The Run II of the Tevatron

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High energy physics is the denomination commonly used to designate the physics of elementary particles, the branch of physics which deals with the building blocks of matter (quarks and leptons, as it presently seems) and their interactions. The reason for this denomination is that high energy beams are necessary to probe short distances, which is why higher and higher energy particle accelerators have been and continue to be built. As of today, the particle accelerator providing the highest energies is the Tevatron, a proton-antiproton collider located at Fermilab [1] (the Fermi National Accelerator Laboratory) near Chicago, Illinois (Fig. 1). Bunches of protons and antiprotons circulate in opposite directions in a 6.28 km long ring, and collide head on at specific locations where two large and complex detectors, named CDF [2] and D0 [3], register the outcome of their interactions. The Tevatron collider operated from 1992 to 1996, at a centre-of-mass energy(1) (twice the beam energy) of 1.8 TeV, delivering to each experiment an integrated luminosity(2) of 120 pb^{-1}. The main achievement of this period, known as Run I, was the discovery of the long sought top quark [4], with a mass of 174 GeV, in 1995.

With the discovery of the top quark, the only missing piece in the highly successful Standard Model of electroweak interactions(3) is the Higgs boson, a very peculiar object since all other particles, which would otherwise be massless, acquire their mass through their interaction with it. Its discovery would therefore be of paramount importance. Essentially all of the current experimental knowledge on the Higgs boson was obtained at CERN, the laboratory of the European Organisation for Nuclear Research near Geneva, where the LEP electron-positron collider was in operation from 1989 to 2000 at centre-of-mass energies up to 209 GeV. Until 1995, data on the Z boson, the neutral mediator of the weak force, were accumulated, allowing precision tests of the Standard Model to be performed. Consistency within this framework of the results thus obtained(4) required a top quark mass in the range 155 to 185 GeV, precisely where it ended up being found at the Tevatron. Together with the measurements of the mass of the charged weak boson W performed both at LEP and at the Tevatron, and of the top quark mass at the Tevatron, the same consistency requirement of the Standard Model now predicts that the mass of the Higgs boson should be lower than 190 GeV [5] (Fig. 2). Finally, direct searches for the Higgs boson [6] performed at the highest LEP energies exclude it for masses below 114 GeV, however with tantalising hints around 116 GeV.

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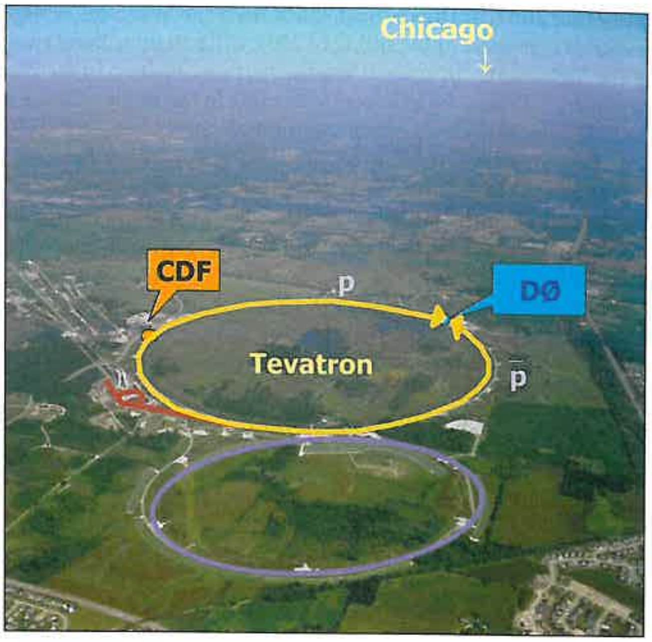
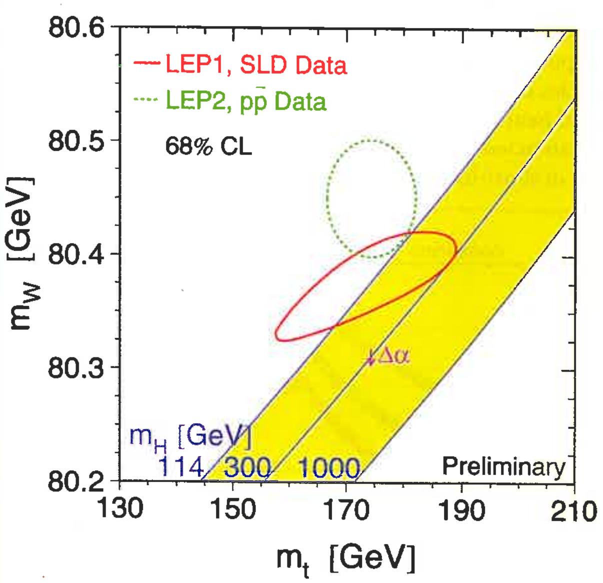
The successor of LEP at CERN will be the LHC (Large Hadron Collider), a 14 TeV proton-proton collider which was essentially designed in view of the discovery of the Higgs boson or of new particles predicted by theories beyond the Standard Model, for masses all the way up to 1 TeV. The construction and commissioning of the LHC and of the associated detectors will however not be complet-



▲ **Fig. 1:** An aerial view of the Fermilab site. The main components of the accelerator system are highlighted: in yellow, the Tevatron, a 2 TeV proton-antiproton collider; in red the initial injection system; in blue the newly constructed main injector and recycler. The locations of the CDF and D0 detectors are also indicated.



▲ **Fig. 2:** Masses of the W boson and of the top quark as measured directly at LEP and at the Tevatron (in green), and as indirectly predicted, based on precision measurements at the Z resonance (in red); the contours drawn correspond to a confidence level of 68%. The yellow band represents the Standard Model prediction for various Higgs boson masses. Direct and indirect measurements are in agreement, and point toward a light Higgs boson. (From Ref. 5.)

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ed before 2007, at the earliest. Until then the Tevatron, which resumed operation in the spring of 2001, will remain without rival at the high energy frontier. It was furthermore realised in the late nineties [7] that a Higgs boson with mass in the range indicated by LEP direct and indirect searches, i.e. between 114 and 190 GeV, could well be within the reach of the Tevatron, provided that a sufficient integrated luminosity is delivered (Fig. 3).

Both the Fermilab accelerator complex and the CDF and D0 detectors were substantially upgraded for this new phase of operation called Run II. On the accelerator side, two entirely new rings, the Main Injector and the Recycler, were constructed, with the goal of increasing the antiproton intensity which had been the main luminosity limitation during Run I. Together with other challenging beam optics improvements, these upgrades should allow the instantaneous luminosity to be progressively increased by a factor of five in a first phase, possibly of up to fifteen in a second one. This would lead to an integrated luminosity of 2 fb^{-1} (i.e., 2000 pb^{-1}) collected by the end of 2005 (Run IIa), and then of up to 3 fb^{-1} every year thereafter (Run IIb). In addition to these luminosity improvements, the proton-antiproton collision energy has been increased to 1.96 TeV.

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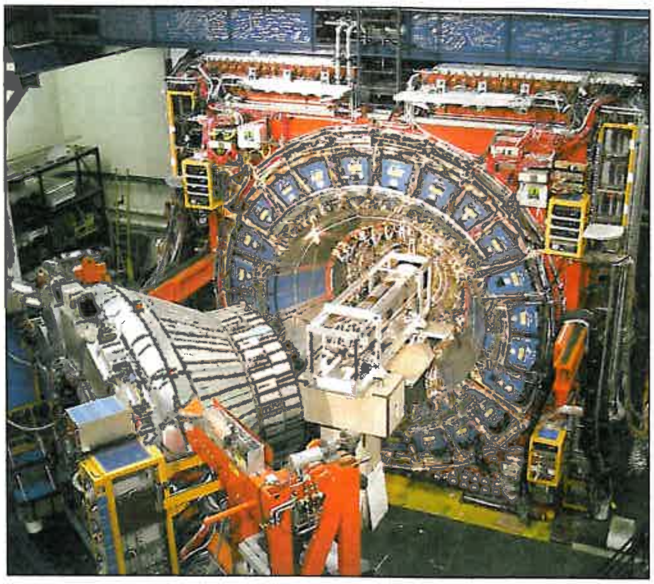
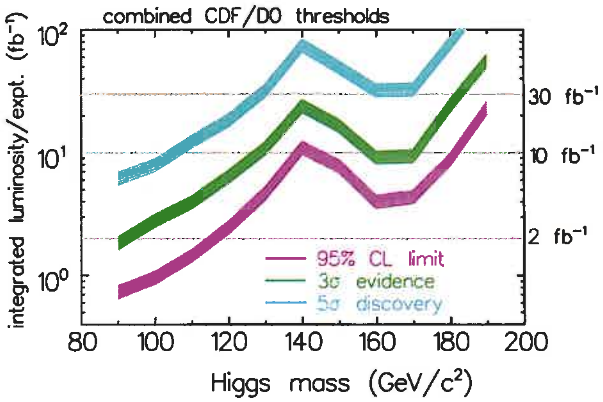
The CDF and D0 detectors had been initially optimised in quite different ways. In the case of CDF (Fig. 4), the emphasis had been put on an excellent detection and measurement of charged particles in a large volume tracking chamber. Silicon detectors placed near the beam pipe allowed secondary vertices to be reconstructed. Such vertices may arise in particular from the decay of short-lived particles such as those containing a bottom quark. The D0 collaboration had decided to rather emphasise precise, homogeneous and hermetic calorimetry (Fig. 5). For Run II, the CDF central tracker was entirely rebuilt, and both the calorimetry and muon detection coverage extended. In the case of D0, the muon coverage was also improved, but the main modification has been the introduction of a superconducting solenoid inside the calorimeter, and within it of a totally new tracking system. In particular, silicon detectors were also installed in D0, so that the intrinsic capabilities of the two experiments are now much more similar than they were during Run I. With the anticipated luminosity, and therefore interaction rate, increases, the silicon detectors of both CDF and D0 will have to be replaced at the end of 2005 by new "radiation hard" ones.



▲ **Fig. 4:** A photograph of the CDF detector, opened during the installation of the silicon detector. From the inside to the outside, the tracking chamber, the calorimeter and the muon chambers can be seen.



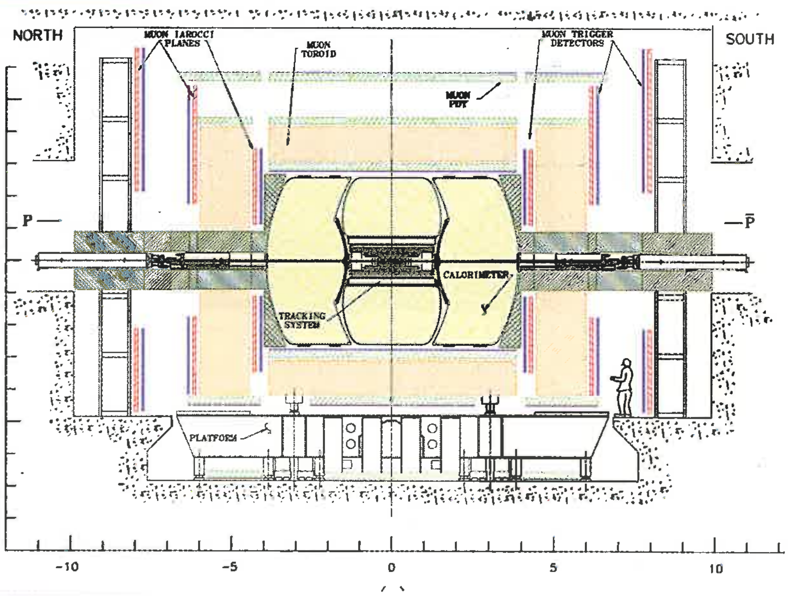
▲ **Fig. 3:** Reach of the Standard Model Higgs boson search at the Tevatron. The curves represent, as a function of the Higgs boson mass, the luminosity which has to be delivered to each of the two experiments in order to allow an exclusion at 95% confidence level (in purple), a 3σ evidence (in green), or a 5σ observation (in blue) to be achieved. (From Ref. 7.)

The Run II of the Tevatron will offer a broad range of physics opportunities:

- The higher luminosity and the increased production cross section will allow a large sample of top quarks to be collected. Because of its large mass (forty times the mass of the second heaviest quark), the top quark properties are quite unusual, and their detailed investigation will become possible. In particular, the uncertainty on its mass could be reduced to ± 2 GeV.

- It should also be possible to reduce to ± 30 MeV the uncertainty on the mass of the W boson. As can be inferred from Fig. 2, this improved precision of the top quark and W boson masses would allow the mass of the Standard Model Higgs boson to be much better constrained. It could even well be that these indirect constraints conflict with the mass lower limit obtained at LEP, which would point to some new physics beyond the Standard Model.

- Direct searches for phenomena beyond the Standard Model will also be pursued, greatly benefiting not only of the higher



◄ **Fig. 5:** A schematic cut view of the D0 detector, showing the various components. Inside out starting from the beam pipe: the silicon and scintillating fiber tracking systems, the superconducting solenoid, the uranium-liquid argon calorimeter, the iron toroid with the muon detectors.

luminosity but also of the higher energy, compared to Run I. For reasons which cannot be addressed in this short article, it is commonly expected that the Standard Model, even if it is experimentally very successful, will break down at a scale not much beyond the few hundred GeV presently probed, therefore possibly within reach of the upgraded Tevatron.

- A huge number of bottom quarks will be produced, which will allow very difficult, but unique, measurements to be performed. In particular, it will be possible to study hadrons containing both a bottom and a strange quarks, which cannot be efficiently produced at the current "b-factories" (5), thus providing additional constraints on the CKM (Cabibbo-Kobayashi-Maskawa) quark mass matrix [8].
- Detailed studies of QCD (quantum chromodynamics, the theory of strong interactions) at the TeV scale will be performed, not only interesting by themselves, but also possibly revealing a quark substructure.

While the above topics can already be addressed with an integrated luminosity of 1 or 2 fb^{-1}, corresponding to Run IIa, the search for the Standard Model Higgs boson will really need the 10 fb^{-1} or more anticipated for Run IIb, as can be seen in Fig. 3. With such an integrated luminosity, it should be possible to exclude at 95% confidence level the whole mass range suggested by LEP precision studies. More optimistically, a 3σ (three standard deviation) evidence, perhaps even a 5σ discovery, could confirm the LEP hint at 116 GeV.

At the time of writing (November 2002), both CDF and D0 are essentially fully commissioned. Since the beginning of Run II, the Tevatron luminosity has been steadily increasing, and has already reached half the Run IIa design value. The current goal is to accumulate before next summer two to three times the integrated luminosity collected during Run I, which, together with the energy increase and with the improvements brought to the detectors, should provide the first harvest of many years of forefront results.

Footnotes:

(1) Energies and masses are measured in electron-Volt (eV) units. One MeV is worth 10^6 eV, one GeV 10^9 eV, and one TeV 10^{12} eV.

(2) Instantaneous interaction rates are proportional to the luminosity of the collider, measured in $cm^{-2}s^{-1}$, and to the cross section of the process considered, measured in cm^2, or rather in pico- or femtobarns (10^{-12} or 10^{-15} barns, where one barn is worth 10^{-24} cm^2). For an integrated luminosity of N pb^{-1} (N fb^{-1}), N events are produced by a process with a cross section of 1 pb (1 fb).

(3) The Standard Model of electroweak interactions is based on the gauge group SU(2)×U(1), with three generations of quarks and leptons. The gauge symmetry is spontaneously broken by the Higgs mechanism.

(4) The SLC (SLAC Linear Collider of Stanford, California) also contributed to these results.

(5) PEP II at Stanford (California), and KEK-B at Tsukuba (Japan)

References

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[2] The CDF Collaboration web site: http://www-cdf.fnal.gov

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[4] "Observation of Top Quark Production in pbar-p Collisions with the Collider Detector at Fermilab", the CDF Collaboration, Phys. Rev. Lett. 74, 2626 (1995);

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[5] The LEP Electroweak Working Group web site: http://lepewwg.web.cern.ch

[6] The LEP Higgs Working Group web site: http://lephiggs.web.cern.ch

[7] Report of the Higgs Working Group of the Tevatron Run 2 SUSY/Higgs workshop (hep-ph/0010338): http://arxiv.org/abs/hep-ph/0010338

[8] See for instance: "A violation of CP symmetry in B meson decays", Y. Karyotakis and G. Hamel de Monchenault, Europhysics News, May/June 2002.