IL NUOVO CIMENTO Vol. 34 C, N. 6 Novembre-Dicembre 2011
DOI 10.1393/ncc/i2011-11046-1

Colloquia: IFAE 2011

The search for the Standard Model Higgs at the Tevatron

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(ricevuto il 29 Luglio 2011; pubblicato online il 29 Novembre 2011)

Summary. — I present a short summary of the Higgs searches at the Tevatron as of Summer 2011. In this paper I will highlight a few turning points of this search.

PACS `14.80.Bn` – Standard-model Higgs bosons.

1. – Introduction

The original title of this talk was "Highlights of High P_T Physics at the Tevatron", but I found rather natural to rename it. I hope it will become understandable during the reading that the quest for the Higgs is a Tevatron story and indeed, the last five years of Tevatron running saw a strong increase of activities on this topic which is now the cornerstone of all high-P_T analyses for both experiments.

2. – Searching the SM Higgs boson

The understanding of the Electroweak Symmetry Breaking (EWSB) mechanism was one of the key ingredients of the physics program for Tevatron Run II. However, as the original plan aimed to deliver $\simeq 2\,\mathrm{fb}^{-1}$ to each experiment, the assumption was to access information about the Higgs indirectly, by precision measurement of M_W and M_{top}. It was only when the option of higher luminosity and of longer running for Run II was set on the table that we realized that even the direct searches were going to be an option. Despite the promise of an integrated luminosity $O(10\,\mathrm{fb}^{-1})$ by the end of Run II, for the first period—until about 2005—the direct searches for the Higgs were pursued by a small group of enthusiast whom were fighting against the low luminosity as by the end of 2005 Tevatron delivered just $< 2\,\mathrm{fb}^{-1}$ (see fig. 1).

By mid-2006, the delay of LHC startup, combined with a good integrated luminosity and a thorough understanding of the detectors, brought the first serious constraint on the SM Higgs [1] where the Tevatron set the 95% CL limit to a $M_H \simeq 160\,\mathrm{GeV}/c^2$ to about 4 times the SM cross section. Since then both experiments have refocused their efforts on the search for the SM Higgs. First step was to re-assess (and change accordingly) all triggers to maximize collection of Higgs-enriched events.

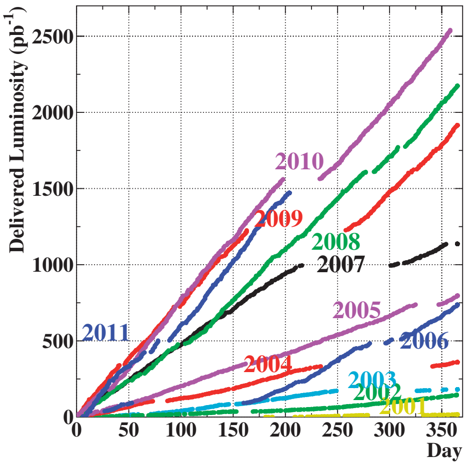

Fig. 1. – Tevatron delivered luminosity in pb^{-1} by calendar year.

2·1. *The Environment*. – Tevatron is the only proton-antiproton collider in operation, and at a c.o.m. energy of $\sqrt{1.96}$ TeV it delivered an integrated luminosity of about $10\,\mathrm{fb}^{-1}$ by the end of April 2011. The two detectors (CDF and D0) collected, with an average data taking efficiency $> 80\%$, more than $8\,\mathrm{fb}^{-1}$ each. They will continue operations until the end of FY 2011 (September 30, 2011) when Tevatron closes after almost 26 years of operation([1]).

The Tevatron operated until 1996 at a peak luminosity $L \simeq 10^{30}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Its upgrade was designed to reach $10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and detectors, as well as their electronics and trigger system, were designed (and largely rebuilt between 1996 and 2001) to cope with such an instantaneous luminosity. In reality, over the last years, collisions routinely start at $L >$ 3–4 $10^{32}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Both collaborations were able to change their triggers and front-end electronics systems to deal with such a large L. The online and offline reconstruction programs have to deal with an average number of $\simeq 4$ interactions per crossing.

The large quantity of data means that the three-level trigger system, writing data at a rate of 100–200 Hz, must reject $> 99.99\%$ of interactions (rate > 50 MHz).

2·2. *Physical objects*. – At CDF and D0, the key physical objects are leptons and jets. Jets are defined by fixed cone algorithms (at trigger and offline level) and, in order to go back to the original parton energy and direction, a number of corrections are applied to the measured jet properties. Therefore the "raw" energy is corrected back by a procedure generically defined "Jet Energy Scale" (JES in short) [2]. In the following by leptons I mean either charged (e and μ) or neutral (ν). Neutrinos are identified by the imbalance of the measured transverse energy (defined at single calorimeter tower level), MET. When JES corrections are applied, MET is modified accordingly. Electrons are high-P_T tracks pointing to a calorimetric EM cluster. In order to separate electrons by fakes, its cluster must be electromagnetic and the related shower is required to have a profile consistent with an electron. Finally track must have a measured P matching the measured energy. Muons are identified as stub in the outer muon chambers, matched to a track in the COT. In several analyses, secondary (*i.e.* non-trigger) muons are also defined using looser requirements in order to improve the acceptance for specific channels. As in

([1]) First proton-antiproton collisions were recorded on October 13, 1985 at a c.o.m. energy of 1.6 TeV. At that time only the still incomplete CDF detector was operating.

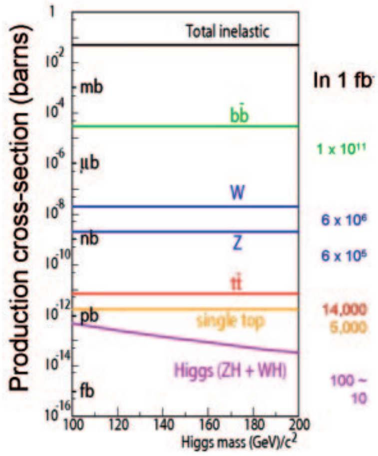

Fig. 2. – Cross section for several processes relevant to the Higgs search.

Higgs searches, high-P_T leptons (e and μ) are mainly used to identity W and Z decays, we also require them to be isolated. This topological requirement futher removes events in which jets fake leptons.

2·3. *Relevant processes.* – In fig. 2 a list of cross sections at c.o.m. energy of 1.96 TeV is shown. It is pretty obvious that, in order to access the EWSB sector, which is at or below the pb level, a strong trigger system is required. Also, in the end, offline analyses must deal with a number of background processes.

At the Tevatron, information on the Higgs sector can be gathered via indirect SM processes that are affected by the Higgs or directly searching for this boson in one of its decay channels. For long time, until the available luminosity was $\approx 1\,\text{fb}^{-1}$, both CDF and D0 have focused on the indirect searches. Precision measurements of M_W and M_{top} set limits on the Higgs as the two masses are related to it through virtual loops.

Direct searches can exploit the Higgs production via $gg \to H$ fusion. For $M_H \le 130\,\text{GeV}/c^2$ the dominant decay ($\approx 80\%$) is $H \to bb$. Therefore this production channel provides a final state with a topology identical to the $p\bar{p} \to bb$ process which has a cross section many orders of magnitude above the Higgs. While the LHC experiments, thanks to the large number of Higgs produced, can exploit this production channel via the (suppressed) $H \to \gamma\gamma$ decay, the Tevatron experiments do not enjoy such a large statistics. The range $M_H \le 130\,\text{GeV}/c^2$ is explored by looking at Higgs+V (either Z or W) production. For larger M_H the Higgs boson decays into VV pairs (WW, ZZ) in which one of the two can be virtual, depending upon the mass. The easiest and background suppressed option, is to look for final states with 4 leptons (at least two charged).

3. – Indirect searches

As already mentioned, within the SM, M_W has (logarithmic) corrections due to loops containing the top quark and the Higgs boson. Therefore the precision measurement of M_W and M_{top} provides a constrain on the Higgs.

So far the single best measurement of M_W belongs to D0 that, with $1\,\text{fb}^{-1}$ obtains $M_W = 80.401 \pm 0.021(\text{stat}) \pm 0.038(\text{syst})\,\text{GeV}/c^2$. The World Average accuracy is $80.399 \pm 0.025\,\text{GeV}/c^2$. In this value Lep II and Tevatron measurements weights evenly. CDF last measurement was done with $200\,\text{pb}^{-1}$ and it was statistically limited. We expect the

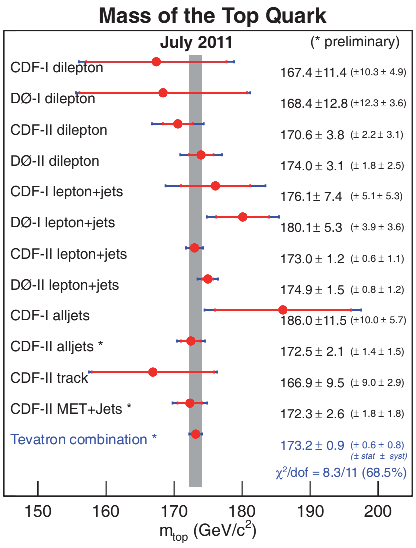

Fig. 3. – Top mass measurements.

release of a new measurement by Fall 2011, with an expected accuracy of $25\,\mathrm{MeV}/c^2$. A single measurement with a precision that should match the WA.

Measurement of the top quark mass at the Tevatron can be performed in many ways and exploiting the various decay channels. The typical strategy is to measure an observable sensitive to the top mass (there are several) and compare it to templates of the same observable as a function of M_{top}. By the maximization of a likelihood fit of the observable to templates containing signal and background the experiments determine the top mass. Two of the most important measurements are performed in the $l + jets$ and dilepton channels. $l + jets$ refers to the topology in which one of the two Ws coming from top decays leptonically and the final state contains four jets. In the dilepton case both Ws decay leptonically and the final state contains only two (b) jets. One can then reconstruct the top quark mass by taking into account the various ambiguities. As in

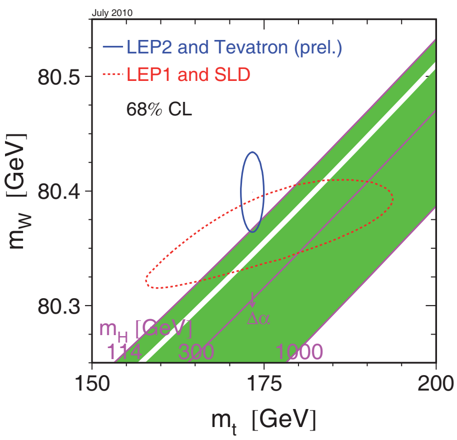

Fig. 4. – Higgs limit in (M_{top}, M_W)-plane.

the $l + jets$ case two of the jets come from a W decay, JES can be constrained *in situ* within the measurement itself. For example with $5.6\,\text{fb}^{-1}$ CDF measured M_{top} in the $l + jets$ channel with an uncertainty of $0.9\,\text{GeV}/c^2$ due to statistical and JES combined and $0.9\,\text{GeV}/c^2$ due to the remaining systematics. Dilepton case is different as the two jets are due to b quarks but in this case the MET is contributed by two neutrinos. As the systematics of the two channels are different, it is important to use them both in the final combination. The new value of the top mass is obtained by using all measurements performed at the Tevatron in $\approx 6\,\text{fb}^{-1}$. Its value, $172.3 \pm 0.9\,\text{GeV}/c^2$ [3] where statistical uncertainty is 0.6 and systematics $0.8\,\text{GeV}/c^2$ has an overall uncertainty below $1\,\text{GeV}/c^2$. It is the first time we go below $1\,\text{GeV}/c^2$ and it will be one of the lasting heritages of the Tevatron (see fig. 3). While this value is not yet included in the current constraints on M_H (see fig. 4) it will further refine its search.

4. – Direct searches

As stated, for $M_H \simeq 130\,\text{GeV}/c^2$, the best way is to search this boson when produced in association with W or Z despite the cross section being an order of magnitude below gluon fusion. When Higgs starts decaying into W pairs, the gluon fusion channel becomes more important as it is easier to trigger on the final state topology and to select it offline.

4·1. *Low-mass Higgs.* – In the low-mass region, WH and ZH candidates are selected by looking at events where the vector boson is produced in association with two or three jets. Therefore the typical topology we deal with is: two leptons (charged, neutral or a combination) and 2–3 jets where one (in most of the analyses two) has been tagged as containing heavy flavour. The backgrounds we must reject are: $t\bar{t}$, WW, WZ, single top EWK production, $W + jets$ and finally multijet events. $W + jets$ and multijet events are measured on data and/or by using a mix of data and Monte Carlo prediction. Multijet events are especially dangerous as, despite the low probability of jets faking W or Z production, their cross section is so large that they remain an important background. In order to estimate di-boson, $t\bar{t}$, single top production, we use theoreticals prediction that are also compared to observation. Indeed both experiments performed the task to measure the cross section of each process. Recently CDF announced a 3 σ evidence of WW/WZ decaying into $l\nu$+heavy flavours [4] measuring a cross section (relative to SM) of $1.08^{+0.26}_{-0.40}$. A channel perfectly emulating the WH production.

In the end we had to develop individual strategies aimed to each of the backgrounds. In this effort we also found some discrepancies with SM predictions. The most important one is the excess in the W + 2 jets M_{jj} distribution [5]. It was found by an analysis originally looking for the $WW/WZ \to jj$ process in the pretagged sample. Despite the clear excess (well above 3 σ) in the untagged sample it defies any characterization. However, as for the background we largely rely on Monte Carlo, work is in progress to better understand whether this excess is real or it is due to a mismodeling of the background itself. Of course we still do not see any excess and set limits. It is remarkable that, in the final combination, $WH \to bb$, $ZH \to \nu nubb$ and $ZH \to ll\nu\nu$ channels bear the same weight.

4·2. *High-mass Higgs.* – For $M_H \geq 135\,\text{GeV}/c^2$ the decay channel into WW (with one or both W on mass shell) becomes more important. By looking into final states with 4 leptons, backgrounds are limited to (mostly) di-boson and $t\bar{t}$ events. In this analysis the most important effort is to widen the acceptance. As CDF has a large number of gaps into the muon detectors it is not possible to limit ourself to the central region ($|\eta| < 1$).

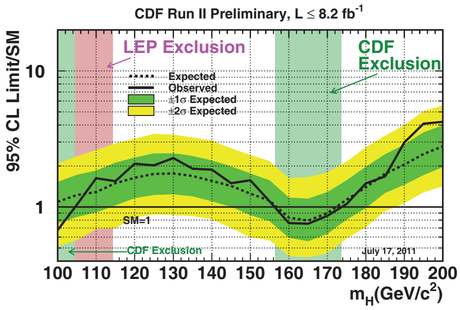

Fig. 5. – Summer 2011: CDF limits.

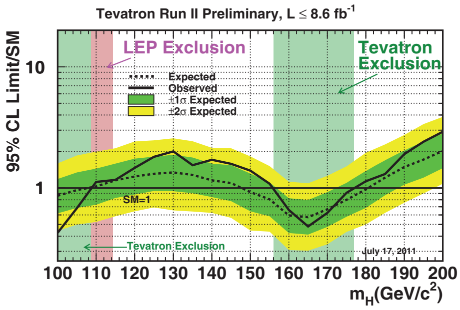

Fig. 6. – CDF and D0 combined limits.

We pursued a strategy aimed to define different categories of *muons*. In this way the experiment extended its coverage up to $|\eta| \approx 2$ and significative limits to Higgs at high mass were obtained (see fig. 5). The most recent CDF and D0 combination is shown in fig. 6.

5. – Conclusion

Two decades of high-P_T physics at the Tevatron allowed the two collaborations to quickly refocus their physics program to search for the Higgs and compete with the LHC experiments. Directs limits since LEP were set in the high-mass region (recently confirmed by LHC results). In the low-mass region, exploting the b tagging capability and a thorough understanding of the different backgounds, CDF and D0 are now close to exclude at 95% CL a Higgs of $115\,\text{GeV}/c^2$. These results in direct searches are complemented by the indirect searches that by fitting precision measurements of M_W (at this point still Tevatron and LEPII combined) and of the top mass (Tevatron combination reached an uncertainty of less than $1\,\text{GeV}/c^2$) set strong limits to the Higgs mass.

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