour at 4.3×10^{12} protons/batch, the average Booster rep rate is 7.1 Hz. To run 500kW to NOνA, the Booster needs to run 5.1×10^{12} protons/batch at 5.9 Hz. This corresponds to a 15% increase in beam loss in the Booster tunnel. Note that to provide NOνA with 700kW at 120 GeV, 27% more beam power is dissipated in the tunnel than is currently lost at 11×10^{16} protons/hour.

It should be assumed that some transmission improvements would occur with the new RFQ replacing the Cockroft Walton pre-accelerator and higher Booster RF voltage, due to installation of new solid-state drivers to the Booster RF system. Since there will have to be improvements made to get to 14×10^{16} protons/hour in the Booster, it is assumed that some of performance increase would be available for this proposal.

2.4.4 Antiproton Stacking Issues

Since the Debuncher cooling is power limited, it is better to send a high intensity pulse at a slower cycle time than a low intensity pulse at a short cycle time. The proposal is based on interleaving stacking pulses every other Main injector ramp cycle. Therefore, on

Main Injector Cycle A, eleven batches are allocated to NOνA and none are allocated to Antiproton Source. On Main Injector Cycle B, nine batches are allocated to NOνA and two are allocated to Antiproton Source.

The Booster batch intensity increases from the current 4.5×10^{12} to 5.5×10^{12}. The antiproton production cycle time increases from the present 2.2 to 3.73 seconds. On the surface, this appears to be 30% drop in flux. However, the longer cycle time improves the stochastic cooling in the Antiproton Source dramatically. By increasing the cycle time to 3.73 seconds, it has been experimentally shown that the antiproton production efficiency will rise from 21×10^{-6} antiprotons/proton to 30×10^{-6} antiprotons/proton for the same number of protons on target. Since the number of protons on target would increase, it is prudent to de-rate the $\bar{p}$ production increase to 26×10^{-6} antiprotons/proton. Since the Debuncher cooling is power limited and the Stacktail cooling is midway between power and gain limited, this is a conservative estimate. The net reduction in antiproton accumulation rate would be 12% .

2.4.5 Tevatron

The proposal to change the Tevatron betatron tune working point has been long established and documented. The concept has been thoroughly developed by A. Valishev [3]. Pushing the Tevatron tune closer to the half–integer (as is done at the B-Factories) will provide up to 50% more tune space than is currently available. Beam-beam effects, presently responsible for $\sim$ 10% luminosity reduction will be suppressed by the tune change allowing for an increase in proton bunch intensity. Additional tune space implies proton intensity can be increased by up to 50%. Complex luminosity evolution simulations have been performed that take into account a multitude of effects such as intra-beam scattering and beam-beam effects. The simulations have showed that the integrated luminosity lost by reduced stacking rate can be completely recovered by a tune change, incerasing store duration and a moderate increase of the proton intensity.

2.4.6 Study time for implementation

Study time is required to prove increased batch intensity operations in the Booster and Main Injector. Significant portions of this study time can be done parasitically during current operations. For commissioning the Main Injector, the proposal does not request anything beyond what is planned for NOνA operations. To change the Tevatron working point, completely revised ramps need to be developed. Such operational changes will require a concentrated effort by the Tevatron Department. In an attempt to maintain close to current operating luminosities during the development, a period of dedicated study over several months is anticipated. Once new working points have been proven, migrating to new operating parameters could be completed in a few weeks.

3 Detectors and Experimental Collaborations

The CDF and DZero experiments are progressing extremely well with data collection, data processing and physics analysis of Run II data. Almost 500 papers have been published by the experiments since the beginning of Run II and active studies are progressing in all areas including top quark studies, precision measurements of electroweak parameters, searches for physics beyond the Standard Model, studies of particles and processes containing b quarks as well as the search for the Higgs boson.

There are exciting options ahead due to the increase in the data set, development of improved experimental methods as well as studies of new topics due to theoretical developments and/or experimental hints. The reach of the experiment in such fundamental measurements as top quark and W boson masses, searches for particles beyond those known today, studies of the processes with CP violation as well as search for the Standard Model Higgs boson with luminosity expected by the end of 2011 is well documented in the CDF and DZero presentations to P5, HEPAP, PAC and funding agencies. Many of these measurements will become the legacy measurements from the Tevatron once the full data set has been analyzed and will remain in textbooks for years to come.

It is necessary but not sufficient to have a well laid-out physics case for extending the Tevatron running beyond the current plan to the end of 2011. Detector reliability and the level of commitment by the collaboration members are also important factors to consider in the decision-making process. CDF and DZero are currently in the process of evaluating both. Below is a brief status report and plan for the coming few months.

3.1 The CDF Experiment

Currently, the CDF detector is operating well—routinely collecting data with 85% efficiency. Each of the individual detectors is performing well. The calorimeters, muon detectors, solenoid, data acquisition and trigger systems show no appreciable sign of aging or give one pause for concern. The central outer tracker, which once had a problem, has recovered fully and gain remains stable at design specification. Only the silicon detector, the single most important detector element, has been and continues to show signs of aging.

The CDF collaboration has long known that radiation would take its toll on the silicon detector. Its current status is excellent. The detector is operating with $> 90\%$ of all channels being active and read out. Layers 0 and 2 of the "SVX" detector have experienced inversion, as predicted and the degradation of S/N observed agrees with early models. Two years ago, CDF experienced cooling problems in the SVX detector, the result of an acidic coolant that weakened the "elbow" joints. The weak points have been addressed and now CDF monitors the coolant properties carefully. The cooling system has been stable for the past two years.

CDF does not yet have a sufficiently clear projection of detector performance beyond 2011 to make any quantifiable statement in this document. The collaboration is working to get to that point but it will take a few months to complete our studies, and the collaboration is now forming a small task force to characterize the expected detector performance vs. integrated luminosity. This task force is divided into several sub-groups. The first group will characterize fully the state of the detector and estimate how each layer will behave as a function of integrated luminosity beyond what we expect to achieve in 2011. The second group will use this information to quantify how the projected detector degradation will impact *b*-tagging. Finally, a third group is looking at whether there are any hardware steps that can be taken to improve the situation. This work is in progress and will lead to a preliminary report in the 2nd quarter of 2010.

3.1.1 CDF Collaboration and Human Power

Currently, the CDF author list is comprised of 538 individuals from 15 countries and 59 institutions. In this group there are approximately 90 students and 90 post docs. The remainder is faculty and laboratory research staff. The collaboration remains evenly split in all categories between scientists from US and non-US institutions.

The collaboration was polled a year ago and asked what the expected future level of commitment would be. From that, CDF anticipates access to ~ 250 FTE this year. That number falls to about 210 in 2011. Note that at the time of the survey, they expected the Tevatron to turn off in 2010. Now that they are expecting to operate the program in 2011, we expect this number to grow.

CDF has recently conducted a survey of all its institutions regarding extending a run through 2014. The vast majority of groups from both the US and abroad support this extended run and find the physics case sufficiently compelling to participate. Garnering this collaboration support is important, but this alone is not sufficient. For the Tevatron program to be successful beyond 2011, a commitment from the laboratory and DOE would be required as soon as possible. There is need to support the experiment to ensure sufficient personnel remain to execute the program well. The physics can be addressed is of fundamental importance and the CDF collaboration is proven capable of executing a sustained continuation of Tevatron operation into the future

3.2 The DZero Experiment

The DZero experiment is progressing extremely well with data collection, data processing and physics analysis of Run II data. Almost 200 papers have been published by the experiment since the beginning of Run II and active studies are progressing in all areas including top quark studies, precision measurements of electroweak parameters, searches for physics beyond the Standard Model, studies of particles and processes containing b quarks as well as the search for the Higgs boson.

3.2.1 Detector Operations

The DZero detector is collecting data with very high efficiency. On average, the data taking efficiency is currently $\sim 90\%$. Since $\sim 5\%$ of the inefficiency is due to front-end readout electronics, the actual experiment downtime is only a few percent, a remarkable achievement for such a complex apparatus. We expect no degradation in data-taking efficiency over the next few years assuming availability of a dedicated team of experts and shifters.

As the original detector had been designed for integrated luminosities below 10 fb^{-1}, careful consideration has to be given to radiation aging of inner detector parts, especially the silicon and fiber tracker detectors. These detectors are expected to experience degradation of their performance beyond 2011. The DZero experiment has commissioned a "Beyond 2011" task force to evaluate the level of deterioration and effects on physics performance and to propose possible mitigations. We expect the results from this task force to become available over the next few months.

3.2.2 Collaboration Interest

The DZero collaboration comprises around 500 collaborators from 87 groups in 19 countries. About half of the collaboration is from non-US Universities and Laboratories. We have a strong commitment from the collaborators, including foreign groups, to participate in data taking, processing and physics analysis of all data collected up to the end of 2011. Some groups and individuals expressed interest in continuing participation if Tevatron runs beyond 2011. In-depth evaluation of the commitments is supported by the experiment's Institutional Board and is currently in progress. Strong support and commitment from US and foreign funding agencies as well as Fermilab is critical to ensure success of the extended Tevatron running.

4 Aspects of the Physics Case

It is not the purpose of this document to provide a comprehensive review of the physics case at the Tevatron. We will simply highlight some aspects of the goals of the program accessible with continued running.

We expect the Tevatron to deliver about 2.5 fb^{-1} per year, with about 2 fb^{-1} recorded and available for physics analysis over the next few years. Such a performance is challenging, but reasonable to achieve without upgrades. Assuming that both experiments will have a 10 fb^{-1} data set available for analysis by the end of 2011, each additional year will add roughly 20% to the data set, yielding a doubling from today. This additional sample can do a great deal for the advancement of HEP. The Tevatron may be on the brink of producing physics results of extraordinary importance on several fronts simultaneously, particularly in the Higgs search. We give here only a brief synopsis of some highlights of the future Tevatron physics potential.

4.1 Standard Model Higgs Boson Searches

The Tevatron has already achieved the milestone of excluding a region of Higgs masses above the old LEP limits. At present the excluded range is 163 – 166 GeV at 95% C.L., which is in the high mass range where gluon fusion production and the $h \to WW$ decay is the dominant search channel. With more data, the high mass exclusion region is expected to grow.

Table 2 summarizes the projected sensitivity to Higgs masses at the Tevatron.

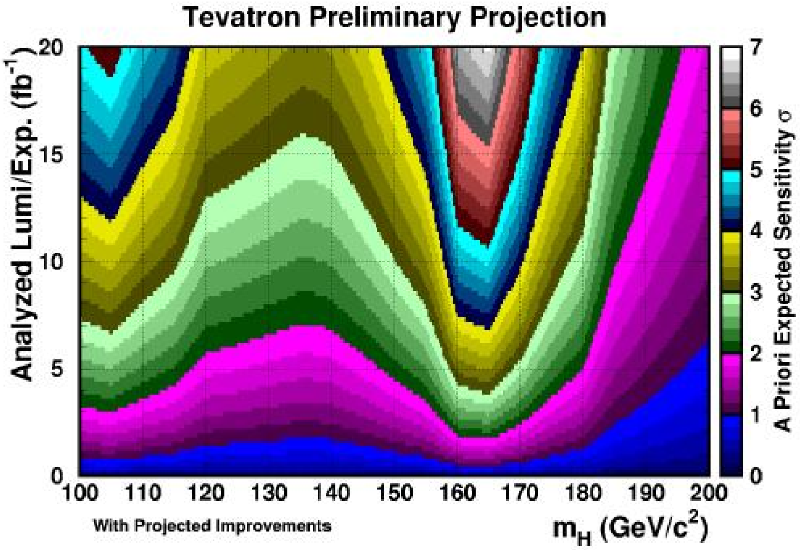

Figure 1: Higgs Boson sensitivity with projected improvements per experiment.

Analyzable Lum/Expt	115 GeV	130 GeV	145 GeV
5 fb^{-1}	2.2 σ	1.7 σ	1.9 σ
10 fb^{-1}	3.1 σ	2.5 σ	2.7 σ
15 fb^{-1}	3.8 σ	3.0 σ	3.2 σ
20 fb^{-1}	4.4 σ	3.5 σ	3.7 σ

Table 2: Sensitivity to the Standard Model Higgs Boson combining all modes. The low mass ≤ 130 GeV mode is principally $q\bar{q} \rightarrow (W,Z)+(h \rightarrow b\bar{b})$; the higher mass ≥ 130 GeV mode is principally $gg \rightarrow h \rightarrow WW^*$.

It is important to note that the lower mass range of the Higgs is favored by the global SM fits. The low mass range will have to be explored fully to understand the mechanism of electroweak symmetry breaking. With Run III, the Tevatron can provide the sensitivity to exclude or discover a low-mass Standard Model Higgs boson at the 3-σ level across the full mass region below WW threshold. Such an exclusion would have deep and revolutionary implications both theoretically and in planning future facilities, in particular the parameters of the next lepton-collider. This is a capability complementary to the power of the LHC at higher masses. The Tevatron will remain the facility with the largest sensitivity in this crucial region for many years. The $h \rightarrow b\bar{b}$ mode may be observable at the LHC, but only with > 30 fb^{-1}. Without direct observation of a $h \rightarrow b\bar{b}$

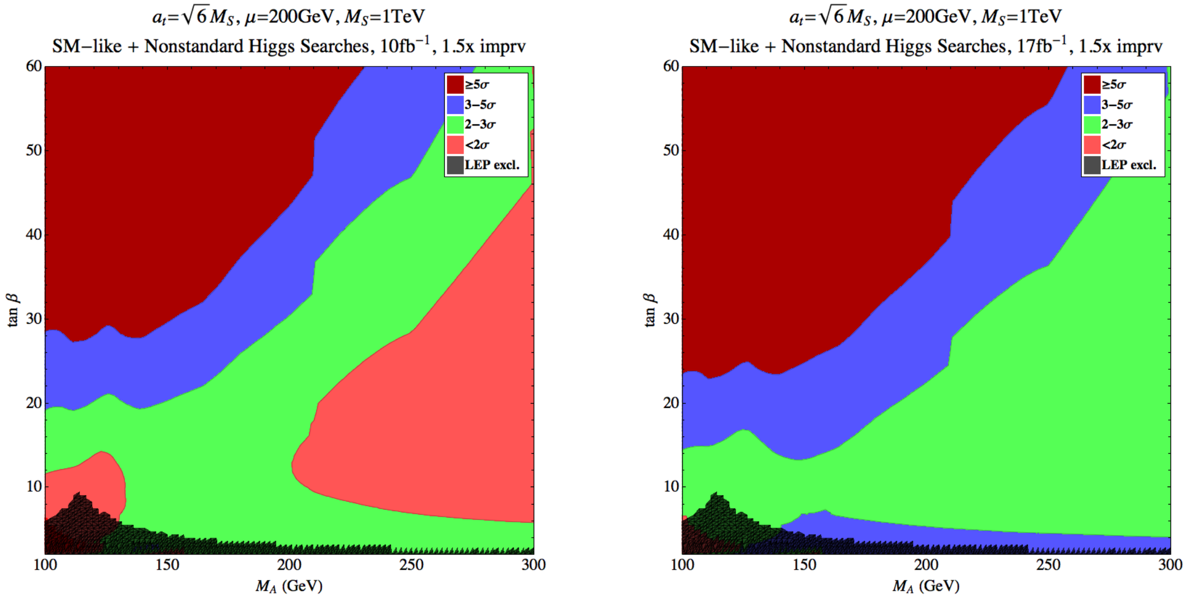

Figure 2: The projected Run III Tevatron sensitivity on the (M_A, $\tan\beta$) plane in the benchmark scenarios of Maximal Mixing for 10 fb^{-1}(*left*) and 17 fb^{-1} (*right*) of integrated luminosity. The sensitivity is obtained as a combination of search channels for the three neutral Higgs bosons and the charged Higgs boson.

signal it is not possible to reach a definite conclusion about the electroweak symmetry breaking mechanism. The Tevatron is likely to be the only way to achieve this over the next few years.

Lastly, if a low-mass SM Higgs does not exist, the Tevatron experimental environment remains complementary to the LHC in searches for new low mass states, having less pile-up, stronger low-p_T trigger capabilities, and fewer photon conversions. Failure to detect evidence for a Higgs signal at the end of Run III will provide conclusive proof of physics beyond the Standard Model.

4.2 Supersymmetric Higgs Boson Searches

By the end of Run III the Tevatron will achieve wide sensitivity to the Higgs parameter space in well-motivated supersymmetric extensions of the Standard Model. The Minimal Supersymmetric Standard Model (MSSM) contains two Higgs doublets and therefore predicts the existence of four physical Higgs particles: a light neutral Higgs boson with Standard Model-like couplings and a mass below 130 GeV, two additional neutral Higgs

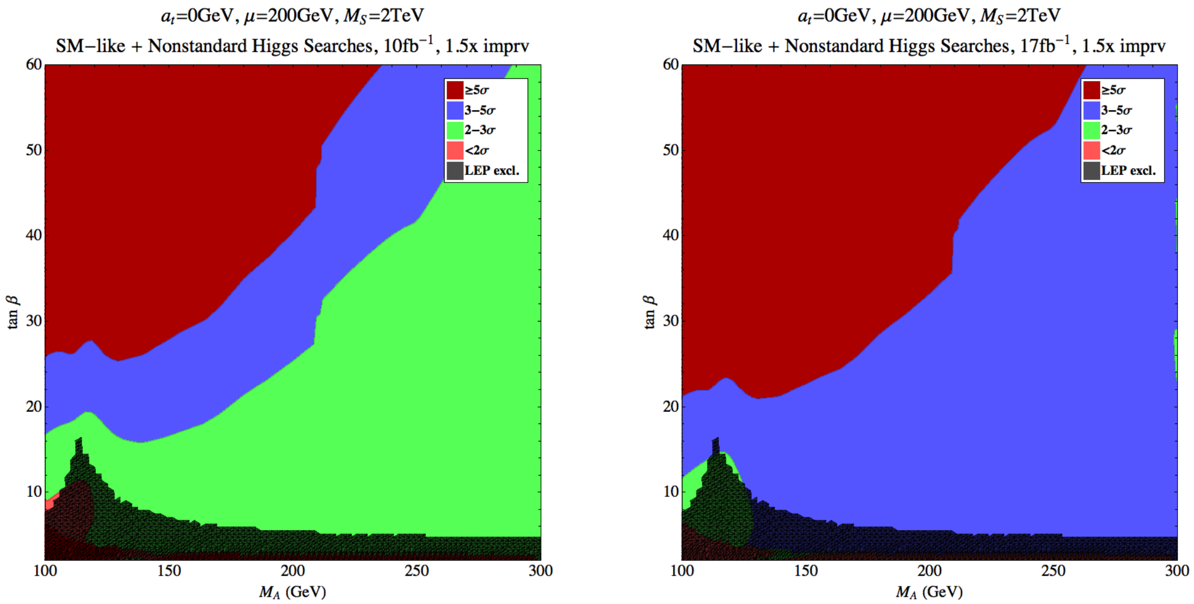

Figure 3: Same as Fig. 2, but for the Minimal Mixing scenario.

bosons with suppressed couplings to gauge bosons but enhanced couplings to the down quarks and charged leptons, and a charged Higgs boson. At tree level, the masses and couplings of these particles depend only on the CP-odd Higgs mass M_A and on $\tan\beta$, the ratio of the vacuum expectation values of the neutral components of the two Higgs doublet fields. Through radiative corrections, some of the masses and couplings can be strongly influenced by other parameters of the MSSM, but benchmark values for these parameters may be used to obtain generic and quantitatively precise projections for the Tevatron sensitivity.

Based on Ref. [4], Fig. 2 demonstrates the projected Tevatron reach with 10 fb^{-1} and 17 fb^{-1} of integrated luminosity for the Maximal Mixing benchmark scenario. In these plots the Tevatron sensitivity to the four Higgs mass eigenstates is combined statistically, including all relevant search channels from both CDF and DZero, at each point on the (M_A, $\tan\beta$) plane.

The parameters of Maximal Mixing [5] are chosen so that on most of the plane the SM-like Higgs mass is in the range of 125 – 130 GeV, saturating the MSSM upper bound on this mass as a function M_A and $\tan\beta$. The nonstandard CP-even Higgs mass and the charged Higgs mass are less sensitive to radiative corrections and both are close to M_A. Fig. 2 shows that while for 10 fb^{-1} there will be significant regions of supersymmetric parameter space that remain uncovered by the Tevatron, for 17 fb^{-1} the Tevatron will have the power to probe the whole (M_A, $\tan\beta$) plane at a level greater than 2σ. For large M_A, the sensitivity is coming primarily from the search for the SM-like Higgs in Wh associated production with $h \to b\bar{b}$. For lower M_A and $\tan\beta > 10$ the search for the nonstandard Higgs states provides a complementary way of probing the supersymmetric Higgs sector. These states are mainly produced in association with bottom quarks, or via the gluon fusion process, and are sought at the Tevatron through their primary decay channels into bottom quarks or tau leptons. Both production mechanisms have cross sections which grow with $\tan^2\beta$. Therefore, for a wide range of M_A and sizeable $\tan\beta$, the projected sensitivity is $\geq 3\sigma$ evidence (diagonal blue band), receiving approximately equal contributions from searches for the nonstandard states and for the SM-like Higgs. For low M_A and large $\tan\beta$ the production of the nonstandard states is strongly enhanced and dominates the sensitivity, providing 5σ significance (red) on a large fraction of the plane. In this region the search for the charged Higgs boson in top quark decays also begins to contribute.

For the Minimal Mixing scenario, the parameters are instead chosen to reduce the radiative corrections to SM-like Higgs mass. The low-scale parameters taken in this scenario arise quite naturally from well-motivated models of supersymmetry breaking such as gauge mediation, and they lead to a light SM-like Higgs mass just above bounds set by LEP. Fig. 3 shows that while for 10 fb^{-1} the Tevatron will be able to probe the whole parameter space at the 2σ level, with 17 fb^{-1} the Tevatron can provide 3σ evidence for the SM-like Higgs in this scenario on essentially the entire plane. As in Maximal Mixing the nonstandard Higgs searches become powerful for low M_A and large $\tan\beta$ and again yield 5σ sensitivity.

Other benchmark scenarios for the MSSM indicate similar Tevatron sensitivities after Run III, with exclusion power over nearly all parameter ranges and large regions with the potential for 3σ evidence for the SM-like Higgs at 17 fb^{-1}. The combination of nonstandard and standard Higgs search channels remains an important tool to probe all possible regions of parameter space, including those associated with CP-violating soft supersymmetry breaking parameters [6, 7]. It is also important to mention that the Tevatron reach for the SM-like Higgs in gluon fusion production with subsequent decay into W boson pairs has the potential to probe supersymmetric scenarios beyond the MSSM in which the SM-like Higgs is heavier than 130 GeV, or whenever the SM-like Higgs coupling to bottom pairs is suppressed [8, 4].

4.3 BSM Physics

Whether or not the SM Higgs boson exists, electroweak symmetry breaking may be a harbinger of some new dynamics. Are there hints for possible new "Beyond Standard Model" (BSM) physics? We note a few of them here:

- Very recently DZero has shown 3.2σ evidence for a like-sign di-muon charge asymmetry in 6.1 fb^{-1} of analyzed data. This is ascribed to CP-violation in the B-meson system. As such, this represents an anomalously large signal, some $\sim 50\times$ in excess of the Standard Model expectations [11]. Flavor physics has placed strong constraints on possible new physics that one can realistically expect to find below the ~ 5 TeV scale. One of the few hints of deviation today is the anomaly in the phase of B_s mixing and comes from the Tevatron itself [12, 14]. Another hint comes from the forward-backward distributions of rare FCNC B modes from the B factories, recently confirmed at the Tevatron [13, 14] Extending the Tevatron program will lead to a definite conclusion on the question of the existence of BSM effects in those channels.

- The DZero search for a "$t\bar{t}$ resonance" with 3.6 fb^{-1} of data [9] includes 17 events in the 800 - 1000 GeV range, with a background of approximately 6.4 events. CDF has performed this search in datasets ranging from 0.7 to 2.8 fb^{-1} with different techniques in both the lepton+jets and all–jets channel. CDF overall observes a smaller excess of events. Extra events on the tail of the M_{tt} distribution can arise from a massive color-octet boson that decays into a pair of new vector-like quarks as expected in many dynamical models (*e.g.*, see [15]). Due to its discovery potential this search is certainly one that ought to be performed with as much luminosity as possible.

- The forward-backward asymmetry of top quark pairs measured at CDF [16] with 3.2 fb^{-1} of data is 2.3σ above the SM prediction. This can be interpreted as new dynamics, *e.g.*, an axigluon [17].

- The $W + b$-jets cross section times branching fraction measured recently at CDF[19] is $2.74 \pm 0.27(stat.) \pm 0.42(syst.)$ pb, whereas the SM prediction [20] is 1.22 ± 0.14 pb. This is a 2.9σ excess.

- BSM physics may appear in charm physics, a unique way to probe up-quark related anomalies. The source of the observed large charm mixing is still not clarified, and the possibility of anomalous CP violation is very attractive. The world's largest and cleanest charm samples are collected at the Tevatron (this is CDF only, due to the impact-parameter trigger). The Tevatron is going to provide the worlds' most precise

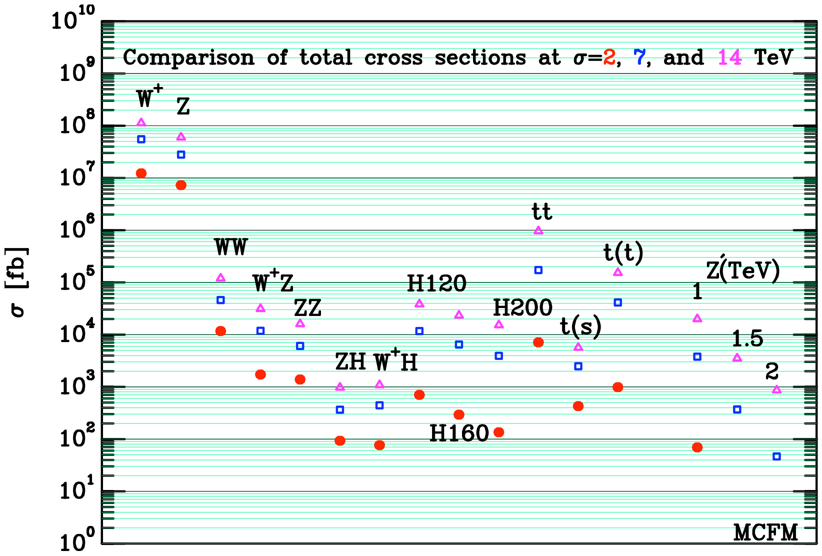

Figure 4: Comparison of total cross section comparison between Tevatron and LHC.

measurements of charm mixing parameters and could discover CP violation in charm, which will be an unambiguous signature of new physics, or exclude it down to the SM expectation. This program is without competition until well into the superB era, as LHCb does not allow precision measurements of CPV in the most promising channels.

Therefore, several deviations from the Standard Model have shown up in the DZero and CDF data. Although it is too early to tell whether they are due to statistical fluctuations or new physics, exploring these and many other conventional channels, particularly in the electroweak domain, constitutes a diverse and rich physics program.

4.4 Complementarity with Other Facilities

The LHC is the only accelerator that has a similar physics program to the Tevatron. With the recent update of the LHC plans, we expect ~ 1 fb^{-1} of integrated luminosity at 7 TeV center of mass energy collected by each LHC experiment by the end of 2011, followed by a twelve to eighteen month shutdown. This means that up to late 2013 and into 2014, when the LHC will have been re-commissioned, the Tevatron will have comparable data sets for important processes such as top quark, W and Z boson production, and others.

In some physics areas, for example top pair production, proton-antiproton collisions provide unique information not accessible to the proton-proton collisions at the LHC. Specialized detectors, like LHCb, are expected to perform better in studies of b quarks,

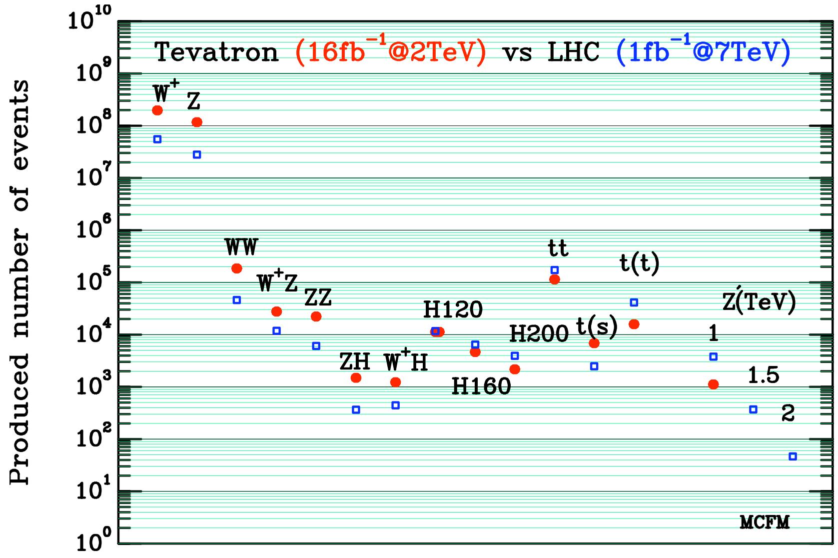

Figure 5: Comparison of Tevatron Run III and LHC at 1 fb^{-1} and 7 TeV in the cms.

and ATLAS/CMS will push heavy particle searches beyond 1 TeV due to the higher center of mass energy of the LHC.

As for the Higgs boson at the LHC operating at 14 TeV, based on the current LHC projection is, 2σ exclusion of the full mass range down to $M_h \approx 115$ GeV requires 1.5 fb^{-1} per experiment. Discovery of the Higgs for $M_h \approx 115$ GeV requires ~ 10 fb^{-1} per experiment at 14 TeV [21]. At 14 TeV the Higgs reach is dominated by the decay into $\gamma\gamma$. Detailed predictions are not yet available for 7 TeV, but the Higgs production gluon fusion cross section is 3.5 times smaller at 7 TeV than at 14 TeV. The Tevatron, however, will remain the only facility to have a chance to see the Standard Model Higgs through about 2014. In addition, as noted in the text, discovery of the $h \to b\bar{b}$ mode at the LHC will require 30 fb^{-1}. Hence the Tevatron results in this channel will be unchallenged until the end of 2015.

Selecting these most exciting areas of studies, the Tevatron program will continue to be competitive on the forefront of physics research well beyond 2011.

5 Conclusions

The Tevatron program is still operating at the pinnacle of its performance. The accelerator is delivering luminosity at record levels and the experiment collaborations continue to make good use of the data – publishing in excess of 100 papers/year and training many new PhD students. Based on the results of the January 2010 "Chamonix Meeting" which outlined the run plan for the LHC over the coming few years, the Tevatron will remain competitive through 2014 over a broad range of physics topics and offers the only opportunity to make any statement on low mass SM Higgs in the coming years. With 16 fb^{-1} analyzable integrated luminosity per experiment, the Tevatron can achieve at least 3 σ in Standard Model Higgs sensitivity across the entire interesting mass region.

We, as a community, should continue to pursue the Tevatron program until it is surpassed by the LHC. The Tevatron has the potential to address the most important and fundamental questions facing the science of elementary particle physics today.

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