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The search for the Standard-Model Higgs boson at hadron colliders

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Summary. — This paper summarises the results of the search for the Standard-Model Higgs boson at the Tevatron and LHC experiments. With their ever-increasing integrated data samples, the CDF and D0 experiments have now ruled out the possibility for the existence of the Higgs boson with mass in the 163–166 GeV/c^2 window. The excluded region is supposed to grow over time as more data is collected and experimentalists refine their searches. At the LHC, data taking at 7 TeV center-of-mass energy has recently started and up to 1 fb^{-1} is expected to be collected by the end of 2011, before a shutdown will halt operations for about a year. Sensitivity projections for the ATLAS and CMS Collaborations are discussed.

PACS 13.85.Rm – Limits on production of particles.
PACS 14.65.Jk – Other quarks (*e.g.*, 4th generations).
PACS 14.80.Bn – Standard-model Higgs bosons.

1. – Description

In the Standard Model (SM), the Higgs mechanism is responsible for the observed breaking of the $SU(2)_L \otimes U(1)$ symmetry, yet the Higgs boson remains the only SM particle that has not been directly observed. The most stringent lower bound on its mass comes from the direct searches at the four LEP experiments, giving $M_{\text{Higgs}} \geq 114.4\,\text{GeV}/c^2$ at 95% confidence level (CL) [1]. Fits to precision measurements of several electroweak parameters suggest the mass of the SM Higgs boson to be $< 157\,\text{GeV}/c^2$ at 95% CL [2]; different authors obtain very similar conclusions [3]. Therefore the production of the Higgs boson is kinematically within reach of the existing hadron colliders such as the Tevatron operating at 1.96 TeV center-of-mass (c.o.m.) energy, and the LHC currently working at 7 TeV c.o.m. energy. The biggest challenges in the Higgs searches consist in its very low production cross section with respect to other standard model processes, and in the fact that its signature is easily mimicked by backgrounds with much larger cross sections. Assuming SM interactions of the Higgs boson with other particles, its production is expected to happen at both colliders mainly through gluon-gluon fusion, or in association with a W or Z boson with smaller cross sections. The branching ratios

(BR) for the Higgs boson are completely determined once its mass is known. In particular, for masses $110 \leq M_{\text{Higgs}} \leq 135\,\text{GeV}/c^2$ (referred to as "low mass" in the following) the $\text{BR}(H \to b\bar{b})$ is dominant, being $\sim 75\%$ for $M_{\text{Higgs}} = 115\,\text{GeV}/c^2$. In the same mass range, the Higgs decay through loop diagrams to two photons is of experimental interest thanks to the very good photon energy resolution, although the $\text{BR}(H \to \gamma\gamma)$ is only $\sim 0.2\%$. At masses $M_{\text{Higgs}} \geq 135\,\text{GeV}/c^2$, the $\text{BR}(H \to WW)$ quickly saturates; different strategies have thus been set up for the two mass regions.

2. – Low mass Higgs searches

The main focus at the Tevatron on the search for low mass Higgs is on the associated production, *i.e.* WH or ZH where $H \to b\bar{b}$. The additional leptons which can result from the decay of the W or Z bosons, whether detected directly or indirectly through missing transverse energy ($\not\!\!E_T$), can be used to suppress backgrounds at the expense of lower cross section for VH as compared to $gg \to H$. The Higgs boson is expected to decay mostly to a pair of b-quarks; all analyses require at least one jet to be tagged as a b-quark jet, and split the samples according to the b-jet multiplicity. Machine learning techniques are used to enhance discrimination between the hypothetical Higgs signal and the many backgrounds. The analyses presented here use on average $4.4\,\text{fb}^{-1}$ of data per experiment; the numbers quoted in this section always refer to the hypothesis of $M_{\text{Higgs}} = 115\,\text{GeV}/c^2$. At the Tevatron due to the limited available dataset the $H \to \gamma\gamma$ search is sensitive only to non-SM physics enhancing the production cross section. On the other hand, at pp collisions at 7 TeV the cross section for SM backgrounds rises much faster than for the WH/ZH signal, thus the process $gg \to H \to \gamma\gamma$ is used as the main channel for investigation of low mass Higgs at the LHC experiments.

2·1. *$ZH \to \ell^+\ell^- b\bar{b}$ search.* – This search has the advantage of allowing a full reconstruction of the final state, but also the drawback of having small acceptance to Higgs production due to low cross section and branching ratios. Less than one Higgs events/fb^{-1} is expected by each collaboration. The signal is isolated by means of machine-learning techniques; in particular CDF uses a two-dimensional neural network, and D0 boosted decison trees. The CDF (D0) Collaboration analyzes 4.1 (4.2) fb^{-1} of integrated luminosity, and sets limits on the Higgs cross section times branching ratio of less than 5.9 (9.1) times the values expected from the SM at 95% confidence level, assuming $M_{\text{Higgs}} = 115\,\text{GeV}/c^2$ [4, 5].

2·2. *$WH \to \ell\nu b\bar{b}$ search.* – The main backgrounds are the production of W bosons in association with heavy flavour quarks, and events with singly or pair produced top quarks. Both collaborations observed single top production in a nearly identical dataset [6]. The CDF Collaboration uses the matrix element technique to discriminate the signal from the backgrounds, while D0 uses neural networks. The collaborations expect to collect about 4 Higgs events/fb^{-1}, and backgrounds are finally discriminated with the use of artificial neural networks. The CDF (D0) Collaboration analyzes 4.8 (5.0) fb^{-1} of integrated luminosity, and set limits on the Higgs cross section times branching ratio of less than 3.3 (6.9) times the values expected from the SM at 95% confidence level, assuming $M_{\text{Higgs}} = 115\,\text{GeV}/c^2$ [7, 8].

2·3. *$WH/ZH \to \not\!\!E_T b\bar{b}$ search.* – This search is devised to have large acceptance to events where $ZH \to \nu\bar{\nu}b\bar{b}$. Due to limited charged lepton identification coverage, and to the difficulty of identifying taus, it has also large acceptance to $WH \to \ell\nu b\bar{b}$ events where the leptons are mostly taus and electrons reconstructed as jets, or non-reconstructed muons. The QCD multijet background dominates by far the sample due to large fluctuations in the jet energies measurements giving rise to an instrumental $\not{E}_T$ signature. Both collaborations use multivariate techniques to suppress the dominant QCD background. CDF measures the single top production cross section in the same dataset [9]. About 4 Higgs events/fb^{-1} are expected by each collaboration. The CDF (D0) Collaboration analyzes 3.6 (5.2) fb^{-1} of integrated luminosity, and set limits on the Higgs cross section times branching ratio of less than 6.1 (3.7) times the values expected from the SM at 95% confidence level, assuming $M_{\text{Higgs}} = 115\,\text{GeV}/c^2$ [10-12].

2˙4. $H \to \gamma\gamma$ *search.* – The signal productions that are considered in the search include the gluon fusion, the WH/ZH associated productions, and the vector boson fusion (VBF). The main sources of background are QCD di-photon production, $\gamma + \text{jet}$ and di-jet productions where the jets fake the photons signature. D0 uses a neural network to suppress by a factor of two the latter background, with negligible signal loss. To search for the Higgs signal, CDF and D0 look for a mass peak in a mass window around the assumed Higgs mass, where they expect about 0.5 events/fb^{-1}. CDF sets a limit of about 20 times the SM prediction at 95% confidence level for Higgs mass in the range 110–150 GeV/c^2 using 5.4 fb^{-1} [13], while D0 sets a similar limit using only 2.7 fb^{-1} of data [14].

3. – High mass Higgs

The high mass region, *i.e.* $M_H > 135\,\text{GeV}/c^2$, is the most sensitive to the hypothetical Higgs presence at both the Tevatron and LHC colliders. Here experimenters focus on the favored $H \to WW$ decays, where the Ws decay leptonically, *i.e.* the $\ell\nu\ell\nu$ final state; hadronically decaying taus are not considered in the current version of the analyses.

3˙1. $H \to W^+W^-$ *search.* – The signal signature allows for leptons, $\not{E}_T$, and eventually jets to open acceptance to HW/HZ and VBF Higgs production. The dominant background of WW production has been measured in this channel [15]. A signal and background probability is computed by matching reconstructed objects to final state particles, and computing the leading order matrix element for the process. This and other kinematic distributions are used as inputs to a neural network employed to discriminate the signal from the many backgrounds. The amount of collected Higgs events are about 7/fb^{-1}. The CDF (D0) Collaboration analyzes 4.8 (5.4) fb^{-1} of integrated luminosity, and set limits on the Higgs cross section times branching ratio of less than 1.4 (1.6) times the values expected from the SM at 95% confidence level, assuming $M_{\text{Higgs}} = 165\,\text{GeV}/c^2$ [16, 17]. The two results produced have been combined thus analyzing effectively more than 10 fb^{-1}, giving the first exclusion of the SM Higgs production in the range 163–166 GeV/c^2 [18]. This is the first limit set on the existence of a SM Higgs boson after the closure of the LEP collider.

The search at the LHC collider will proceed in a very similar manner. The CMS Collaboration expects to exclude the region 145–190 GeV/c^2 using the above channel and the $H \to ZZ \to \ell\ell\ell\ell$ decays, analyzing 1 fb^{-1} collected at 7 TeV, and expand the excluded range by about 5 GeV/c^2 per side once combining with the corresponding ATLAS results [19].

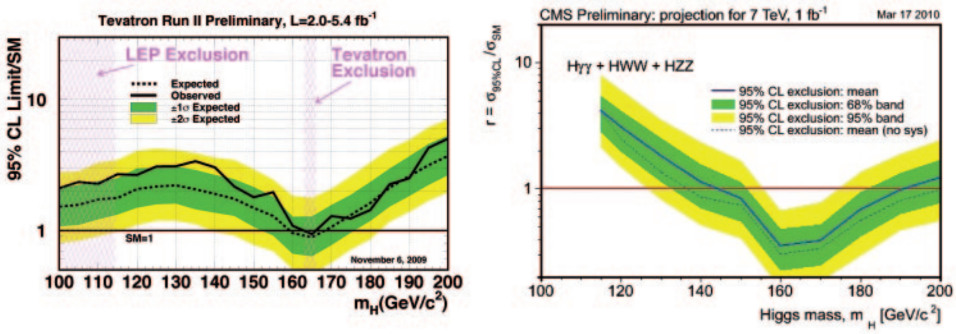

Fig. 1. – Limit on $\sigma_H \times$ BR at 95% confidence level, as a function of the Higgs mass. The left plot shows the combined CDF and D0 searches in all analyzed channels. The right plot shows the CMS projection for $1\,\text{fb}^{-1}$ of data collected at 7 TeV, expected by the end of 2011.

3·2. *$H \to W^+W^-$ search in the presence of a 4th generation of quarks.* – A fourth generation of fermions is not excluded by the SM; fits to electroweak data allows the existence of a 4th generation of quarks with masses in the 300–600 GeV/c^2 range, *i.e.* above the current Tevatron experimental limits. In this scenario $gg \to H$ cross section is enhanced by a factor of ~ 9 due to the presence of additional heavy quarks in the triangle loop. The analysis strategy is similar to the one used in the SM Higgs case, except that the collaborations consider only the $gg \to H \to WW$ signal, and ignore the contributions from WH, ZH, and VBF. The Tevatron experiments exclude a SM-like Higgs boson with a mass in the range 130–210 GeV/c^2 [20]. The CMS Collaboration expects to exclude the existence of the Higgs boson in the presence of a 4th generation of fermions all the way up to 570 GeV/c^2 using $1\,\text{fb}^{-1}$ at 7 TeV [19].

4. – Conclusion and the near future

The search for this elusive particle at the Tevatron takes advantage of two well-understood detectors, where dedicated searches are deployed for most of the production and decay modes predicted by the SM. All searches in the different channels are then combined to give the Tevatron upper limits to the production of a SM Higgs boson, or its exclusion. At low mass, the next natural step toward this goal would be to measure diboson production cross section with the same signature as WH/ZH: $WZ \to \ell\nu b\bar{b}$ and $ZZ \to \nu\bar{\nu}b\bar{b}$. Projections indicate that the Tevatron experiments should start excluding the 115 or more GeV/c^2 Higgs using $10\,\text{fb}^{-1}$ of data. Some improvements are needed to exclude the low mass range above the LEP bound with large confidence. As can be seen in fig. 1, the two Tevatron experiments have now excluded the presence of the SM Higgs boson in the mass range 163–166 GeV/c^2. The Tevatron collider is expected to more than double the available dataset by the end of 2011, and projections of the current sensitivity gives the ability, in absence of a signal, to exclude the mass range region up to 185 GeV/c^2. Refining the analyses might extend the exclusion by extra 5 GeV/c^2 per side. If an excess is to be found in the allowed region, there are sizeable chances of observing a 3σ excess of Higgs production.

Discovery of the Standard-Model Higgs boson at $5\,\sigma$ significance is very unlikely at the Tevatron, unless the production rate should be enhanced, for example by a fourth generation of quarks, whose direct and indirect search is being actively pursued at the Tevatron, and planned for the LHC experiments. The search for the Higgs production at the LHC with the first data at 7 TeV would be very similar at high mass to the Tevatron ones, due to the large cross section. The CERN management predicts to collect about $1\,\mathrm{fb}^{-1}$ of data by the end of 2011: given the larger cross sections, this amount of data will give the chance to CMS and ATLAS Collaborations to obtain comparable sensitivity to the concurrent Tevatron results. At low mass there are ongoing studies on looking at WH/ZH production with the signature of a boosted Higgs-jet. For the time being, the main search mode is still considered to be $H \to \gamma\gamma$ that will have sensitivity to SM cross sections only after colliding beams with $E_{com} = 14\,\mathrm{TeV}$ and integrating a very large dataset. At high mass, using $1\,\mathrm{fb}^{-1}$ at 7 TeV the CMS and ATLAS Collaborations expect each to exclude the Higgs boson with mass in the region 145–190 GeV/c^2. The combination of the two results should extend the sensitivity by about $5\,\mathrm{GeV}/c^2$ per side. While there is ongoing discussion on whether to extend the Tevatron up to 2014, possibly giving the chance to integrate almost $20\,\mathrm{fb}^{-1}$ and have a strong statement for a Higgs in the low mass regions, the long-term interest is in the LHC configuration at 14 TeV com energy. With a luminosity of the order of $100\,\mathrm{fb}^{-1}$ or more, it will be possible to discover the Higgs boson in all the theoretically favored mass range up to almost 1 TeV, and study the detailed properties of this particle as its mass, width, and couplings to other known particles.

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