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Standard Model Higgs Searches at the LHC

L.R. Flores-Castillo, on behalf of the ATLAS and CMS Collaborations
University of Wisconsin-Madison

The search for the Higgs boson, a key component in the Standard Model description of electroweak symmetry breaking, is a major goal of the physics program at the Large Hadron Collider (LHC) at CERN. Both ATLAS and CMS, experimental collaborations at LHC, have done extensive simulation and performance studies to optimize their strategies for this search. Some of these studies are discussed, as well as the resulting discovery potential (as a function of the Higgs boson mass), for the main experimental signatures that will be addressed by the two collaborations.

1. Introduction

One of the main experimental goals of the LHC physics program is the search for the Higgs boson, a scalar particle predicted in the Standard Model as a key component of the electroweak symmetry breaking mechanism [1]. So far, direct experimental searches for the Higgs boson have been able to put a lower limit on its mass (114.4 GeV/c^2 at 95% confidence level). Also, using the recent precise measurements of the W and top masses, the LEP Electroweak Working Group [3] quotes an upper limit of about 144GeV/c^2 (95% confidence level; this value increases to 182GeV/c^2 when including the direct search limit of 114.4GeV/c^2 [2]).

The ATLAS and CMS experiments, both close to completion and scheduled to begin taking data in mid 2008, have been designed to be sensitive to many of the possible signatures of the Standard Model Higgs boson. This paper is a partial overview of the corresponding searches. Section 2 briefly describes the main production mechanisms of the Higgs boson; the next section discusses some of the decay channels of interest for experimental searches. Section 4 then goes over the expected experimental conditions at the LHC. Section 5 discusses a selection of search channels, and the expected significance of these searches is summarized on section 6 for both ATLAS and CMS.

2. Standard Model Higgs production

Figure 1 shows the Higgs production cross sections, in the Standard Model, as a function of the Higgs mass for the most important processes at the LHC. For the mass range favored by current limits (and well above, up to about 1 TeV), the main production mechanism is gluon-gluon fusion via a top quark loop (labeled as $gg \to H$ in the plot); *Vector Boson Fusion* (VBF), labeled Hqq in fig. 1) is about an order of magnitude below gg fusion; however, VBF-restricted searches can still be very powerful, as we'll describe in section 5. Associated production with a W or Z bosons (WH, ZH), and with a top quark pair ($t\bar{t}H$) have even lower cross sections, but can still be used in search strategies. Currently, QCD computations of these cross sections are available at either NLO (next to leading order) or NNLO, with uncertainties of 10-20% for gluon-gluon fusion, ~5% for VBF, ~10-20% for $t\bar{t}H$ and ~5% for WH, ZH production.

3. Higgs decays

Figure 2 shows the branching ratios of the Standard Model Higgs boson as a function of Higgs mass. Below the weak vector bosons are kinematically accessible (at around $2m_W$), the dominant mode is $b\bar{b}$, which is, however, a hard channel to use for searches due to the huge $b\bar{b}$ background. The $H \to \tau\tau$ decay, with a smaller branching ratio, has a much higher potential. The decay into

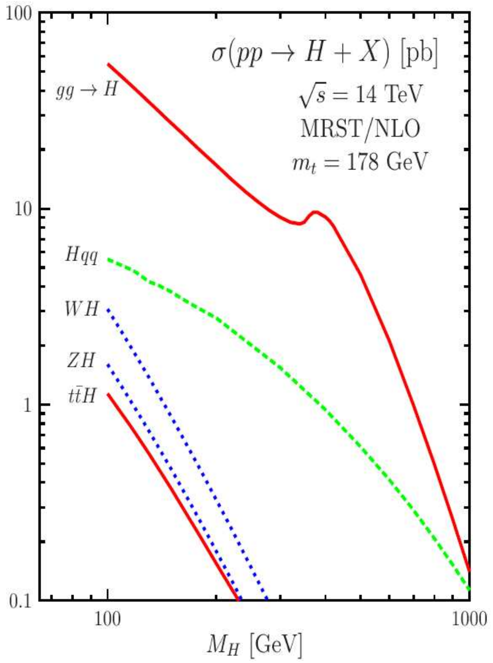

Figure 1. Higgs production cross sections in the main channels at LHC (from [4])

two photons can also be used at low masses if a high enough rejection against jets is achieved.

Once the WW and ZZ modes are available, they provide powerful probes for the search. The former because it takes about 95% of the branching ratio, the latter because, if the two Z bosons decay into lepton pairs, provides a signature that is easy to trigger on, and which allows the full reconstruction of the Higgs mass. For m_H less than about 200 GeV, the natural width of the Higgs boson is well below experimental resolution, and it grows very rapidly after that.

4. LHC startup and physics environment

As of this writing, the LHC startup is well under way. All magnets are already in the tunnel; electrical, cryogenic and vacuum interconnections are in progress, while many ATLAS and CMS detector subsystems, already installed on the caverns, are entering the commissioning phase.

Proton-proton collisions are expected to start in mid 2008 at the full 14 TeV center of mass energy. During the first, “low-luminosity” phase, with an instantaneous luminosity of 10^{33} $cm^{-2}s^{-1}$, each experiment will be able to gather about 30 fb^{-1} of data. Later, the “high-luminosity” phase, at 10^{34} $cm^{-2}s^{-1}$, will run up to an integrated luminosity of the order of 300 fb^{-1}.

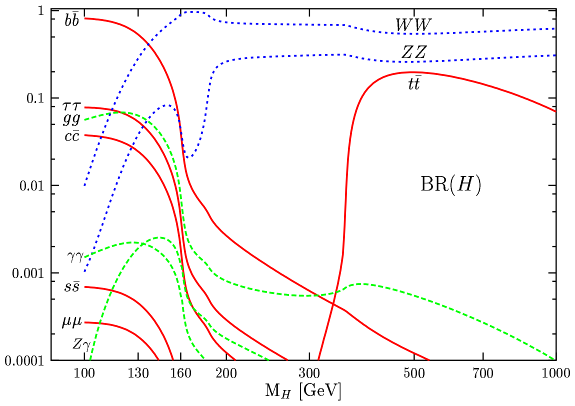

Figure 2. Decay branching ratios of the Standard Model Higgs boson (from [4])

One important consequence of the running conditions at LHC is the fact that, in both regimes, there will be multiple pp interactions per bunch crossing; the expected number is ~ 2 for low luminosity and about 25 for high luminosity, which entails a degradation of the energy resolution and the particle identification capabilities of both detectors. In what follows, we'll be focusing on the low luminosity phase of the Higgs searches.

The total inelastic cross section at LHC is expected to be around 80 mb. On the other hand, starting from a Standard Model Higgs production cross section in the pb range, branching ratios and reconstruction efficiencies will reduce the expected signal rates to the order of fb or tens of fb; i.e., 12 orders of magnitude below the total rates.

The ATLAS and CMS detectors, described in detail elsewhere ([7], [8]), were designed to have powerful identification capabilities in order to cope with this environment. Photon reconstruction, for example, can achieve an 80% efficiency while having a rejection factor of a few thousands against jets. Jet rejection factors of up to 10^5 are expected for electron reconstruction (also for an efficiency around 80%). The rejection against light flavor jets is expected to be of the order of 100 for the identification of B-jets, and higher for tau leptons.

Both detectors also have an excellent lepton energy resolution (of $\sim$ 1-2% for leptons between 20 and 50 GeV), and good performance on the reconstruction of jets and missing transverse energy.

5. Higgs searches

Depending on the Higgs mass, different signatures become more or less relevant for the search. For masses just above the LEP limit, the natural width of the Higgs is of the order of a few MeV, allowing for the hunt of narrow resonances via the decays $H \to \gamma\gamma$ and $H \to ZZ^{(*)} \to 4\ell$. As we get closer to $m_H = 2m_Z$, the 4-lepton channel becomes more significant, as does also the search for $H \to WW \to l\nu l\nu$, in which the invariant mass reconstruction is precluded by the neutrinos, and is hence a number-counting analysis.

Extensive, GEANT-based full simulation studies have been done for both experiments to assess the discovery potential with many signatures. In what follows, a few of these channels are briefly described. For in-depth accounts of these studies, the reader is referred to [9], [10] and [11].

5.1. $H \to \gamma\gamma$

This channel, interesting for Higgs masses below 140 GeV, relies on the precise reconstruction of photon energy and on the high rejection against jets. CMS has a better energy resolution, but the high granularity of the ATLAS liquid Argon calorimeter allows a precise determination of the primary vertex. In the end, both experiments have similar sensitivity on this channel. Currently, both signal and background are computed at NLO. Besides the simple cut-based analysis, both experiments have explored several refinements that improve the signal significance by 30 to 40%, to above 8 for $m_H = 130$ GeV and an integrated luminosity of 30 fb^{-1}.

5.2. $H \to ZZ^{(*)} \to 4\ell$

For m_H above 130 GeV, the 4-lepton channel becomes important due to the precise energy reconstruction that both detectors have for electrons and muons. The main backgrounds for this channel are the continuum ZZ^* production, $Zb\bar{b}$ and $t\bar{t}$. The last two can be strongly reduced using lepton isolation and impact parameter cuts. Also, the non-resonant $t\bar{t}$ background can be reduced requiring the invariant mass of one lepton pair to be close to the Z boson mass. For the ZZ continuum, its $q\bar{q}$ component is known at NLO, and the gluon fusion component is usually accounted for by adding an extra 20%. It is a very clean channel, and has hence been labeled the "golden channel" for the search, but it has a low rate below 130 GeV and around 165 GeV. Elsewhere (and up to about 600 GeV), its expected significance is in excess of 5 sigma for 30 fb^{-1}.

5.3. $H \to WW^{(*)} \to l\nu l\nu$

As mentioned above, the 4-lepton channel has a low sesitivity for m_H around 160 GeV. The reason is precisely the rapid turn-on of the WW mode, which significantly reduces the fraction decaying into ZZ. As a result, the decay $H \to WW^{(*)}$ is especially important around 160 GeV, both because its branching ratio becomes close to 100% and because the "golden" ZZ channel is weakened there. The main backgrounds are $t\bar{t}$, which can be rejected via a jet veto, and the WW continuum, which has different angular correlations than those present in the signal. The two neutrinos in the final state preclude the full reconstruction of the Higgs invariant mass, forcing to cast this analysis as a counting experiment. In turn, this implies that the level of the backgrounds has to be carefully estimated, preferably through the use of control samples, so as to reduce the dependence on MonteCarlo to a minimum. For $m_H \sim$ 130GeV, using NLO cross sections and including the effect of systematic uncertainties, this channel alone could yield a 5 sigma effect with little above 1fb^{-1} of integrated luminosity.

5.4. Vector Boson Fusion searches

Higgs production via VBF has a very distinct experimental signature that can be used to significantly reduce backgrounds. The Higgs decay products are typically central, and come accompanied by two forward "tagging" jets, which are well separated in pseudo-rapidity. On top of this, there is no jet activity in the central pseudo-rapidity region. When one imposes such strong set of conditions on the topology of events, the relatively low level of the VBF Higgs production cross section (as compared to gluon-gluon fusion) is enough to yield significant excesses over Standard Model backgrounds in various channels. One such example is the search of VBF $H \to \tau\tau$.

5.4.1. VBF $H \to \tau\bar{\tau}$

This channel has been studied for two cases: when both taus decay to leptons, and when one tau decays to a lepton and the other to hadrons. Besides the VBF cuts mentioned above, a cut is applied on the missing transverse momentum (due to the neutrinos from the tau decays). Even when both final states contain neutrinos, it is still possible to reconstruct the Higgs mass using the collinear approximation [6]; i.e., assuming that neutrino directions coincide with the visible decay products of the taus, and computing accordingly how they would share the total missing transverse momentum. As a result, the resolution of the Higgs mass reconstruction is limited by the missing energy resolution, which for a 150 GeV Higgs is of the order of 10 GeV/c^2. The main background is in this case the production of Z+2 jets, where the Z decays to a tau pair (and the jets are forward enough to tag the event as VBF).

6. Discovery potential

Figures 3 and 4 summarize the expected significance, as a function of the Higgs mass, of many of the channels that have been studied at ATLAS and CMS, respectively. Both figures correspond to an integrated luminosity of 30 fb^{-1}. Note that the ATLAS estimations are based on LO cross sections, while the CMS plot shown, obtained more recently, corresponds to NLO. Once that difference is taken into account, one finds that both experiments have similar sensitivity.

In a large fraction of the mass range considered, the most significant channel is $H \to ZZ^{(*)} \to 4\ell$.

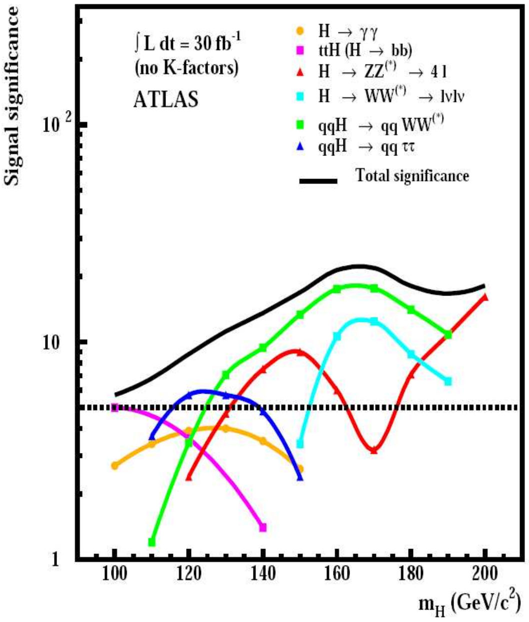

Figure 3. ATLAS discovery potential for the Standard Model Higgs boson searches (from [10]), as obtained from LO cross sections.

Around m_H=160 GeV, the WW modes are also important. The relatively low mass region, favored by current limits, has been studied using many signatures, the results of which can be combined to provide a good discovery potential with an integrated luminosity as low as 10 fb^{-1}.

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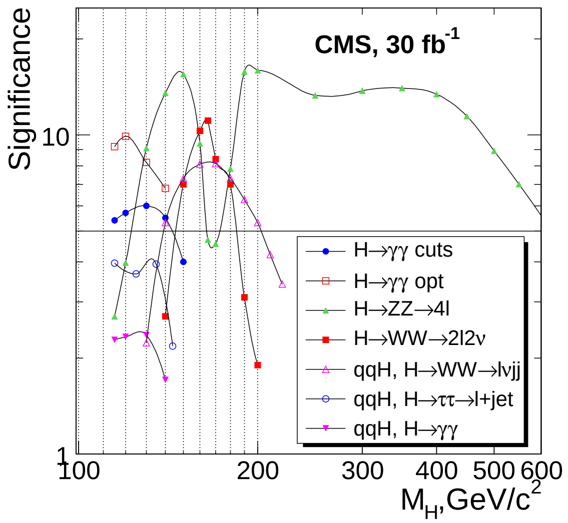

Figure 4. CMS discovery potential for the Standard Model Higgs boson searches (from [11]). NLO cross sections were used.

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