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High mass Higgs search and combined discovery prospects at LHC

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The prospective analyses for the search of the Standard Model (SM) Higgs boson decaying in to $ZZ^* \to 4$ leptons ($4e$, 4μ or $2e2\mu$) or $WW^* \to l\nu l'\nu'$ (l or l' = e or μ) with the ATLAS and the CMS detectors at the CERN LHC pp collider are presented. Signal and background datasets obtained with a detailed Monte Carlo simulation of the detectors response are treated using a complete reconstruction chain. An evaluation of expected 95% C.L. exclusion limit in early Higgs boson searches is presented. It is showed that these two channels alone should allow for excluding the SM Higgs boson in the mass range of 140-230 GeV by the time when CMS or ATLAS collect 1 fb^{-1} of data at a center-of-mass collision energy of 14 TeV. An estimate of how the change of the center-of-mass energy from 14 to 10 TeV would impact the Higgs boson exclusion limits is also given.

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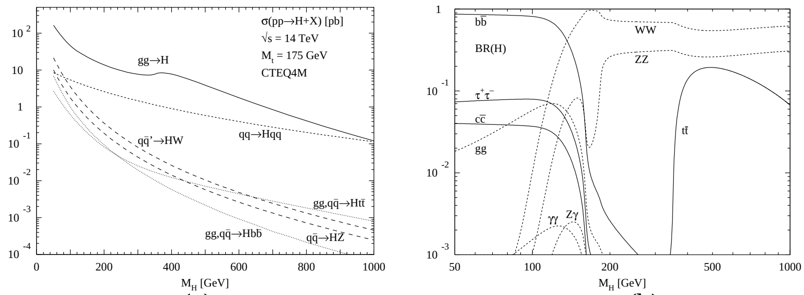
1. SM Higgs Physics as of today

The Standard Model of electroweak and strong interactions predicts the existence of a unique physical Higgs boson, the quanta of the scalar field responsible for electroweak symmetry breaking. Although the mass m_H of this scalar boson is a free parameter of the theory some constraints can be derived. Direct searches at the e^+e^- collider LEP set a lower bound at 114.4 GeV at 95% CL; Tevatron recently excluded the mass range between 160 and 170 GeV at 95% C.L. On the other hand indirect limits can also be inferred from high precision electroweak data exploiting the m_H sensitivity to loop corrections; assuming the complete validity of the SM the Higgs should have mass lower then 168 GeV at 95% CL. Nevertheless the unique request that comes from the SM theory is that m_H should be lower then 1 TeV to respect the unitarity of the vector boson fusion process. Moreover the SM is incomplete because the scale of electroweak symmetry breaking (and the mass of the Higgs) is quantum mechanically unstable. If we want the SM to be valid up to the Planck scale we have to request an incredible fine tuning between the energy scale and the parameters of the theory that force $130 < m_H < 180$ GeV. If we consider the more likely scenario in which the SM is just an effective theory valid up to a lower scale (at which new physics may appear) this request is relaxed. This arguments are enough to justify the effort in searching a SM-like Higgs boson also at higher masses with respect to the range indicated by the SM precise measurements.

2. SM Higgs Physics at LHC

The LHC, which startup is planned for november 2009, is designed to collide protons at a center of mass energy of 14 TeV with a very high luminosity (10^{34} cm^{-2}s^{-1}). The LHC will thoroughly probe the TeV energy regime for the first time and of course one of the main goals of the two general purpose detectors, ATLAS [1] and CMS [2], will be to search for the Higgs in all its possible energy range (100 GeV-1 TeV). As shown in Fig. 1-a, the main Higgs production mode at the LHC is the gluon-gluon fusion. The vector boson fusion accounts for $\sim$ 20% and reaches the gluon fusion at $\sim$ 1 TeV/c^2. The Higgs production cross-section is of the order of $1pb$ to be compare to the inclusive p-p one which is $100mb$. Considering the low luminosity scenario (2×10^{33} cm^{-2}s^{-1}) the expected rates are: 10^6 for $b\bar{b}$ events, 0.8 for Higgs events (m_H =120 GeV). In this environment only leptonic or semileptonic final states can be employed for rare decays.



(a) (b)

Figure 1: (a) Higgs production cross sections as a function of its mass. (b) Higgs decay branching ratios as a function of its mass.

3. High Mass Higgs search

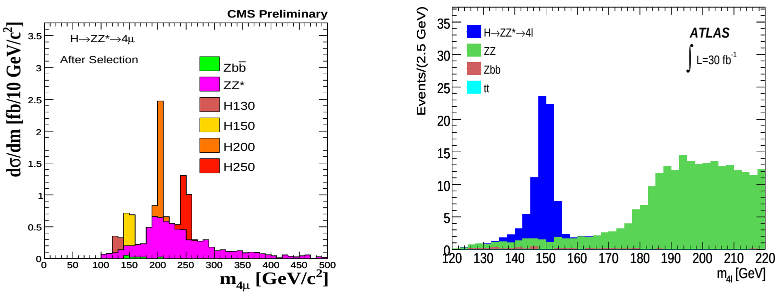
For masses above 140 GeV/c^2, the Higgs decays mainly in weak bosons (Fig. 1-b). The $H \to WW$ mode has the highest branching ratio ($\sim$ 3 times higher than $H \to ZZ$). When the decay into two real W became possible, around $m_H \sim 160$ GeV, the BR in to WW increase up to ~ 1 due to the threshold effect and the ZZ decay channel is less sensitive.
Due to the hadronic environment, in the region $140 < m_H < 600$ GeV the most performant channels are $H \to WW^* \to 2l2\nu$ and $H \to ZZ^* \to 4l$ (l=e, μ); these channels will be considered in the follow.

3.1 $H \to ZZ^* \to$ 4 leptons ($4e$, 4μ or $2e2\mu$) analysis

The four leptons channel represents the golden channel over a wide mass range for its clear signature: 4 isolated, high p_t leptons emerging from the primary vertex. With NLO cross section compilation $\sim$ 90 events of $H \to ZZ^* \to 4\mu$ with 20 fb^{-1} of data ($\sim$ 1 year at low luminosity) are expected. The main backgrounds for this channel are: $ZZ^* \to 4l$, $Zb\bar{b} \to 2lb\bar{b}$, $t\bar{t} \to 2Wb\bar{b}$ (where 2 leptons are supposed to come from the b decays).This analysis relies completely on the lepton reconstruction, identification and isolation as well as on their energy-momentum measurement; the precise energy-momentum measurement translate in a precise Higgs boson mass measurement and so in a narrow peak emerging from the background. The identification of isolated leptons emerging from the primary vertex allows for a drastic reduction of QCD-induced source of misidentified ("fake") leptons.Latest results from both experiments [3] [4] show the power of a simple m_H independent sequence of cuts which provides a clean sample of $4l$ events while preserving the highest signal selection efficiency. After a sequence of cuts done in order to get rid of QCD events (QCD-lepton enriched sample, Z+jets, W+jets) a tighter selection is applied in order to fight against the backgrounds $Zb\bar{b}$, $t\bar{t}$ where leptons are coming from semi-leptonic decays of bottom mesons. These leptons are likely to be accompanied by hadronic products from the fragmentation and the decay processes initiated in the b-quark jets. Moreover they have a large impact parameter with respect to the primary vertex because of the long life time of the b-hadron. Thus, a selection incorporating leptons isolation complemented by impact parameter measurements has the potential for powerful rejection. The results of the CMS analysis optimized for $1\,fb^{-1}$ of data are showed in Fig. 2-a; the ATLAS analysis at $30\,fb^{-1}$ leads to the $4l$ invariant mass spectrum showed in Fig. 2-b.
In evaluating the final significance the effect of theoretical uncertainties (mainly due to PDF and QCD scale) and of the main experimental systematics uncertainties have been considered. Moreover, on the basis of the foreseen in-situ determination of the detector performances, uncertainties foreseen for data-driven methods to measure the main backgrounds (ZZ and $Zb\bar{b}$) have been taken into account. Both ATLAS and CMS analyses at $30\,fb^{-1}$ [3] [5] show that the $H \to ZZ^* \to 4l$ channel has a high sensitivity in the $200 < m_H < 400$ GeV range and in the 150 GeV region where a significance of 5σ can be reached. The CMS analysis at $1\,fb^{-1}$ [4] shows that a signal evidence with a significance above 2σ is found unlikely in all the mass range considered; in absence of a significant deviation from SM background the Higgs can be excluded if $m_H \geq 185$ GeV.

3.2 $H \to WW^* \to 2l2\nu$ (l=e, μ) analysis

The signal event signature is two isolated high p_t leptons with a small opening angle in the transverse plane and a small invariant mass, significant E_t^{miss} and no hard jets in the central detector.



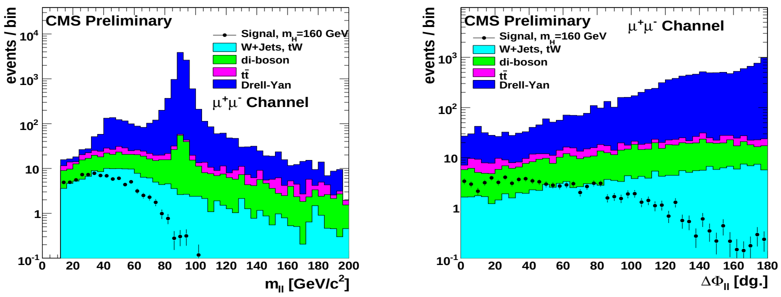
(a) (b)

Figure 2: (a) CMS analysis at $1 fb^{-1}$: $4l$ invariant mass after the events selection. (b) ATLAS analysis at $30 fb^{-1}$: $4l$ invariant mass after the events selection.

This signature is found to be highly sensitive for a Higgs in the mass range between 155 and 180 GeV. With NLO cross section compilation $\sim$ 3000 events of $H \to WW^* \to 2e2\nu$ with 20 fb^{-1} of data ($\sim$ 1 year at low luminosity) are expected. This channel is favoured by the branching ratio with respect to the previous one, but the final state is more complex: due to undetected neutrinos no Higgs mass peak could be reconstructed and a discovery/exclusion of a Higgs of a certain mass hypothesis relies on a *counting experiment*. The dominant SM backgrounds are the continuum W^+W^- and $t\bar{t}$ production. An important element for this analysis is an effective selection of e and μ which should preserve high efficiency for true isolated leptons from W boson decays, while providing a strong suppression of leptons from heavy quark decays or fake leptons from jets. After the identification of the leptons which could originate from W boson decays, in both ATLAS and CMS latest analyses [3] [6], the signal events selection is done vetoing all events with reconstructed jets in the central region and applying an upper cut on the two isolated-dileptons invariant mass and on the angle between them in the transverse plane (Fig. 3-a and Fig. 3-b). The central-jet veto is done mainly to reduce $t\bar{t}$ events in which central jets are slightly favoured. The angle $\Delta\Phi_{ll}$ between the isolated leptons in the transverse plane is especially useful to minimize the contribution of the non resonant WW background where this angle is expected to be large as the leptons are preferentially emitted back-to-back, while it tends to be small in the decay of the scalar Higgs. The upper cut on the invariant mass of the lepton-pair is mainly used to reduce the contamination by leptons coming from Z boson decays. In the ATLAS analysis a cut on the transverse mass m_t of the WW system as defined in [7] and on the p_t of that system are also applied.
A precise estimation of the $t\bar{t}$ and WW background as well as of the lepton fake-rate is crucial to this analysis; data-driven methods have been devised and the their uncertainties estimated. Including these uncertainties the multivariate analysis technique of the CMS analysis at 1 fb^{-1} shows that, combining all three final states (ee, $\mu\mu$, $e\mu$), a SM Higgs could be found at 5σ around 160 GeV; from the upper limit calculation the SM Higgs can be excluded in 150-190 GeV region. The ALTAS analysis at 10 fb^-1 shows that a SM Higgs could be found at 5σ in 140-180 GeV region.

4. Combined channels results

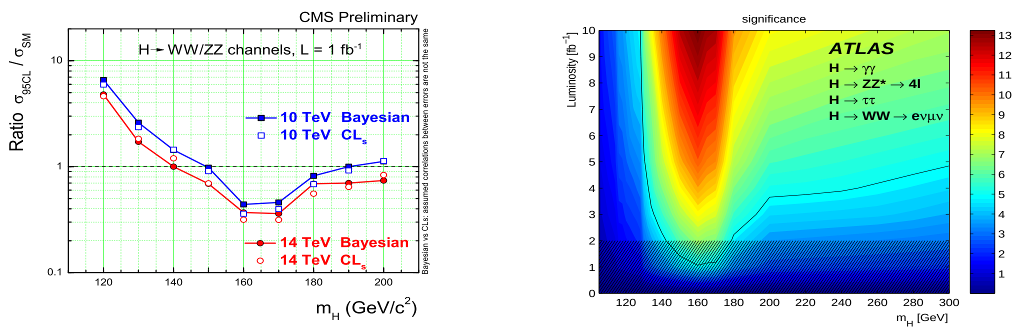
The statistical combination of the results of the CMS analyses (HZZ, HWW) at $1 fb^{-1}$ shows



(a) (b)

Figure 3: Invariant mass of the di-lepton system (left) and azimuthal angular separation between the two leptons (right) for the $\mu^+\mu^-$ channel after pre-selection cuts and central jet veto ($m_H = 160$ GeV).

that a SM Higgs can be excluded in the mass range 140-230 GeV; this range is restricted to 150-190 GeV if the change of the LHC center-of-mass collision energy from 14 to 10 TeV (foreseen for the first year run) is considered (Fig. 4-a). The ATLAS combination of all the main analyses results shows that with $5\,fb^{-1}$ of data at 14 TeV a high mass SM Higgs (140-450 GeV) can be discovered.



(a) (b)

Figure 4: (a) CMS analysis at $1\,fb^{-1}$: projected exclusion limits for the SM Higgs at 14 and 10 TeV center of mass energies. (b) Significance contours for different SM Higgs masses and integrated luminosities. The thick curve represents the 5σ discovery contour.

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