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Proposal for Running the Tevatron Collider in 2012-2014

Executive Summary

Prepared by
Dmitri Denisov, Giovanni Punzi,
Stefan Söldner-Rembold, Robert Roser

On behalf of the CDF and DZero Collaborations

We propose a Tevatron program based on extension of the Tevatron collider operations for three years from the beginning of FY 2012 through FY 2014. This additional running offers a unique opportunity of a profound discovery unraveling the mystery of electroweak symmetry breaking and observing evidence for the Standard Model Higgs boson.

In addition to potential of providing at least a 3σ evidence for the Higgs boson in the full allowed mass range the outcome of the proposed run extension will be to: (1) more than double the currently existing data sets of both collaborations up to a total luminosity of 16 fb^{-1}; (2) increase the discovery potential of the Tevatron for a wide variety of physics analyses which will benefit from the additional statistics (3) provide continued training of young scientists at the premier Department of Energy research facility.

Overview

The most important issue facing modern High Energy Physics is the origin of electroweak symmetry breaking and 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 super-symmetric, 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 the mass range 114 GeV < M_H < 145 GeV at 95% C.L.

We are only 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.

The Tevatron collider has provided about 8 fb^{-1} per experiment of analyzable data to date, and is running extremely well. The Tevatron experiments are just now reaching the threshold of sensitivity to electroweak symmetry breaking effects. The low mass qq -> W/Z + (H -> bb) sensitivity is such that it is finally beginning to experimentally probe the Standard Model predictions for the Higgs boson. There is also an assortment of tantalizing excesses seen in various other search channels. These may be the first hints of new physics, expected to be revealed at the electroweak scale. The next few year’s present opportunities for the Fermilab Tevatron to continue providing physics results at the frontier of knowledge, from its systematic multichannel program addressing the search for the Higgs as well as a variety of searches and other precision measurements in the Standard Model.

The LHC is not expected to replace the Tevatron in key electroweak modes, such as the low mass Higgs search, for several years in the future. From the literature and conference proceedings, the fundamental H $\rightarrow$ bb 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 transverse energy jets, expected no sooner than with an integrated LHC luminosity of order 30 fb^{-1}. The bb decay channel is crucial to our understanding of the nature of a possible Higgs-like signal to be discovered. Without a direct observation of the most abundant Higgs decay mode, it is not possible to reach a definite conclusion about the Higgs mechanism of electroweak symmetry breaking. It must be noted that the H $\rightarrow$ bb decay is the least likely to be suppressed in presence of new physics beyond the Standard Model. The Tevatron appears to be the only way to investigate this in the foreseeable future. A 3σ 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. From this perspective, the Tevatron will remain preeminent for at least three years beyond the current intended end of operation in 2011.

Tevatron Luminosity Projections

The Tevatron Collider is currently operating at its peak performance:

- The average yearly integrated luminosity reaches 2.5 fb^{-1}
- The average weekly integrated luminosity exceeds 50 pb^{-1}
- The average peak luminosity is over $300x10^{30}$ $cm^{-2}sec^{-1}$
- The Tevatron spends on average over 130 hours per week in colliding stores

Assuming no major upgrades and rate of delivering luminosity similar to the last year, including periodic maintenance shutdowns, the Tevatron is expected to deliver to both experiments up to 19 fb^{-1} by the end of 2014. Assuming similar data taking efficiency as over last few years CDF and DZero collaborations expect to collect 16 fb^{-1} of analyzable luminosity for complex analyses such as Higgs boson searches by the end of 2014.

Standard Model Higgs Boson Searches

The Tevatron has already achieved the milestone of excluding a region of Higgs masses above the LEP limits using 6 fb^{-1} of data as shown in Figure 1. At present the excluded range is 158 – 175 GeV at 95% C.L., which is in the high mass range where gluon fusion production and the $H \rightarrow WW$ decay is the dominant search channel. This important accomplishment is the result of several factors: the availability of a large data sample, excellent detectors performance, refined understanding of calibrations, and advanced analysis techniques that have been sharpened by years of accumulated experience. From this point, the high mass exclusion region is expected to grow rapidly.

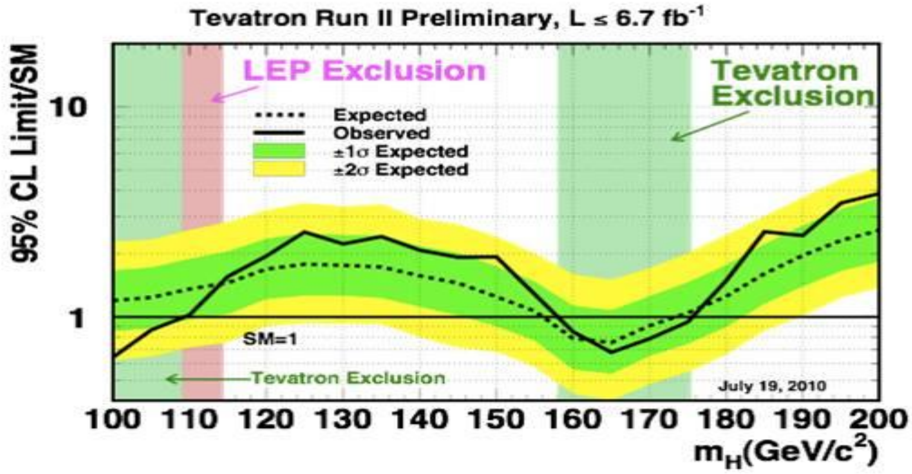

Figure 1. Tevatron Higgs search results as presented at ICHEP 2010.

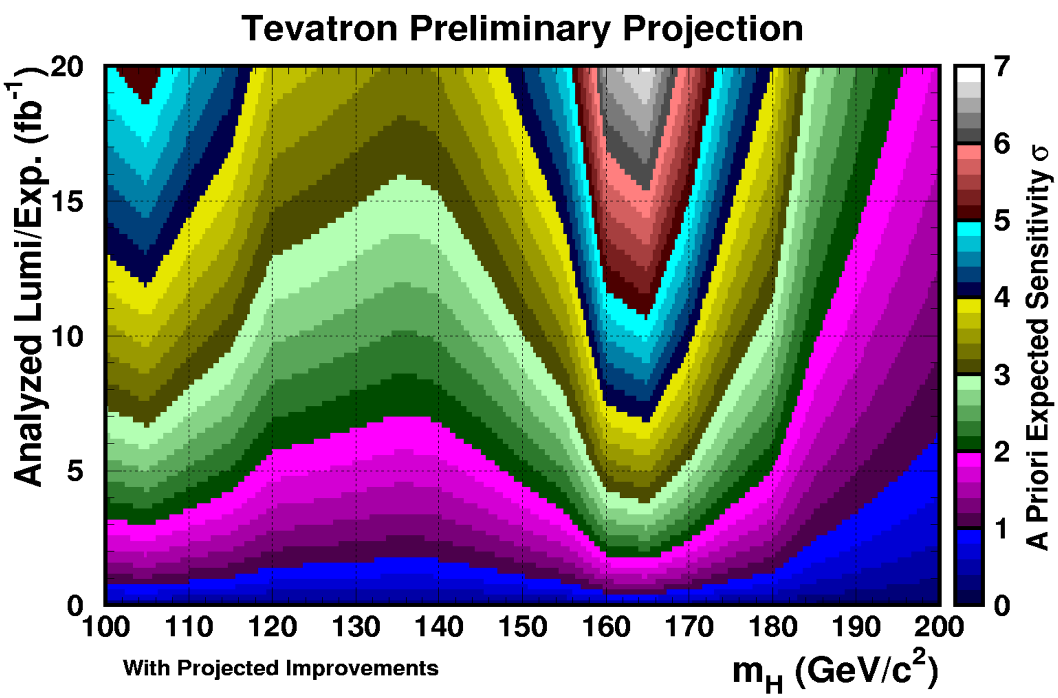

Figure 2. Tevatron Higgs boson sensitivity projection.

The lower range of the Higgs boson mass of 115-145 GeV is the region favored by the global Standard Model fits. The low mass range will have to be explored fully to understand the mechanism of electroweak symmetry breaking since that's where the Higgs boson is expected to be. As shown in Figure 2, with 16 fb^{-1}, the Tevatron will provide the sensitivity to detect a low-mass Higgs boson at the 3σ level or better across the full mass region below 185 GeV. This is a capability complementary to the power of the LHC at higher masses. WH and ZH associate

Higgs boson production, key channels for the low mass H→ bb detection, have lower backgrounds from W+jets and top pairs production at the Tevatron due to proton-antiproton initial state and Tevatron center of mass energy. Without direct evidence of H → bb signal it is not possible to reach a definite conclusion about the electroweak symmetry breaking mechanism. Extension of the Tevatron run is the only way to achieve this over the next few years.

Importance of Additional Luminosity

Searches similar to the low mass Higgs boson require a certain amount of integrated luminosity before the sensitivity to the expected signal is reached. Figure 3 illustrates the threshold luminosity effect for a low mass (115 to 135 GeV) Higgs boson searches. Plotted as a function of integrated luminosity is the fraction of the Higgs mass region where Tevatron will have sensitivity above 3σ. This information is extracted from Figure 1. Once base amount of 8 fb^{-1} is accumulated the progress is becoming fast. Running the Tevatron for three additional years provides an opportunity to achieve above 3σ sensitivity in all allowed by Standard Model mass range.

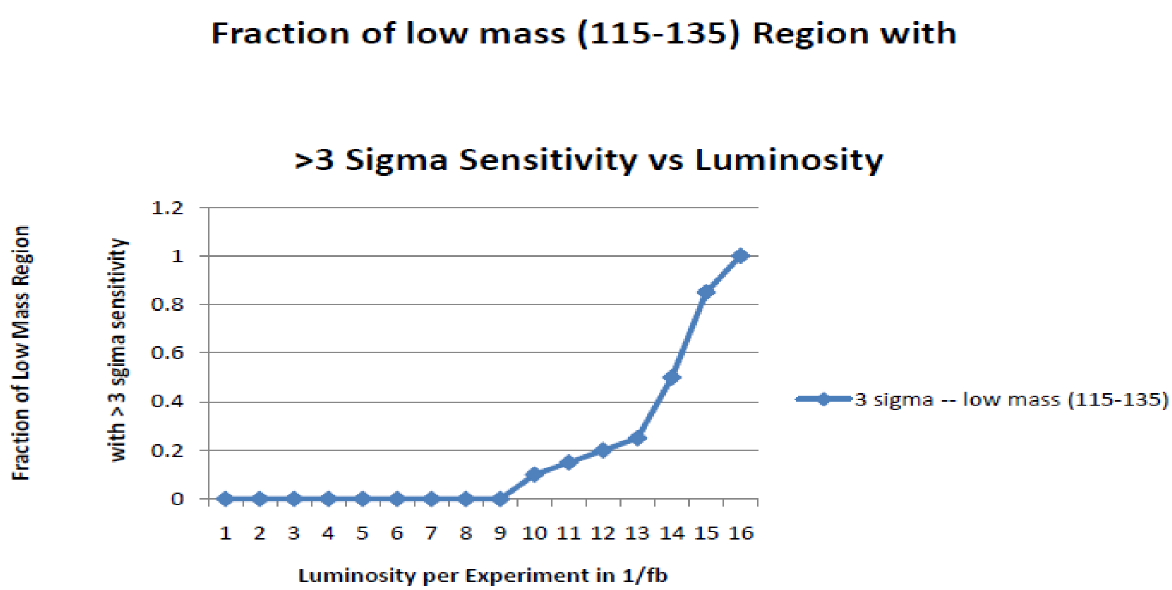

Figure 3. The fraction of the Higgs mass region (115→135 GeV) with at least 3σ sensitivity vs. luminosity/experiment.

A Rich and Complementary Physics Program Beyond Standard Model Higgs Boson Searches

The Tevatron produces a continuous flow of physics results, publishing ~2 innovative papers every week in the most prestigious physics journals, and most of them are not about the Higgs boson. While the understanding of the electroweak symmetry breaking is the single most important result that can be pointed out as the goal for the Tevatron run extension, there is a tremendous potential for other physics results with major impact on the field. It is impossible in a short summary to detail full physics potential, so we review some of the planned research directions.

- **Measurements that get a special advantage from the p-pbar environment.** The primary example in this category is CP-violation, which strongly limits the range of allowed models of new physics up to scales of several TeV. There are good a priori reasons to expect the existence of some non-SM CP-violating processes, and finding them is of comparable importance to addressing electroweak symmetry breaking. Precision measurements at the 1% level or better are accessible at the Tevatron due to the CP-symmetric initial state (p-pbar), and symmetry of the detectors that allow cancellation of systematics. Some of these measurements already show tantalizing effects, like the recently published di-muon asymmetry result from the DZero experiment, showing the first indication of a deviation from the Standard Model picture of CP-violation. Other measurements are exploring a completely new field, as the recent CPV-measurement with the D^0 mesons at CDF, yielding a substantial improvement in precision with respect to previous B-factories data. This has provided a proof of feasibility of an exciting program of precision measurement with a unique possibility to find anomalous interactions in up-type quarks. A non CP-related example in this category is the forward-backward asymmetry in top quark production. Current measurements by both CDF and DZero indicate an asymmetry above the Standard Model prediction. If this persists with more data, it can be interpreted as new dynamics. This is not an easy measurement to replicate in a proton-proton environment.

- **Searches for Higgs boson in super-symmetric extensions of the Standard Model.** The Tevatron can also probe some well-motivated, super-symmetric extensions of the Standard Model, that predict the existence of a light Higgs with Standard Model-like properties and a mass below 130 GeV. This includes non-standard Higgs bosons with enhanced couplings to the down quarks and charged leptons, as well as charged Higgs boson. The precise properties of these Higgs bosons depend on several parameters, but considering the combined projections for Higgs boson searches at CDF and DZero with 10 fb^{-1} the Tevatron can probe the MSSM Higgs sector. Increasing the integrated luminosity to 16 fb^{-1} can lead to evidence for the SM-like Higgs boson in all allowed mass range. The combination of non-standard and Standard Model Higgs boson search channels become very important to probe all possible regions of parameter space, including those associated with CP-violating soft super-symmetry breaking parameters. At luminosities higher than 10 fb^{-1} the Tevatron searches become complementary to a 7 TeV LHC, at LHC luminosities of a few fb^{-1}. The Tevatron searches will cover regions of parameter space that are difficult to probe at the LHC.

• **Precision measurements that took many years to perfect, and can be further improved ("legacy measurements").** Examples are the top quark mass and the W boson mass. Both are fundamental parameters of the Standard Model and crucial inputs to the electroweak fits. It is important to know them with high precision and these measurements will be improved with additional data. They are not only important quantities in their own right, together they can be used to indirectly constrain the SM Higgs mass.

• **Measurements close to an important boundary for new physics.** There is a wide list of examples in this category, some of which are close to sweeping up a significant region of new theoretical models parameter space, or already show some excesses. The addition of the extended run data has a potential to either unveil a discovery or significantly constraint the new physics and exclude large class of theoretical models. Although several of these measurements will be also within the LHC reach, in most cases the Tevatron contribution will be important and considering the importance of the topics, the Tevatron will play critical role in establishing discoveries on a firm basis. Some notable examples are: B_s oscillations mixing phase, FCNC decays, 4th generation quarks searches, effective mass of pairs of top quarks, and charm mixing.

• **Measurements of the Standard Model processes providing precious comparisons points/background estimation for the LHC measurements.** Measurements at the Tevatron will provide critical information, such as PDF sets, analysis methods, understanding of background processes and many others for the success of the LHC physics program.

Status of Detectors and Collaborations

Both collaborations underwent organized by Fermilab tracking systems review in the Summer of 2010 to assess whether the detectors are robust and capable of operating efficiently for three additional years of running. The external committee evaluated the performance of the trackers vs. integrated luminosity and found methodology used for aging estimates by CDF and DZero sound. Based on the hardware degradation resulting from radiation damage, the experiments then estimated the impact on b-tagging of jets, isolated lepton efficiencies, and ultimately on Higgs boson acceptance. The conclusion of these studies, presented in details at the Fermilab PAC meeting in August 2010, is that the detectors will perform well through 2014 and while they will experience some degradation the ultimate impact on Higgs boson acceptance is minimal.

As part of preparations for the August 2010 PAC meeting, each collaboration performed a survey of its institutions to understand whether sufficient human resources exist in order to execute ambitious physics program in the 2012-2014 period. The conclusion from these surveys is that both collaborations have resources in order to collect and process the data, perform the Higgs boson searches as well as resources to carry out large number of exciting physics analyses described earlier in this document.

Conclusions

The Tevatron program is operating at the peak of its performance. The accelerator is delivering luminosity at record levels and the collaborations continue to make good use of the data – publishing in excess of 100 papers/year and training excellent young scientists with 60 PhD thesis defended over last year alone. The Tevatron will remain competitive through 2014 over a broad range of physics topics and offers the opportunity to make significant statement on the Higgs boson searches in the coming few years. With 16 fb^{-1} of integrated luminosity per experiment, the Tevatron can achieve at least 3σ Higgs boson sensitivity across the entire allowed mass region in the most abundant $H \rightarrow bb$ decay mode. The Tevatron program has the potential to address the most important and fundamental questions facing the science of elementary particle physics today and we, as a community, should continue to pursue it.