HIGGS SEARCHES AT LEP AND AT THE TEVATRON

Patrick Janot (E-mail: Patrick.Janot@cern.ch)
CERN, EP Division, CH-1211 Geneva 23

ABSTRACT

After years of efforts to push the LEP performance to, and indeed beyond, the limits of what had been believed possible, hints of a signal of a Higgs boson at $115\,\mathrm{GeV}/c^2$ appeared in June 2000, were confirmed in September, and confirmed again in November. Spending an additional six-month period with LEP would have given the unambiguous opportunity of a fundamental discovery. Instead, this possibility was handed over to the Tevatron, for which at least six more years will be needed to confirm the existence of a Higgs boson around $115\,\mathrm{GeV}/c^2$. The upgrades performed at LEP and needed at the Tevatron, together with the physics outcomes, are briefly mentioned in turn.

1   LEP (1989-2000): "2001, A Spoilt Odyssey"

As described in P. Renton's presentation [1], the Luminosity, the Energy and the Precision (L,E,P) of the measurements made at LEP and SLD (available

at the time of the conference) allowed an indirect prediction of the Higgs boson mass to be made in the framework of the standard model,

$$m_{\mathrm{H}} = 118^{+63}_{-42}\,\mathrm{GeV}/c^2,\tag{1}$$

as obtained with the as-yet most precise determination of the QED coupling constant evaluated at the Z mass. [2] The prediction of such a light Higgs boson emphasized the interest of the direct search at LEP.

All searches carried out during the first phase of LEP through the Higgstrahlung process $e^+e^- \to H f\bar{f}$ were unsuccessful, and led to a lower limit of $65.6\,\mathrm{GeV}/c^2$ on the standard model Higgs boson mass at 95% C.L. [3] It was time, in 1995, to go to the second phase of LEP. As shown in Fig. 1, a centre-of-mass energy of 192 GeV (which was foreseen to be reached with the available equipment) allowed a 5σ-sensitivity of $100\,\mathrm{GeV}/c^2$ to be achieved on the standard model Higgs boson mass, through the search for the process $e^+e^- \to HZ$. Similarly, a centre-of-mass energy of 209 GeV (actually reached in 2000) increased this sensitivity to $115\,\mathrm{GeV}/c^2$.
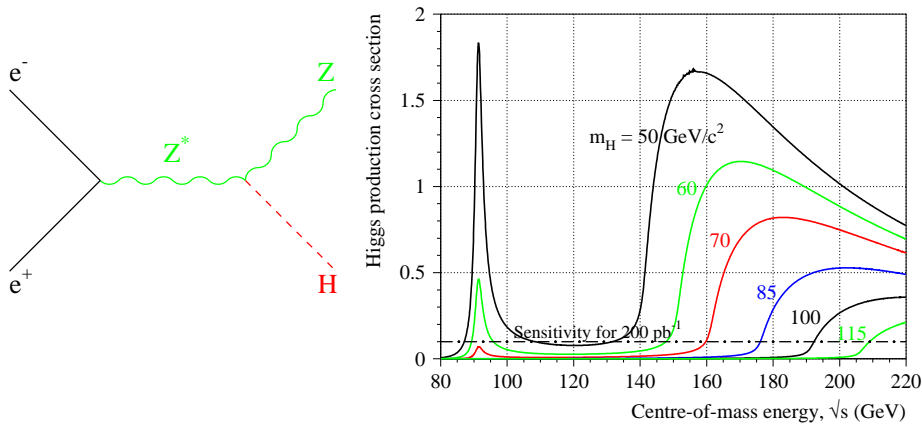

Figure 1: Higgs boson production process at LEP 2 (left) and cross section as a function of the centre-of-mass energy for several Higgs boson mass values. Also indicated (dash-dotted line) is the 5σ-sensitivity reached with $200\,\mathrm{pb}^{-1}$.

The search for the HZ process proceeds through three clear topologies, originating from the dominant decay channels of the Higgs (mostly in $b\bar{b}$ for the mass range of interest at LEP) and of the Z bosons:

- an identified lepton pair, electrons or muons, accompanied by two b jets, when $Z \rightarrow e^+e^-, \mu^+\mu^-$, in less than 10% of the cases;

- an acoplanar pair of b jets, accompanied with missing energy and mass, when $Z \rightarrow \nu\bar{\nu}$, in 20% of the cases;

- a four-jet final state when the Z decays into hadrons, in the remaining 70% of the existing configurations;

easily selected with efficiencies ranging from 40% (for the four-jet final state) to 80% (for the leptonic final state). However, the presence of irreducible backgrounds with large production cross sections (such as, e.g., $e^+e^- \rightarrow ZZ, W^+W^-$ or $q\bar{q}$, which all contribute to the four-jet topology) requires a careful treatment on a event-by-event basis to determine the "signal-ness" of each candidate.

To this end, each event was characterized by its kinematic properties, its reconstructed mass in the Higgs boson hypothesis, and its b-quark content. These characteristics were combined with likelihood methods or neural networks, and the combined output was used to assign (with large simulated event samples of signal and background) a signal-to-noise ratio (s/b, Higgs-mass-hypothesis dependent) to each candidate. The overall negative log-likelihood of a given sample of N candidate events,

$$L(m_{\mathrm{H}}) = -2\log Q \quad \text{with} \quad Q = \prod_{i=1}^{N} \left(1 + \frac{s_i}{b_i}(m_{\mathrm{H}}) \right), \qquad (2)$$

smaller in presence of signal than it would be with background events only, was used to quantitatively estimate the result of the search. Because the signal cross section decreases rapidly when m_{H} increases, the separation between the likelihood of a signal-like and a background-like experiment is expected to become smaller as m_{H} reaches the "kinematic limit" of HZ production, i.e., $m_{\mathrm{H}} \sim \sqrt{s} - m_{\mathrm{Z}}$. The typical expected shape of L as a function of the hypothetical Higgs boson mass, should the Higgs boson weigh $115\,\mathrm{GeV}/c^2$, is displayed in Fig. 2 for the luminosity actually recorded by the four LEP experiments in 2000, at centre-of-mass energies between 205 and 209 GeV. The minimum of the expected curve shows the most probable hypothetical mass pointed at by the event sample.

With a combination of the events from the four LEP experiments, a 3σ sensitivity of $115\,\mathrm{GeV}/c^2$ was achieved, thanks to the large integrated luminos-
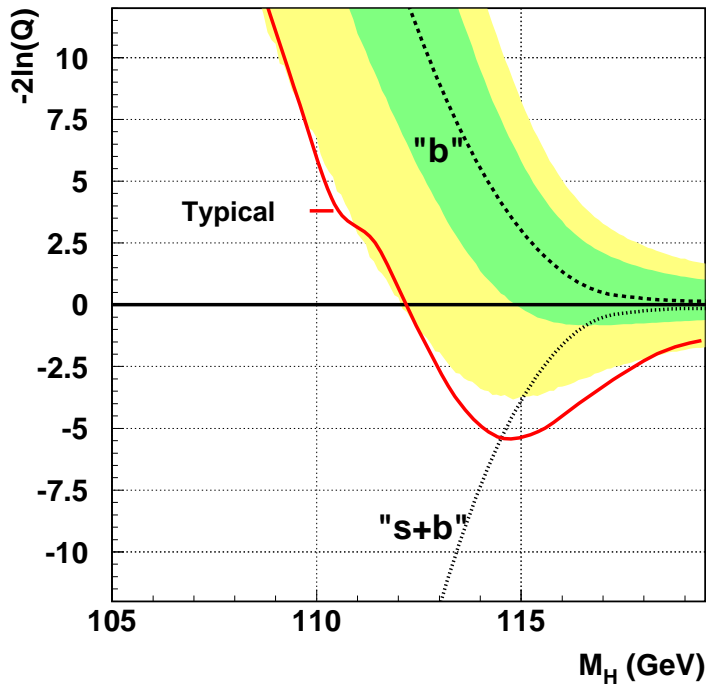
Figure 2: Typical neg've log-likelihood curve of the LEP data sample for a Higgs boson mass of $115\,\mathrm{GeV}/c^2$. The dashed curves display the expected mean value of the minimum, should the sample contain either only background (curve "b") or signal as well (curve "$s + b$"), as a function of the Higgs boson mass. The shaded bands show the 68% and 95% compatibility bands with the background-only hypothesis.

ity produced at and above $206\,\mathrm{GeV}$. Such high centre-of-mass energies would not have been reached if it were not for the great ingenuity and utmost efforts to take advantage of all possible resources of the accelerator. Indeed, the existing accelerating equipment (288 Nb/Cu superconducting cavities, installed between 1995 and 1999, with a design accelerating gradient of 6 MV/m) was aimed at delivering a maximum centre-of-mass energy of $192\,\mathrm{GeV}$. The following actions were then taken, and their effect on the centre-of-mass energy and the Higgs boson mass 3σ sensitivity are displayed in Table 1.

    i. The cryogenic installation was upgraded (as foreseen for the LHC) to al-

Table 1: Effect on $\sqrt{s}$ and on the 3σ-sensitivity on m_{H} of the various improvements brought to LEP in its last two years of running.

Action	Effect on $\sqrt{s}$ (GeV)	m_{H} sensit.(GeV/c^2)
(i) Cryogenics upgrade	$192 \to 204$	$100 \to 112$
(ii) One klystron margin	$204 \to 205.5$	$112 \to 113$
(iii) Mini-ramps to no margin	$205.5 \to 207$	$113 \to 114$
(iv) Eight Cu cavities	$207 \to 207.4$	$114 \to 114.25$
(v) Orbit correctors	$207.4 \to 207.8$	$114.25 \to 114.5$
(vi) Smaller RF frequency	$207.8 \to 209.2$	$114.5 \to 115.1$

low the accelerating gradient of the superconducting cavities to be gradually increased from 6 MV/m to 7.5 MV/m, for a global gain of 650 MV. The overall stability of the cryogenic system was also greatly improved with this upgrade.

ii. With this gain in stability, the RF margin was reduced from 200 MV (corresponding to a margin of two klystrons allowed to trip without losing the beams) to 100 MV (only one klystron margin) with only moderate a reduction of the average fill duration.

iii. At the end of each fill, mini-ramps to a no-margin situation were performed, allowing another 100 MV to be gained for a duration of approximately fifteen minutes (the average time between two klystron trips).

iv. Eight warm Cu cavities (from the first phase of LEP) were re-installed for an additional of gain of 30 MV.

v. Unused (mostly uncabled) orbit correctors were powered in series to act as magnetic dipoles, thus increasing the bending length of LEP and allowing the beam energy to be increased while keeping constant the energy loss by synchrotron radiation .

vi. The radio-frequency was slightly reduced (by 100 Hz out of 350 MHz), to benefit from the dipolar magnetic field seen by the beam in the focusing quadrupoles and from the additional margin brought by the resulting shortening of the bunches.

Altogether, these improvements allowed the maximum centre-of mass energy to be raised from 192 to 209.2 GeV, and the 3σ-sensitivity on the standard model Higgs boson mass to be increased from 100 to $115.1 \, \text{GeV}/c^2$. The evolution of the sensitivity as a function of time since 1996, displayed in Fig. 3, is essentially driven by the number of superconducting cavities installed in LEP (176 in 1996, 240 in 1997, 272 in 1998 and 288 in 1999). It is worth noting that 372 cavities (*i.e.*, as many as could possibly be installed in the LEP tunnel) would have allowed a large integrated luminosity to be produced at centre-of-mass energies in excess of $220 \, \text{GeV}$.
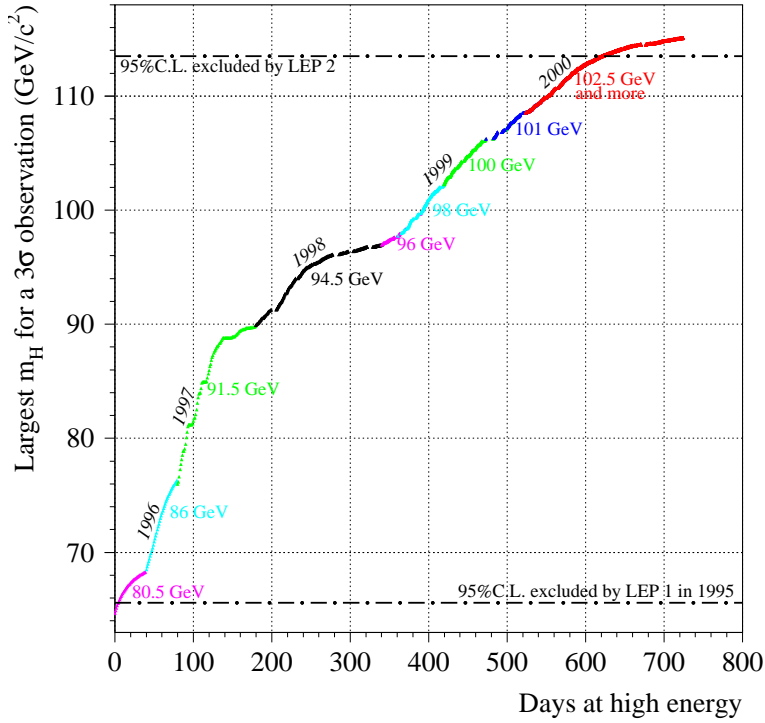

Figure 3: Evolution of the 3σ-sensitivity on m_{H} (and of $\sqrt{s}$) from 1996 to 2000.

Because, until June 2000, no noticeable excess of signal-like candidate events had been seen in the LEP data, the whole m_{H} range between 0 and $114.1 \, \text{GeV}/c^2$ was excluded at the 95% confidence level. In June 2000, sizeable luminosity at centre-of-mass energies above $206 \, \text{GeV}$ (*i.e.*, above the kinematic

threshold for a Higgs boson of $115\,\mathrm{GeV}/c^2$) started to be steadily delivered. From this moment onwards, signal-like events compatible with the production of a Higgs boson with mass $115\,\mathrm{GeV}/c^2$ were regularly recorded by the LEP experiments. The reconstructed masses of the fourteen most significant events (selected with a cut corresponding to an integrated signal-to-noise ratio of about 1.0), their s/b values, the topologies and the experiments in which they were detected are summarized in Table 2.

Table 2: Signal-to-noise s/b at $115\,\mathrm{GeV}/c^2$, reconstructed Higgs mass (in GeV/c^2), final state channel and experiment for the fourteen most signal-like events (selected with $s/b > 0.3$) corresponding to an expected purity of 50%.

s/b	Rec. mass	Channel	Experiment
4.7	114	$\mathrm{Hq\bar{q}}$	ALEPH
2.3	112	$\mathrm{Hq\bar{q}}$	ALEPH
2.0	114	$\mathrm{H\nu\bar{\nu}}$	L3
0.90	110	$\mathrm{Hq\bar{q}}$	ALEPH
0.60	118	$\mathrm{He^+e^-}$	ALEPH
0.52	113	$\mathrm{Hq\bar{q}}$	OPAL
0.50	111	$\mathrm{Hq\bar{q}}$	OPAL
0.50	115	$\mathrm{H\tau^+\tau^-}$	ALEPH
0.50	115	$\mathrm{Hq\bar{q}}$	ALEPH
0.49	114	$\mathrm{H\nu\bar{\nu}}$	L3
0.47	115	$\mathrm{Hq\bar{q}}$	L3
0.45	97	$\mathrm{Hq\bar{q}}$	DELPHI
0.40	114	$\mathrm{Hq\bar{q}}$	DELPHI
0.32	104	$\mathrm{H\nu\bar{\nu}}$	OPAL

The characteristics of the fourteen events displayed in Table 2 are those determined as of November 2000. (A more recent update was not available at the time of the conference; no final update exists either at the time of writing.) Seven background events were expected in this data sample (and therefore seven signal events, should the Higgs boson weigh $115\,\mathrm{GeV}/c^2$), in close agreement with the number of events observed. It is important to note that this agreement is independent of the s/b cut chosen, *i.e.*, on the expected signal purity of the event sample. In addition, the fourteen events are divided

into

- Nine four-jet (Hqq̄) candidate events (expected fraction 70%);

- Three missing energy (Hνν̄) candidate events (expected fraction 20%);

- Two leptonic (H$\ell^+\ell^-$, H$\tau^+\tau^-$) candidate events (expected fraction 10%);

in close agreement with the expected HZ fractions, and into

- Six events in ALEPH;

- Three events in OPAL;

- Three events in L3;

- Two events in DELPHI;

to be compared with ~ 1.7 background events expected in each experiment. Such distribution is, for these small statistics, well compatible with a democratic production in the four LEP experiments.

The overall observation therefore shows an impressive consistency with the signal hypothesis with $m_{\rm H} = 115\,{\rm GeV}/c^2$, regarding the total cross-section, the distribution in the four experiments and in the three final states, and the distribution of s/b. The increase of the excess significance closely followed, since June 2000, that expected from the presence of a $115\,{\rm GeV}/c^2$ Higgs boson, as shown in Fig. 4. The final negative log-likelihood, with a minimum, corresponding to 2.9 standard deviations away from the background expectation, at

$$m_{\rm H} = 115^{+0.7}_{-0.3}\,{\rm GeV}/c^2, \qquad (3)$$

is also displayed in Fig. 4. More details, figures and cross-checks, further showing the robustness of the interpretation, are discussed in Refs. [4, 5].

In a preliminary update released after the conference, [6] with data reprocessed from L3, ALEPH and OPAL, and with additional systematic studies, the excess of signal-like events is still present, at a mass of $115.6\,{\rm GeV}/c^2$. (A 2.9σ excess is still observed by those three experiments, slightly damped by DELPHI's unreprocessed, preliminary data.) In particular, the presence of the events with the largest s/b values is confirmed. Unfortunately, if the Higgs boson weighs $115\,{\rm GeV}/c^2$, it is not before an e^+e^- linear collider starts producing HZ data that events with such a high purity will be seen again.
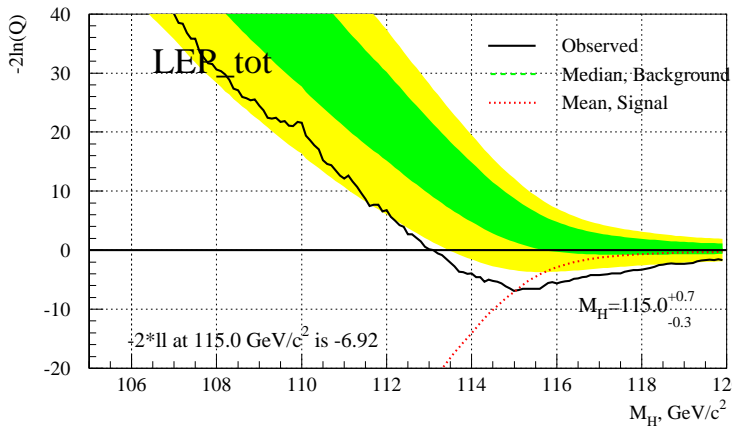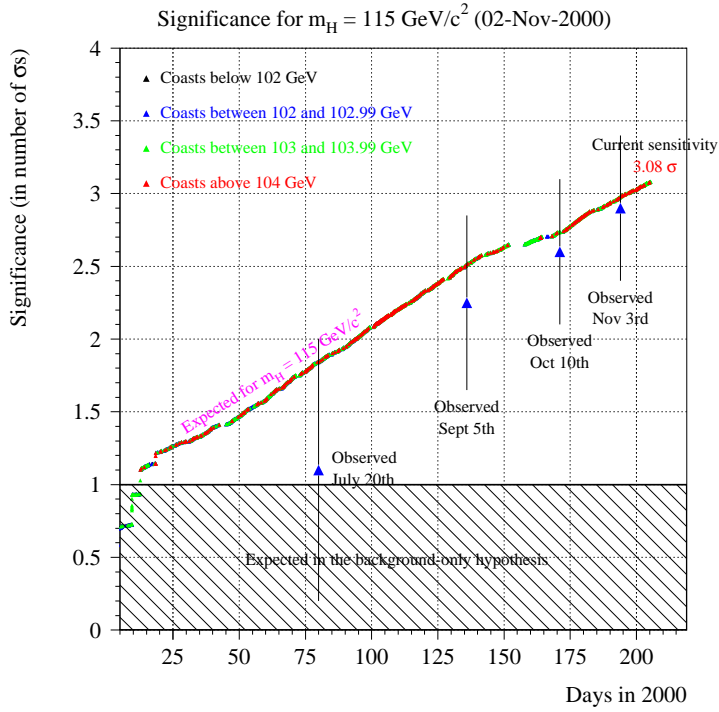
Figure 4: Top: Increase of the observed combined significance at $m_{\mathrm{H}} = 115\,\mathrm{GeV}/c^2$ in 2000, compared with an online estimate of the significance expected in the signal-plus-background hypothesis. Bottom: Negative log-likelihood as a function of the hypothetical standard model Higgs boson mass.

With six more months of LEP running in 2001, *i.e.*, with an integrated luminosity of $200 \, \text{pb}^{-1}$ and an upgraded centre-of-mass energy above 208.5 GeV (made possible with a few available additional cavities and few accelerator tricks), the almost 3σ excess could have turned into an unambiguous $5.5^{+0.6}_{-0.9}\sigma$ discovery, and have led to the reconstructed mass spectrum displayed in Fig. 5, should the Higgs boson mass indeed be around $115 \, \text{GeV}/c^2$. Similarly, in the null hypothesis, the new data would have allowed to demonstrate that the excess seen in 2000 was due to a statistical fluctuation.
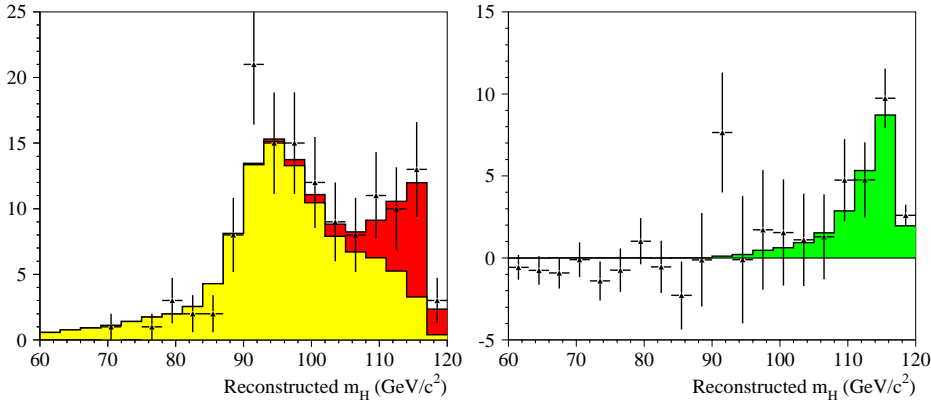

Figure 5: Expected reconstructed mass spectrum of the most significant events (with an s/b value in excess of 0.5) after a six-month run of LEP in 2001, should the Higgs boson mass indeed be around $115 \, \text{GeV}/c^2$. Left: Raw spectrum; Right: Background subtracted spectrum, with an expected excess of 28 events.

In contrast, CERN's Director General decided to shut down LEP for ever on November 17th, 2001, at 4:15pm.

2   Tevatron (2001-2007++): "Back to the future"

Next-in-line for the Higgs boson search is the Tevatron. Run 2 started nearly at the time of the conference, and is supposed to last at least until LHC starts delivering useful data for this search (*i.e.*, at least until 2007). About $0.1 \, \text{fb}^{-1}$ of data were collected by both experiments, CDF and D0, during the Run 1 at a centre-of-mass energy of 1.8 TeV. The goal of Run 2 is to increase this figure

to 2, 4 and $15\,\mathrm{fb}^{-1}$ in 2003, 2004 and 2007 respectively, at an upgraded 2 TeV centre-of-mass energy.

The dominant Higgs production process in p$\bar{\mathrm{p}}$ collisions at $\sqrt{s} = 2\,\mathrm{TeV}$ is the gluon-gluon fusion gg $\to$ H $\to$ b$\bar{\mathrm{b}}$. However, due to the overwhelming dijet QCD background, the only practicable processes are similar to that dominant at LEP, q$\bar{\mathrm{q}} \to$ HZ and q$\bar{\mathrm{q}}' \to$ HW. Beyond LEP sensitivity, the cross sections of these processes are below $0.2\,\mathrm{pb}$. The possible final states, for a Higgs boson mass below $130\,\mathrm{GeV}/c^2$ (for which H $\to$ b$\bar{\mathrm{b}}$ dominates) are sketched in Fig. 6.
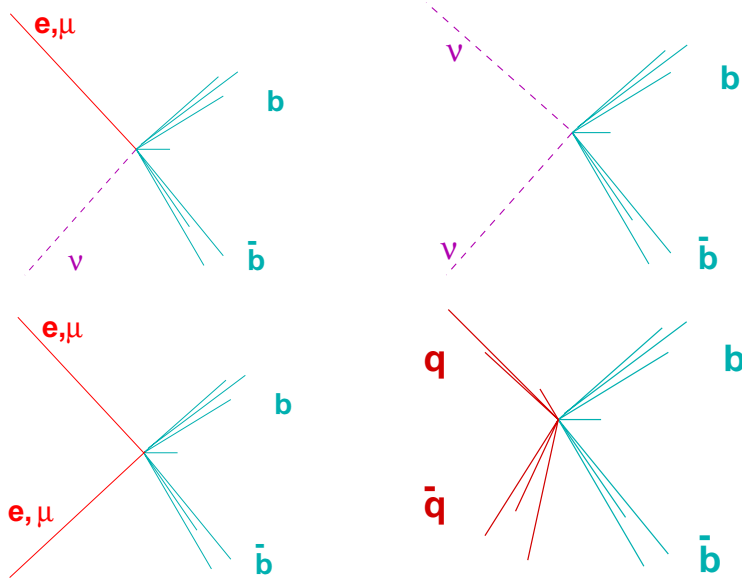
Figure 6: Final states for $m_{\mathrm{H}} < 130\,\mathrm{GeV}/c^2$, with H $\to$ b$\bar{\mathrm{b}}$. Other final states are studied for $m_{\mathrm{H}} > 130\,\mathrm{GeV}/c^2$, with H $\to$ WW*.

These four final states have already been studied at the Tevatron in Run 1. The CDF reconstructed Higgs boson mass distributions [7] show no apparent excess over the expected background. However, the sensitivity is well short of the standard model expectations: a 95% C.L. upper limit of about $7\,\mathrm{pb}$ was set on the HV (where V stands for W and Z) production cross section times the H $\to$ b$\bar{\mathrm{b}}$ branching fraction, to be compared with a standard model cross section of $0.25\,\mathrm{pb}$ for $m_{\mathrm{H}} = 115\,\mathrm{GeV}/c^2$ (see Fig. 7).
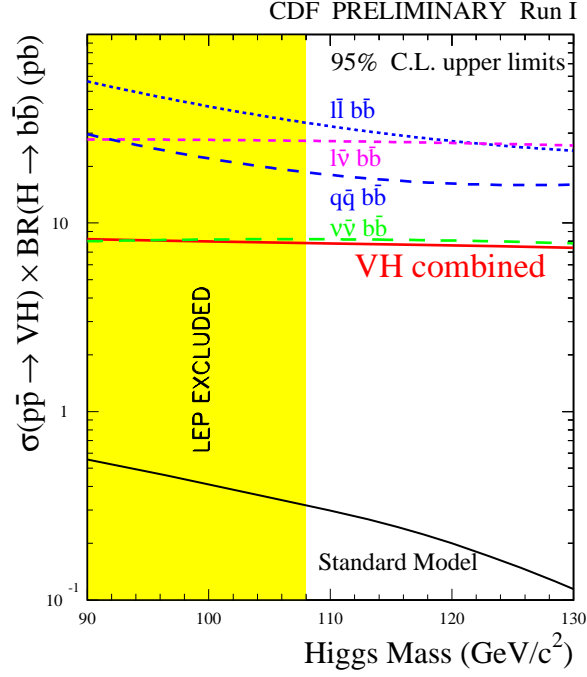
Figure 7: Upper limit set by CDF on the HV production cross sections times the H → bb̄ branching fraction with data taken in Run 1, compared with the standard model prediction. The comparison with LEP limits is incorrectly quoted here and in Ref. [7]. A proper comparison as a function of $\sigma \times BR$ is shown in Ref. [8].
.

The missing factor of 27 in sensitivity corresponds to a factor of 700 in effective integrated luminosity, *i.e.*, CDF alone would need $\sim 70\,\mathrm{fb}^{-1}$ (resp. $450\,\mathrm{fb}^{-1}$) to achieve a 95% C.L. (resp. 5σ) sensitivity for $m_\mathrm{H} = 115\,\mathrm{GeV}/c^2$ if nothing had been changed either to the detector or to the analyses. The upgrades envisioned to reduce the needs down to a couple of fb^{-1} (resp. $15\,\mathrm{fb}^{-1}$) are listed in Table 3 and briefly addressed in turn in the following.

Table 3: Upgrades envisioned to reduce the needs in integrated luminosity for the search for the standard model Higgs boson in Run 2. The expected 95% C.L. limit on the HV production cross section, the integrated luminosity needed per experiment to exclude a $115\,\mathrm{GeV}/c^2$ Higgs boson, and that needed to find it are given.

Improvement	σ_{95} (pb)	$\mathcal{L}_{95}$ (fb^{-1})	$\mathcal{L}_{5\sigma}$ (fb^{-1})
Now (CDF, 0.1 fb^{-1})	6.0	70	450
2 expts ($\times 2$)	4.2	35	220
$\sqrt{s} = 2\,\mathrm{TeV}$ ($+30\%$)	3.7	25	150
Lepton acc. ($+30\%$)	3.3	20	125
b tagging eff. ($+50\%$)	2.7	15	95
Mass resolution (-30%)	2.0	8	50
NN analyses eff. ($+30\%$)	1.6	5	35
Trigger eff. ($\times 2$)	1.1	2.5	15

2.1 *Two experiments for Higgs search?*

Most of the D0 subdetectors are new with respect to Run 1. In particular, a superconducting solenoid and a silicon microstrip tracker were installed which will greatly improve the b-tagging capabilities (and therefore the Higgs boson search efficiency) of D0. Many other new components will allow D0 to catch up on and possibly exceed CDF performance.

2.2 *Tevatron energy upgrade*

The Run 2 beam energy goal is $980\,\mathrm{GeV}$ ($\sqrt{s} = 1.96\,\mathrm{TeV}$). A heavy programme of cryogenics upgrade (with central helium liquefier upgrades, installation of more cold compressors and heat exchangers, swapping of the weakest magnets to the coldest regions, ...) over the past eight years made this upgrade possible. The Tevatron ran successfully at $980\,\mathrm{GeV}$ in the 1×8 bunch configuration on April 3-5, and the design 36×36 bunch configuration. All dipoles were ramped up to $1010\,\mathrm{GeV}$, and all low-β quadrupoles to $1030\,\mathrm{GeV}$, thus leaving a comfortable margin for operations at $1.96\,\mathrm{TeV}$.

2.3 *Lepton Id and b-tagging acceptance*

The CDF detector also underwent major upgrades in the past five years, with a brand new eight layers silicon tracking system (of which three layers down to a pseudo-rapidity of 3.0), new end-plug calorimeters and forward muon detectors, extending full electron and muon coverages down to $|\eta| = 3.6$ and 1.5, respectively. The b-tagging and lepton-Id coverage is similar in D0.

2.4 *Other detector and analysis improvements*

Other potential improvements are worth a factor of 6 in integrated luminosity, but they remain to be carefully worked out. First, the dijet mass resolution ought to be improved from 15 to 10%, which requires good and constant energy-flow capabilities. Algorithms are currently being thought of and developed. Second, analysis efficiencies are hoped to be increased by 30% by neural network techniques and by designing more subtle selections than those described in Ref. [9]. Finally, only future will tell if trigger efficiencies (especially b-jet triggers, particularly difficult to simulate) can indeed be doubled.

2.5 *Results and Luminosity needed*

Taking into account all the above improvements, the expected $b\bar{b}$ mass distribution for the most copious channel (WH $\to \ell\nu b\bar{b}$) with $10\,\mathrm{fb}^{-1}$ and for $m_{\mathrm{H}} = 120\,\mathrm{GeV}/c^2$, is shown in Fig. 8. Once combined with all other channels, the luminosity needed to reach a 95% C.L. exclusion, 3σ observation or 5σ discovery sensitivity is displayed in the same figure as a function of the hypothetical Higgs boson mass.

For a Higgs boson mass of $115\,\mathrm{GeV}/c^2$, a significance of 2σ is expected to be reached in 2003 with $2.5\,\mathrm{fb}^{-1}$, 3σ in 2005 with $5\,\mathrm{fb}^{-1}$ and 5σ in 2007 with $15\,\mathrm{fb}^{-1}$. [9] These figures were revisited by independent LHC studies at $2\,\mathrm{TeV}$ [10], and were found to be slightly smaller (1, 2 and 3σ, respectively). While a 3σ hint would certainly be enough to convince the community of the existence of a $115\,\mathrm{GeV}/c^2$ Higgs boson (it would then be a confirmation of LEP's hints), the situation becomes much more difficult above 115-$116\,\mathrm{GeV}/c^2$ for which a 5σ signal would be needed to claim a discovery.
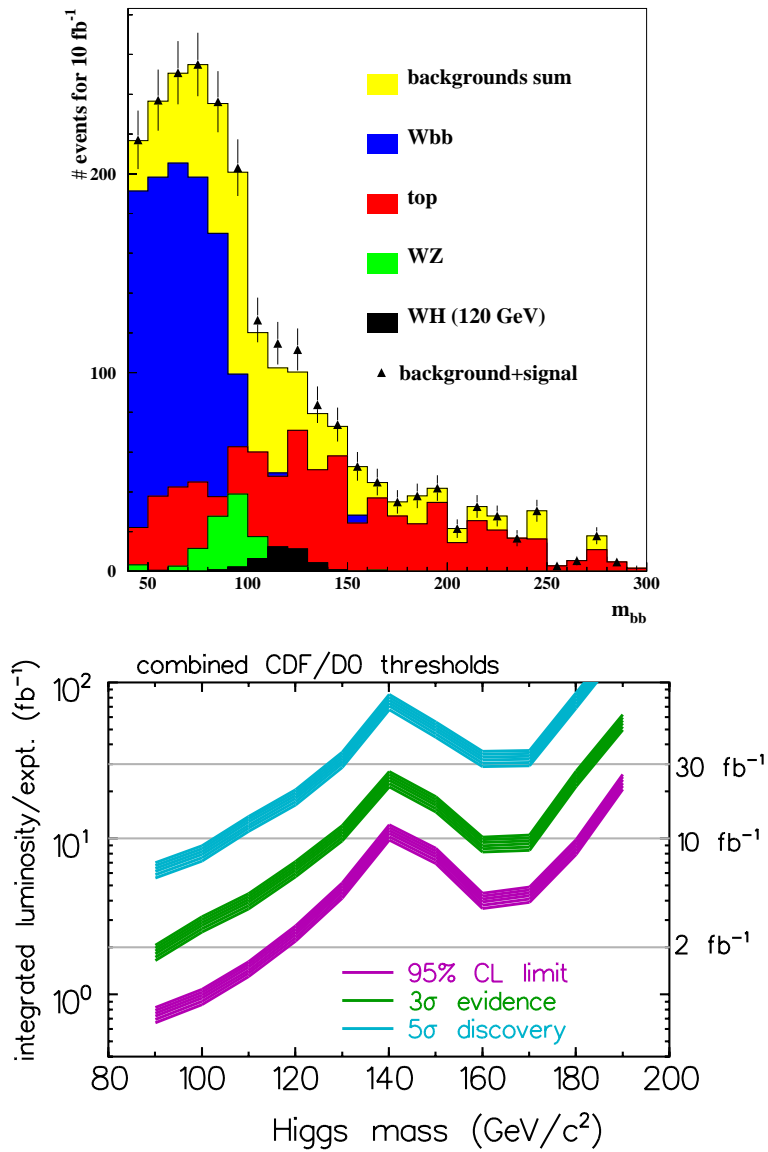
Figure 8: Top: $b\bar{b}$ mass distribution in the HW $\to$ $b\bar{b}\ell\nu$ final state, with $10\,\text{fb}^{-1}$ and $m_H = 120\,\text{GeV}/c^2$. The histograms represent the contributions of the background processes. The triangles with error bars include that of the Higgs boson. Bottom: Minimum luminosity needed to exclude (bottom curve) or discover (top curve) a standard model Higgs boson;

2.6 *Luminosity upgrades*

When all techniques alluded to in Sections 2.1 to 2.4 are implemented, the integrated luminosity has still to be increased by a factor of 150 with respect to Run 1 to reach a 5σ sensitivity for $m_{\mathrm{H}} = 115\,\mathrm{GeV}/c^2$, and to extend the 95% C.L. sensitivity domain beyond that already excluded by LEP 2. Because the number of antiprotons drives the luminosity of a $p\bar{p}$ collider, it is necessary to produce, collect, handle and recycle many more antiprotons than at Run 1. These requirements imply a series of ambitious upgrades of the booster, the accumulator, the main injector, the transfer lines and the Tevatron itself (Fig. 9), some of which have already been completed, some of which are currently being commissioned, and some of which still entail large technical uncertainties.
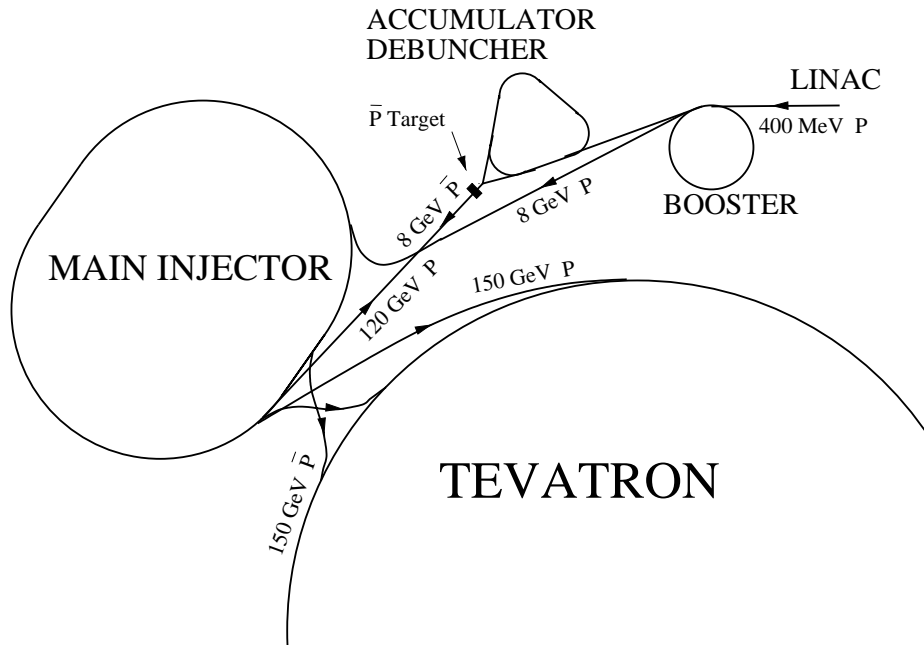

Figure 9: Layout of the Fermilab accelerator complex for collider operations

A comprehensive description of these upgrades can be found in Ref. [11]. Only a brief account of these improvements is given here.

- Booster upgrades for p̄ production

  At Run 1, the Booster proton intensity was limited by the integrated radiation losses, mostly due to beam losses. To reduce these losses, the Booster is being upgraded by *(i)* increasing the extraction aperture; *(ii)* reinforcing the radiation shielding; and *(iii)* installing more corrector magnets to improve the optics, and more beam collimators to localize losses in the safest areas.

- Accumulation upgrades for p̄ collection

  Once more protons are available from the booster, the next goal is to increase the number of antiprotons collected per proton on target. To do so, the Lithium-lenses magnetic focusing after the target was increased (by increasing their gradient from 700 to 900 T/m) and so was the accumulator aperture by beam pipe modification, larger septum magnet aperture, and improved beamline optics.

- Cooling upgrades for p̄ handling

  More antiprotons have then to be cooled, possibly faster than at Run 1. The stochastic cooling system was therefore replaced by a brand new system with twice as large a bandwidth, which increases the cooling rate by a factor of 4. In addition, operating the cooling pickups at 4 K drastically improves their signal-to-noise ratio and, therefore, their efficiency. Finally, electron cooling is foreseen in the main injector to deal with large antiproton intensities, for which stochastic cooling becomes less efficient.

- Main injector upgrades for p̄ accumulation

  Because the intensity of the proton source (prior to the target) is limited by space charge effects, two batches with small momentum offset are planned to be steered with two independent RF systems (with two different frequencies). The two resulting antiproton batches are merged later on in the main injector by bringing the two frequencies close to each other, thus allowing twice as large a p̄ accumulation. Finally, it is planned to decelerate unused antiprotons in the Tevatron at the end of each collider store, so as to re-inject, keep and cool them in the Recycler for later use.

With all the above upgrades, the p̄ production rate and the number of antiprotons accumulated for each store are expected to increase as shown in Table 4.

Table 4: Antiproton production rates and numbers of p̄ produced for each collider store measured in Run 1b and expected in Run 2.

Run	Run 1b (maximum)	Run 2a (average)	Run 2b (average)
Year	1993-1996	2001-2003	2005-2007
Rate	6×10^{10} / hr	10×10^{10} / hr	52×10^{10} / hr
Number	0.33×10^{12}	1.1×10^{12}	11×10^{12}

The integrated luminosity expected from these upgrades is indicated in Table 5. With the proton and antiproton intensity increase, more bunches are needed to reduce the beam-beam tune shift, the background in the detectors and the number of interactions per crossing. Ultimately, the bunches will have to cross with a nonzero angle to keep the multiple interactions in the detectors to a manageable level, although it will reduce slightly the luminosity as well.

Table 5: Integrated luminosity delivered per experiment (per week and total) in Run 1b and expected to be produced per experiment in Run 2.

Run	Run 1b (maximum)	Run 2a (average)	Run 2b (average)
Duration	For one year	For two years	For three years
Config.	6×6 bunches	36×36 bunches	140×103 bunches
Per week	$3.2 \, \text{pb}^{-1}$	$17 \, \text{pb}^{-1}$	$105 \, \text{pb}^{-1}$
Total	$0.14 \, \text{fb}^{-1}$	$1.5 \, \text{fb}^{-1}$	$14 \, \text{fb}^{-1}$

2.7 Perspectives and Outlook

The observability of a $115 \, \text{GeV}/c^2$ Higgs boson at Tevatron Run 2 relies on the realism of the performance ascribed to the foreseen improvements.

On the one hand, some of the assumptions may look slightly optimistic: a 10% dijet mass resolution was assumed, to be compared with 15% measured in Run 1, and 12% expected in ATLAS and CMS; the aggressive assumptions on the b-tagging, neural network and trigger performance remain to be demonstrated; a fast detector simulation was used throughout, although it is known to

always give too good results; negligible systematic uncertainties were assumed, while any 5% systematic effect on the background would limit possible signal effects to 2σ for a typical signal-to-noise ratio of 10%; the silicon trackers will have to be replaced in 2004, which requires a shutdown of the accelerator; and the integrated luminosity to be *collected* by CDF and D0 by 2007 was assumed to $15\,\text{fb}^{-1}$, which relies on the success of a solid, but very ambitious upgrading programme.

On the other hand, some of the assumptions are rather conservative: the analyses used throughout are first-pass analyses, and may be improved; other relevant channels may contribute to Higgs production (e.g., $t\bar{t}H$); the expected signal significance was computed with simple event counting, while events can certainly be weighted "à la LEP" to improve the sensitivity; and LHC might even be further delayed, which would extend the period during which $15\,\text{fb}^{-1}$ have to be accumulated by CDF and D0.

Although only future will tell us whether Run 2 will be in a position to confirm or not LEP's hints at $115\,\text{GeV}/c^2$ before the LHC, the present conjuncture is undoubtedly favourable to the Tevatron.

3   Conclusion

After twelve years of outstanding Physics at LEP, the precision electroweak measurements led to the prediction of the Higgs boson mass in the framework of the standard model,

$$m_{\text{H}} = 118^{+63}_{-42}\,\text{GeV}/c^2. \tag{4}$$

More LEP running at high energy and at the Z pole would have allowed to reduce the uncertainty on the prediction from electroweak measurements to $\pm15\,\text{GeV}/c^2$, which shows that LEP was stopped well before its Physics programme was over (as SLC was). Direct searches for the HZ process unveiled an excess of signal-like events corresponding to an almost 3σ effect, compatible in every aspects with the production of a standard model Higgs boson of mass

$$m_{\text{H}} = 115.0^{+0.7}_{-0.3}\,\text{GeV}/c^2, \tag{5}$$

in remarkable agreement with Eq. 4. (After the conference, further analysis and systematic studies of the existing data, although still preliminary, confirmed qualitatively this effect at $115.6\pm1\,\text{GeV}/c^2$ with a slightly reduced significance.)

Six more months of LEP running in 2001 could have confirmed the hints and turn them into a 5σ discovery.

Instead, about five to ten years are now needed for a possible confirmation. Who is going to confirm is not yet clear: Many upgrades are still to be carried out to reach $15\,\mathrm{fb}^{-1}$ in 2007 at the Tevatron, and many costs are still to be covered to see LHC starting in 2007. [12] The end of the decade may be thrilling.

References

1. P. Renton, *Electroweak Physics at the Z pole*, these proceedings.

2. A.D. Martin, J. Outhwaite and M.G. Ryskin, *Phys. Lett.* B **492**, 69 (2000)

3. P. Janot, in *Perspectives on Higgs Physics II*, World Scientific, Ed. G.L. Kane, Vol. 17, 104 (1997); http://alephwww.cern.ch/~janot/gordy.ps.gz

4. The LEP working group for Higgs boson searches, *Standard model Higgs boson at LEP: Results with the 2000 data; Request for running in 2001* (2000), see http://alephwww.cern.ch/~janot/LEPCO/lephwg.ps

5. The LEP working group for Higgs boson searches, *A hint for the standard model Higgs boson at LEP: Frequently asked questions, and their answers* (2000), see http://alephwww.cern.ch/~janot/LECO/qanda.ps

6. ALEPH, DELPHI, L3, OPAL and the LEP working group for Higgs boson searches, *Search for the standard model Higgs boson at LEP*, CERN-EP/2001-055 (2001)

7. CDF Coll., *Phys. Rev. Lett.* **81** (1998) 5758.

8. The transparencies of this talk, http://alephwww.cern.ch/~janot/etoile.pdf

9. Report of the Tevatron Higgs working Group, Eds, M. Carena et al., hep-ph/0010338 (2000)

10. F. Gianotti, talk given at the LHCC (July 2000)

11. M. Church, *Substantial upgrades to Tevatron luminosity*, hep-ex/0105041 (2001)

12. See for instance http://user.web.cern.ch/CERN/LHC.html