

**Fermi National Accelerator Laboratory**

**FERMILAB-Conf-98/059-T**

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February 1998

Published Proceedings of the *4th International Conference on Physics Potential and Development of Muon Colliders*, San Francisco, California, December 10-12, 1997

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

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# The Top Quark and Higgs Boson at Hadron Colliders

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**Abstract.** To provide context for discussions of experiments at future muon colliders, I survey what is known and what will be known about the top quark and the Higgs boson from experiments at hadron colliders.

## INTRODUCTION

When we discuss whether there should be muon colliders in our future, we must answer a number of important questions.

What machines are possible? When? At what cost?

What are the physics opportunities?

Can we do physics in the environment? (What does it take?)

How will these experiments add to existing knowledge *when they are done?*

The aim of this talk is to provide a survey of what we might expect to know about the top quark and the Higgs boson before a  $\mu^+\mu^-$  collider operates [1].

## THE HADRON COLLIDERS

Let us take a moment to recall the characteristics of the hadron colliders that will contribute to the study of the top quark and Higgs boson. The combination of the Fermilab Tevatron and the new Main Injector with the CDF and DØ detectors will in the future bring us  $\bar{p}p$  collisions at 2 TeV. In Fermilab parlance, the data now under analysis come from Run I: 100 pb<sup>-1</sup> at 1.8 TeV, recorded in 1994–1996. We look forward to the first 2-TeV data. The approved quantum of data is Run II: 2 fb<sup>-1</sup> in 2000–2002. Beyond the approved running, we are enthusiastic about the physics prospects for another

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high-luminosity run while the Tevatron defines the energy frontier. Although the laboratory hasn't taken a position, we refer to this possibility as Run III:  $30 \text{ fb}^{-1}$  by the year 2006.

On that time scale, the Large Hadron Collider at CERN will open the study of  $pp$  collisions at 14 TeV in the ATLAS and CMS detectors. A modest goal for the beginning of the LHC era is to accumulate  $\int \mathcal{L} dt = 100 \text{ fb}^{-1}$  in 2005–2009.

Three elements inform the way we think about experiments in these high-energy hadron colliders. First, they promise high sensitivity from high integrated luminosity. Second, the success of  $b$ -tagging in the hadron-collider environment encourages the hope that heavy-flavor tags, and perhaps even triggers, can make future experiments more sensitive to the exotic events that may signal new physics. I have in mind here both the CDF Silicon Microvertex Detector (SVX), with resolution  $\sim 11 \mu\text{m}$ , and the “soft”-lepton tag used by CDF and DØ to identify the transition  $b \rightarrow c\ell\nu$ . Third, both the physics and the experimental approach to the new energy regime are colored by the great mass of the top quark.

## THE TOP QUARK

The top quark has been observed at the Tevatron in the reaction [2]

$$\bar{p}p \rightarrow t \bar{t} + \dots$$

$\left\{ \begin{array}{l} \hookrightarrow W^- \bar{b} \\ \hookrightarrow W^+ b \end{array} \right.$

In the Tevatron experiments, the  $b$ -quarks are identified as displaced vertices or through soft-lepton tags. The channels studied to date are dileptons (including  $\tau + (e, \mu)$ ), lepton + jets, and all jets.

### Top Mass

The top mass has already been determined to impressive precision. An “unofficial” average including the latest data from CDF and DØ is [3]

$$m_t = 174.3 \pm 5.3 \text{ GeV}/c^2 .$$

Within the electroweak theory, fermion masses are set by the scale of electroweak symmetry breaking  $v$  and by apparently arbitrary Yukawa couplings,

$$m_f = \frac{\zeta_f v}{\sqrt{2}} \approx (176 \text{ GeV}/c^2) \cdot \zeta_f .$$

It is striking that the top quark's Yukawa coupling  $\zeta_t \approx 1$ . Does this mean that top is special, or might top be the only “normal” fermion, with a mass close to the electroweak scale?

## Top Lifetime

The top-quark lifetime is governed by the semiweak decay  $t \rightarrow bW^+$ ; the decay width is given by [4]

$$\Gamma(t \rightarrow bW^+) = \frac{G_F m_t^3}{8\pi\sqrt{2}} |V_{tb}|^2 \left(1 - \frac{M_W^2}{m_t^2}\right)^2 \left(1 + \frac{2M_W^2}{m_t^2}\right).$$

If there are three generations of quarks, so that we can use  $3 \times 3$  unitarity to determine  $|V_{tb}| = 0.9991 \pm 0.0002 \approx 1$ , then  $\Gamma(t \rightarrow bW^+) \approx 1.55$  GeV. This corresponds to a top lifetime,

$$\tau_t \approx 0.4 \times 10^{-24} \text{ s},$$

that is very short compared with the time-scale for confinement,

$$1/\Lambda_{\text{QCD}} \approx \text{few} \times 10^{-24} \text{ s}.$$

As a consequence, the top quark decays before it can be hadronized. No discrete lines will be observed in the  $t\bar{t}$  spectrum, and there will be no dressed hadronic states containing top. This freedom from the confining effects of the strong interaction means that the characteristics of top production and the hadronic environment near top in phase space should be calculable in perturbative QCD. The fact that top is, in this sense, the purest, freest quark we have to study will have important consequences for future experiments.

## Top Production

It is useful to summarize some important characteristics of top pair production. At the Tevatron, at 1.8 TeV, the top-pair production cross section is  $\sigma \approx 6$  pb [5]. Approximately 90% arises from the reaction  $q\bar{q} \rightarrow t\bar{t}$ , and only about 10% from the reaction  $gg \rightarrow t\bar{t}$ . Top is a heavy particle for the Tevatron, and this is reflected in the dominance of  $q\bar{q}$  collisions. The measured cross sections are in reasonable accord with this estimate. CDF measures  $7.6_{-1.5}^{+1.8}$  pb [6], while DØ has determined  $5.5 \pm 1.8$  pb [7].

At the LHC, the pair-production cross section rises to  $\sigma \approx 800$  pb. The origin of the top events is markedly different. In 14-TeV  $pp$  collisions, the reaction  $q\bar{q} \rightarrow t\bar{t}$  accounts for only about 10% of the rate, whereas  $gg \rightarrow t\bar{t}$  accounts for 90%. At the LHC, top will be a moderately light particle.

## Future Top Yields

For Run II, the Tevatron energy will increase to 2 TeV. Accordingly, the top-pair production cross section will rise by about 40%. In a run of  $30 \text{ fb}^{-1}$

**TABLE 1.** Anticipated top-quark yields in future Tevatron runs

Mode	2 fb <sup>-1</sup>	30 fb <sup>-1</sup>	S/B
Dilepton	80	1200	5:1
$\ell + 3\text{jets}/1b$	1300	20000	3:1
$\ell + 4\text{jets}/2b$	600	9000	12:1
Single top (all)	170	2500	1:2.2
Single top ( $W^*$ )	20	300	1:1.3

at 2 TeV, approximately 225K  $t\bar{t}$  pairs will be produced. I show in Table 1 a *Snowmass '96* projection of the number of top events available for study in the Tevatron's Run II and Run III [8]. The LHC is a veritable fountain of tops: it will produce  $8 \times 10^6$   $t\bar{t}$  pairs in a modest-luminosity exposure of only 10 fb<sup>-1</sup>.

It seems reasonable to expect that experiments at the Tevatron and LHC will determine the top-quark mass within  $\delta m_t = (1-2)$  GeV/ $c^2$ .

## Measuring $|V_{tb}|$

By studying the number of top events in which they register 0, 1, or 2  $b$  tags, CDF measures [9] the fraction of top decays that lead to  $b$  quarks in the final state as

$$B_b \equiv \frac{\Gamma(t \rightarrow bW)}{\Gamma(t \rightarrow qW)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} = 0.99 \pm 0.29 .$$

If there are three generations, so that  $|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$ , this measurement leads to a lower bound on the strength of the  $tbW$  coupling,

$$|V_{tb}| > 0.76 \text{ (95\% CL)}.$$

Without the three-generation unitarity constraint, we learn only that

$$|V_{tb}| \gg |V_{td}|, |V_{ts}|.$$

Increased sensitivity in the forthcoming runs should lead to significant improvements in  $\delta B_b$ . For Run II, we anticipate  $\pm 10\%$ , and for Run III,  $\pm$  a few percent. At the LHC, it should be possible to reduce the uncertainty to about  $\pm 1\%$ .

Direct measurement of the coupling  $|V_{tb}|$  will become possible in single-top production through the reactions  $\bar{q}q \rightarrow W^* \rightarrow t\bar{b}$  and  $gW \rightarrow t\bar{b}$  [10]. The cross sections for both reactions are  $\propto |V_{tb}|^2$ . We can expect to measure the coupling with an uncertainty  $\delta|V_{tb}| = \pm(10\%, 5\%)$  in Run II and III, using

both the virtual- $W^*$  channel and  $gW$  fusion. I am not aware of any detailed studies for the LHC environment, but the fact that the  $gW$  fusion cross section is a hundred times larger than at the Tevatron means that there will be a very large sample of single-top events.

## Searches for new physics

Top decay is an excellent source of longitudinally polarized gauge bosons. In the decay of a massive top,  $W$ -bosons with  $|\text{helicity}| = 1$  occur with weight = 1, while longitudinally polarized  $W$ -bosons with helicity = 0 occur with weight =  $m_t^2/M_W^2$ . If the decays of top proceed by the standard  $V - A$  interaction, we therefore expect that the longitudinal fraction  $f_0 = (m_t^2/M_W^2)/(1 + m_t^2/M_W^2) \approx 70\%$ . The polarization of the  $W$ -boson is reflected in the decay angular distribution of leptons from its subsequent decay:

$$\frac{d\Gamma(W^+ \rightarrow \ell^+ \nu_\ell)}{d(\cos\theta)} = \frac{3}{8}(1 - f_0)(1 - \cos\theta)^2 + \frac{3}{4}f_0 \sin^2\theta.$$

In experiments at the Tevatron, it should be possible to determine the longitudinal fraction to  $\delta f_0 = \pm 3\%$  in Run II. The LHC experiments will improve the measurement to  $\pm 1\%$ . Departures from the canonical expectation would give a hint of unexpected structure at the  $t\bar{b}W$  vertex.

The flavor-changing-neutral-current decays

$$t \rightarrow \begin{pmatrix} g \\ Z \\ \gamma \end{pmatrix} + \begin{pmatrix} c \\ u \end{pmatrix}$$

are unobservably small ( $\ll 10^{-10}$ ) in the standard model [11], but the present indirect constraints on the  $Zt\bar{c}$  couplings would permit branching fractions as large as a few percent [12]. The ultimate sensitivity at the Tevatron might reach about 1% for these decays, while the LHC experiments could reach a level of  $\sim 10^{-4}$ .

It is possible that the rare decay  $t \rightarrow bWZ$ , with a branching fraction  $\sim 10^{-6}$  in the standard model, might be detectable at the LHC.

Because top is so massive, top decays may surprise by providing a conduit to final states that would otherwise be reached with difficulty. One of the favorite targets is the search for a charged scalar or pseudoscalar  $P^+$  in the semiweak decay  $t \rightarrow bP^+$ . Such charged scalars may occur in multi-Higgs models, supersymmetry, and technicolor. Both CDF and DØ have reported searches [13].

## Resonances in $t\bar{t}$ Production?

We have noted that the top quark decays before it can be incorporated into a color-singlet hadron. That fact does not exclude the possibility that some new object might include tops among its decay products. Because objects associated with the breaking of electroweak symmetry tend to couple to fermion mass, the discovery of top opens a new window on electroweak symmetry breaking. Indeed, top-condensate models and multiscale technicolor both imply the existence of color-octet resonances with masses of several hundred  $\text{GeV}/c^2$  that decay into  $t\bar{t}$ . In technicolor models [14], the prime candidate is a colored pseudoscalar produced in the elementary reactions

$$gg \rightarrow \eta_T \rightarrow (t\bar{t}, gg).$$

Topcolor models [15] typically include a colored vector state that would appear in the reactions

$$q\bar{q} \rightarrow V_8 \rightarrow (t\bar{t}, b\bar{b}).$$

The first hint for such objects would come from the observation of structure in the  $t\bar{t}$  invariant mass spectrum. A first look from CDF, based on a small sample, resembles the conventional spectrum.

## Top-Quark Measurements: Summary

Until the LHC operates, top-quark measurements will only be possible at the Tevatron. The LHC will, in time, be a prodigious source of tops. We expect that the top-quark mass will be determined within  $\delta m_t \approx 1\text{-}2 \text{ GeV}/c^2$  at both the Tevatron and the LHC. The production cross section should be measured to  $\pm 5\%$  at the Tevatron, and to  $\pm$  a few % at the LHC. The branching fraction  $\delta\Gamma(t \rightarrow bW)/\Gamma(t \rightarrow qW)$  will improve to  $\pm 10\%$  in Run II,  $\pm$  a few percent in Run III, and  $\pm 1\%$  at the LHC. Studies of single-top production should yield  $\delta|V_{tb}| \approx \pm 10\%$  in Run II, and  $\pm 5\%$  in Run III at the Tevatron. In the current Tevatron experiments, searches are under way for  $t\bar{t}$  resonances, rare decays, and other signs of new physics.

## THE HIGGS BOSON

The central challenge in particle physics is to explore the 1-TeV scale and elucidate the nature of electroweak symmetry breaking. A key element in this quest is the search for the Higgs boson, the agent of electroweak symmetry breaking in the standard electroweak theory. The unique opportunity offered by a muon collider to construct a ‘‘Higgs factory’’ using the formation reaction  $\mu^+\mu^- \rightarrow H$  calls attention to a not-too-heavy Higgs boson, as favored in supersymmetric models. In such models, it is plausible that the mass of the



lightest Higgs boson—which has much in common with the standard-model Higgs boson—is no more than  $\sim 130 \text{ GeV}/c^2$ . It is important to bear in mind that a heavy Higgs boson remains a logical possibility, as we shall see momentarily. I will abbreviate to the search for the standard-model Higgs boson in what follows.

## Constraints on the Higgs Mass

One of the shortcomings of the electroweak theory is that it fails to make a prediction for the mass of the Higgs boson. Perhaps the most general statement that can be made is the upper bound derived [16] from the requirement of perturbative unitarity,

$$M_H \lesssim \left( \frac{8\pi\sqrt{2}}{3G_F} \right)^{1/2} \approx 1 \text{ TeV}/c^2 .$$

This condition is the most straightforward way to expose the importance of the 1-TeV scale.

We can obtain sharper constraints, in the form of upper and lower bounds, at the price of assuming that no new physics intervenes up to a cutoff scale  $\Lambda$ . The so-called “triviality” bound says that, for a given value of  $M_H$ , the electroweak theory makes sense up to a scale [17]

$$\Lambda < M_H \exp \left( \frac{4\pi^2 v^2}{3M_H^2} \right) .$$

Read the other way, if we regard the electroweak theory as an effective theory, apt up to some scale  $\Lambda$ , the triviality bound gives an upper limit on  $M_H$ . If, for example, we demand that the electroweak theory apply up to the Planck scale, the Higgs-boson mass must not exceed  $175 \text{ GeV}/c^2$ .

The requirement that the electroweak vacuum correspond to an absolute minimum of the Higgs potential in the face of quantum corrections leads to a lower bound,

$$M_H^2 > \frac{3G_F\sqrt{2}}{16\pi^2} (2M_W^4 + M_Z^4 - 4m_t^4) \dots ,$$

that also depends on the scale of new physics [18]. If we exclude any new physics up to the Planck scale, then  $M_H \gtrsim 130 \text{ GeV}/c^2$ .

These are informative constraints—given the assumptions that lead to them—but they do not really narrow the search. Crucial guidance comes from the direct searches for the standard-model Higgs boson, specifically from the study of the reaction  $e^+e^- \rightarrow HZ$  at  $161 + 172 + 183 \text{ GeV}$  in experiments at LEP2. The four LEP experiments examine the  $qqbb, \nu\nu qq, \tau\tau qq$ , and  $(ee + \mu\mu)qq$  channels. Recent running at  $\sqrt{s} = 183 \text{ GeV}$  is sensitive to Higgs-boson masses up to about  $82 \text{ GeV}/c^2$ . Next year’s running at  $192 \text{ GeV}$  should allow a search up to  $M_H \approx 96 \text{ GeV}/c^2$ .

## Clues about $M_H$

Precision electroweak measurements are sensitive to the Higgs-boson mass through radiative corrections. The constraints that arise on  $M_H$  depend on the selection and weighting of the data set and on assumptions made about the light-quark contribution to the vacuum polarization for  $\alpha(M_Z)$ . I quote three recent analyses by Erler and Langacker [19] to illustrate the range of possibilities.

Including all the precision electroweak data at face value and using a selection of measured cross sections for  $e^+e^- \rightarrow$  light hadrons to determine  $\alpha(M_Z)$ , their best fit for the Higgs-boson mass is  $M_H = 69_{-43}^{+85}$  GeV/ $c^2$ , which corresponds to the bounds

$$M_H < \left\{ \begin{array}{c} 236 \\ 287 \\ 413 \end{array} \right\} \text{ GeV}/c^2 \text{ at } \left\{ \begin{array}{c} 90\% \\ 95\% \\ 99\% \end{array} \right\} \text{ CL.}$$

The central value lies in the range already excluded by direct searches for the standard-model Higgs boson. Using instead perturbative QCD to compute  $\delta\alpha_{\text{had}}^{(5)}$ , they find a best fit of  $M_H = 97_{-48}^{+79}$  GeV/ $c^2$ , which implies the bounds

$$M_H < \left\{ \begin{array}{c} 229 \\ 273 \\ 377 \end{array} \right\} \text{ GeV}/c^2 \text{ at } \left\{ \begin{array}{c} 90\% \\ 95\% \\ 99\% \end{array} \right\} \text{ CL.}$$

In spite of the shift of the central value, the upper bounds are relatively stable against the change in  $\alpha(M_Z)$ .

However, we may notice that the implications of individual precision measurements are not entirely consistent. For example, SLD's measurement of  $A_{\text{LR}}$  favors very low—unphysically low—values of  $M_H$ . Having no basis to exclude any measurements, one can follow the Particle Data Group prescription and rescale the weights of all the inconsistent measurements. Using measured cross sections for  $e^+e^- \rightarrow$  light hadrons to determine  $\alpha(M_Z)$ , Erler and Langacker then find  $M_H = 122_{-77}^{+134}$  GeV/ $c^2$ , which leads to the noticeably different bounds

$$M_H < \left\{ \begin{array}{c} 329 \\ 408 \\ 613 \end{array} \right\} \text{ GeV}/c^2 \text{ at } \left\{ \begin{array}{c} 90\% \\ 95\% \\ 99\% \end{array} \right\} \text{ CL.}$$

I have reviewed this work at some length to show the fragility of our current estimates of the Higgs-boson mass. I will nevertheless focus on the case of a light Higgs boson, because only a light Higgs boson will be accessible at the Tevatron.

The branching fractions of a light Higgs boson are shown in Figure 1. The most promising channel for searches at the Tevatron will be the  $b\bar{b}$  mode, for which the branching fraction exceeds about 50% throughout the region preferred by supersymmetry and the precision electroweak data.

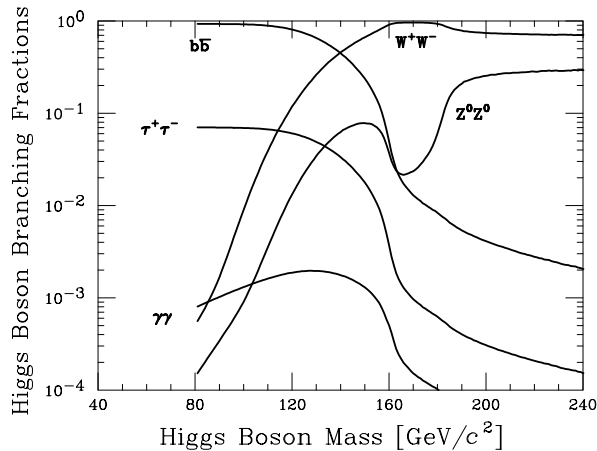


FIGURE 1. Branching fractions of a light Higgs boson.

## Tevatron Search Strategies

At the Tevatron, the direct production of a light Higgs boson in gluon-gluon fusion  $gg \rightarrow H \rightarrow b\bar{b}$  is swamped by the ordinary QCD production of  $b\bar{b}$  pairs. Even with an integrated luminosity of  $30 \text{ fb}^{-1}$ , the experiments anticipate only  $< 1\text{-}\sigma$  excess, with plausible invariant-mass resolution. It will be possible to calibrate the  $b\bar{b}$  mass resolution over the region of the Higgs search in Run II: the electroweak production of  $Z^0 \rightarrow b\bar{b}$  should stand well above background and be observable in Run II.

The high background in the  $b\bar{b}$  channel means that special topologies must be employed to improve the ratio of signal to background and the significance of an observation. The high luminosities that can be contemplated for a future run argue that the associated-production reactions

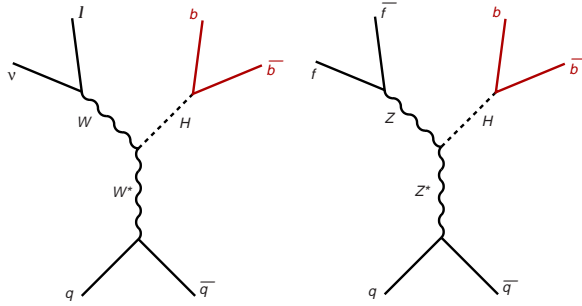
$$\begin{array}{l} \bar{p}p \rightarrow HW + \text{anything} \\ \quad \quad \quad \swarrow \searrow \\ \quad \quad \quad \ell\nu \\ \quad \quad \quad b\bar{b} \end{array}$$

and

$$\begin{array}{l} \bar{p}p \rightarrow HZ + \text{anything} \\ \quad \quad \quad \swarrow \searrow \\ \quad \quad \quad \ell^+\ell^- + \nu\bar{\nu} \\ \quad \quad \quad b\bar{b} \end{array}$$

are plausible candidates for a Higgs discovery at the Tevatron [20]. The Feynman diagrams for these processes are shown in Figure 2.

The prospects for exploiting these topologies were explored in detail in connection with the TeV2000 and TeV33 study groups at Fermilab [21]. Taking into account what is known, and what might conservatively be expected,



**FIGURE 2.** Feynman diagrams for the associated production of a Higgs boson and an electroweak gauge boson.

about sensitivity, mass resolutions, and background rejection, these investigations show that it is unlikely that a standard-model Higgs boson could be observed in Tevatron Run II. (Note, however, that the ability to use  $W \rightarrow q\bar{q}$  decays would markedly increase the sensitivity.) The expected number of signal and background events in Run II are collected in Table 2. The prospects are much brighter for Run III. Indeed, the sensitivity to a light Higgs boson is what motivates the integrated luminosity of  $30 \text{ fb}^{-1}$  specified for Run III. The number of events projected for Run III, collected in Table 3, show that a Tevatron experiment could explore the range of Higgs-boson masses up to about  $125 \text{ GeV}/c^2$ , covering the entire range favored by light-scale supersymmetry.

We can make this result a little more transparent by plotting, in Figure 3, the luminosity needed for a three- or five-standard-deviation observation of the Higgs boson at the Tevatron. We see that, in the  $WH$  modes discussed, an integrated luminosity of  $2 \text{ fb}^{-1}$  is insufficient to detect the standard-model Higgs boson at an interesting mass. About  $10 \text{ fb}^{-1}$  would permit the observation of a Higgs boson discovered at LEP2, while  $30 \text{ fb}^{-1}$  would make it possible to explore masses up to about  $125 \text{ GeV}/c^2$ . With about  $10 \text{ fb}^{-1}$ , one could expect a  $3\text{-}\sigma$  indication for the Higgs boson throughout the low-mass

**TABLE 2.** Number of signal and background events in Run II ( $2 \text{ fb}^{-1}$ ) for  $WH$  and  $ZH$  processes, and signal significance [22].

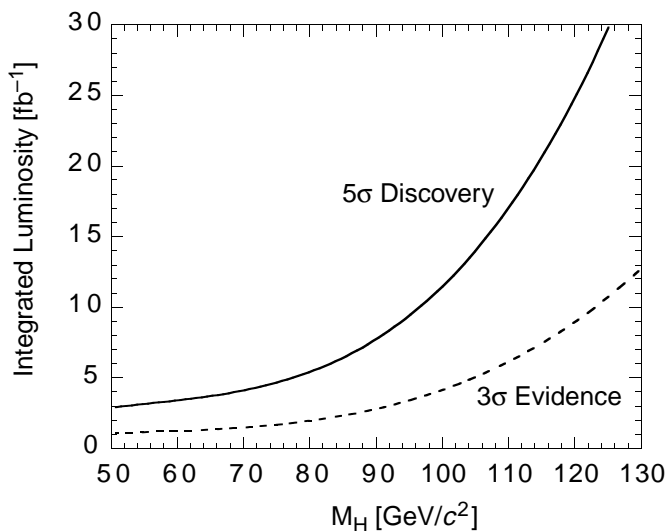
$M_H[\text{GeV}/c^2]$	60	80	90	100	110	120
$WH$ signal $S$	45	28		15		8
Background $B$	139	84		53		30
$S/\sqrt{B}$	3.8	3.1		2.1		1.4
$ZH$ signal $S$			7	6	5	3
Background $B$			36	33	31	25
$S/\sqrt{B}$			1.2	1.1	1.0	0.7

**TABLE 3.** Number of signal and background events in Run III ( $30 \text{ fb}^{-1}$ ) for  $WH$  and  $ZH$  processes, and signal significance [22].

$M_H[\text{GeV}/c^2]$	60	80	90	100	110	120
$WH$ signal $S$	681	420		228		117
Background $B$	2085	1260		789		456
$S/B$	0.33	0.33		0.29		0.26
$S/\sqrt{B}$	14.9	11.8		8.1		5.5
$ZH$ signal $S$			108	92	82	51
Background $B$			533	495	462	378
$S/B$			0.20	0.19	0.18	0.13
$S/\sqrt{B}$			4.7	4.1	3.8	2.6

régime.

A slightly different cut on the same information is provided in Figure 4. There I show the significance of observations in the  $WH$  and  $ZH$  channels for runs of 2 and  $30 \text{ fb}^{-1}$ . While the  $ZH$  channel probably would not suffice for an independent discovery, it could provide good supporting evidence—and complementary measurements—to an observation in  $WH$ .



**FIGURE 3.** Luminosity required for the observation of a Higgs boson in  $WH$  associated production at the Tevatron.

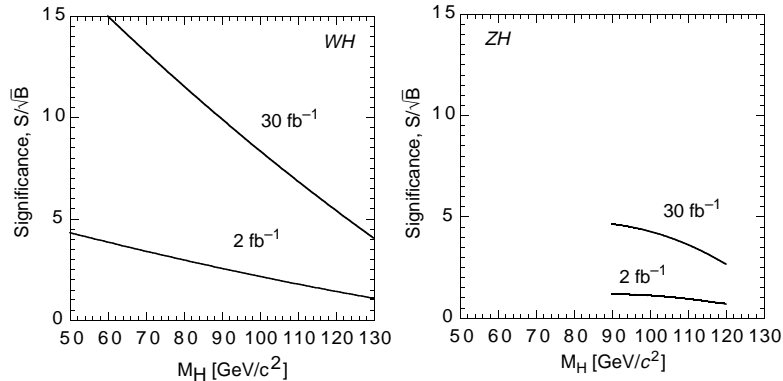


FIGURE 4. Significance of Higgs observation in Tevatron Run II & Run III.

## Higgs at the Tevatron: Summary

If the Higgs boson is discovered at LEP2, then it should be observed at the Tevatron in  $WH$  with  $\int \mathcal{L} dt \lesssim 10 \text{ fb}^{-1}$ . If the Higgs boson lies beyond the reach of LEP2,  $M_H \gtrsim (95-100) \text{ GeV}/c^2$ , then a  $5\text{-}\sigma$  discovery will be possible in the  $WH$  channel in a future Run III of the Tevatron ( $30 \text{ fb}^{-1}$ ) for masses up to  $M_H \approx 125 \text{ GeV}/c^2$ . This prospect is the most powerful incentive that we have for Run III. To support this discovery, a  $3\text{-}\sigma$  observation will be possible in  $ZH$  in Run III for masses up to  $M_H \approx 110 \text{ GeV}/c^2$ . In combination, the two observations at the Tevatron would imply a  $\pm 15\%$  measurement of the ratio of couplings  $g_{WWH}^2/g_{ZZH}^2$ . If the coupling strength  $g_{ZZH}$  and the branching fraction  $B(H \rightarrow bb)$  are known from experiments at LEP2, the observations at the Tevatron would make it possible to determine  $g_{WWH}$  to  $\pm 10\%$ . Over the range of masses accessible at the Tevatron, it should be possible to determine the mass of the Higgs boson to  $\pm(1-3) \text{ GeV}/c^2$ .

## Higgs at the LHC: Summary

The capabilities of the LHC experiments to search for, and study, the Higgs boson are thoroughly documented in the Technical Proposals [23]. I will confine myself here to a few summary comments.

A  $5\text{-}\sigma$  discovery is possible up to  $M_H \approx 800 \text{ GeV}/c^2$  in a combination of the channels

$$\begin{array}{l}
 H \rightarrow Z Z \\
 \left. \begin{array}{l} \lrcorner \\ \lrcorner \end{array} \right\} \begin{array}{l} \ell^+ \ell^- \\ \ell^+ \ell^-, \end{array}
 \end{array}$$

$$\begin{array}{c}
 H W \\
 \left\{ \begin{array}{l} \rightarrow \ell \nu \\ \rightarrow b \bar{b} \end{array} \right.
 \end{array}$$

and

$$H \rightarrow \gamma\gamma \text{ or perhaps } \tau^+\tau^-.$$

The reach of LHC experiments can be extended by making use of the channels

$$\begin{array}{c}
 H \rightarrow Z Z \\
 \left\{ \begin{array}{l} \rightarrow \ell^+\ell^- \text{ or } \nu\bar{\nu} \\ \rightarrow \text{jet jet,} \end{array} \right.
 \end{array}$$

and

$$\begin{array}{c}
 H \rightarrow W W \\
 \left\{ \begin{array}{l} \rightarrow \ell \nu \\ \rightarrow \text{jet jet.} \end{array} \right.
 \end{array}$$

For Higgs-boson masses below about  $300 \text{ GeV}/c^2$ , it should be possible to determine the Higgs mass to  $100\text{-}300 \text{ MeV}/c^2$  [24].

## SUMMARY REMARKS

The Tevatron exists, and will produce important results on the top quark and Higgs boson through the next decade. We can expect considerable improvements in the determinations of  $m_t$  and  $M_W$ , as well as increasingly telling searches for nonstandard production and decay in Run II ( $2 \text{ fb}^{-1}$ ). In the realm of what might be possible thereafter, what we have called Run III ( $30 \text{ fb}^{-1}$ ) holds great promise for refining our knowledge of top properties, including the measurement of  $|V_{tb}|$  in single-top production. Run III would also extend the search for a light Higgs boson throughout the low-mass region favored by supersymmetry. On a related note, if low-scale supersymmetry exists, there is every reason to expect that it should be found at the Tevatron.

During the week of this workshop, the United States sealed its commitment to participate in the construction of the Large Hadron Collider at CERN. The LHC will be a fountain of tops:  $\sim 8$  million pairs will be produced per year at a luminosity of  $\mathcal{L} = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ ; hundreds to thousands of interesting events will be detected each day. The LHC will extend the search for the agent of electroweak symmetry breaking toward 1 TeV. It will have good sensitivity to the standard-model Higgs boson throughout the interesting range. The LHC will explore the spectrum of superpartners up to  $\sim 1 \text{ TeV}/c^2$  and make possible detailed measurements of supersymmetric parameters. Opening a new energy frontier, the LHC will also offer many other possibilities for exploration.

## ACKNOWLEDGEMENTS

It is a pleasure to thank Dave Cline and his staff for the stimulating and pleasant atmosphere of the workshop. I am grateful to Jens Erler, Steve Kuhlmann, Scott Willenbrock, and John Womersley for advice and assistance in the preparation of this talk.

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