Search for light Higgs boson at LHC via production through Weak Boson Fusion

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Abstract

The LHC potential for observing a light Higgs boson produced through Weak Boson Fusion mode, $qq \rightarrow qqH$, is presented. For non-hadronic decays modes of the Higgs boson the process is identified with a final state containing two energetic forward-backward jets, separated with a large rapidity and a hadronically quiet central region. The use of these properties, combined with special features of some of the decay modes enhances the potential of an early discovery of a light Higgs boson both in the Standard Model and beyond. The recent studies done in the context of CMS experiment are discussed.

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1 Higgs Boson Discovery at LHC

The primary goal of the large hadron collider (LHC), is to unravel the mystery of the electroweak symmetry breaking. The search for the Standard Model (SM) Higgs boson has therefore been one of the main motivations behind enormous efforts put in by the omni-purpose p-p experiments, ATLAS and CMS, in the LHC. The first collisions at the LHC, at a centre-of-mass energy of 14 TeV, are expected by June 2007. By 2010 the accumulated luminosity will be 30 fb$^{-1}$/experiment, increased to 100 fb$^{-1}$/year eventually when the machine will run with the design luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$. As shown in Fig. 1, the SM Higgs boson will be detected in more than one channel over the whole mass range ($m_H$) from 80 GeV/c$^2$ to $\sim 1$ TeV/c$^2$. The experimentally favoured domain (at 95% C.L.) is bounded from below at 114.4 GeV/c$^2$ by direct searches at LEP (Ref. [1]) and from above at 219 GeV/c$^2$ by electroweak precision measurements at LEP and SLD (Ref. [2]). The luminosity required by CMS to cover the lower part of this favoured region is displayed in Fig. 2. The weak boson fusion (WBF) mode for the Higgs boson production at the LHC, $qq \rightarrow qqH$, can strengthen the discovery potential in this low mass region. The discovery in this region can be strengthened, as suggested by D.Zeppenfeld et.al. in recent years (Ref. [3]), with an integrated luminosity even smaller than 30 fb$^{-1}$. Because the minimal supersymmetric extension of the standard model (MSSM) predicts the existence of a scalar Higgs boson (h or H) with a mass below or around 130 GeV/c$^2$ and with standard-model like couplings the results for the SM Higgs boson can be applied directly to estimate the potential for the MSSM Higgs bosons. WBF process is also ideally suited for the detection of an invisibly decaying Higgs boson.

Figure 1: Expected statistical significance ($S/\sqrt{B}$) with 30 fb$^{-1}$ for SM Higgs in CMS with LO cross-sections for all processes.

Figure 2: Integrated luminosity required to explore the region $m_H \leq 150$ GeV/c$^2$ with NLO cross sections for the inclusive $H \rightarrow \gamma\gamma$, for $H + \text{jet}$ with $H \rightarrow \gamma\gamma$ and for $H \rightarrow ZZ^{*} \rightarrow 4\ell \ell'$ and $H \rightarrow WW^{*} \rightarrow \ell\ell\nu\nu$.

2 The Higgs boson Search in WBF Process

The WBF process has distinct signatures which provides good handle against potential backgrounds from $t\bar{t}$, single W/Z + jets and QCD multi-jet events, though the rate is smaller by about an order of magnitude compared to the gluon-fusion process. In the signal channel the underlying dynamics of simultaneous
W or Z emissions from the incoming quarks and their subsequent fusion to a Higgs boson results in two energetic jets in the forward and backward regions. The absence of colour exchange between the scattered quarks and the colourless Higgs boson leads to low hadronic activity in the central region, when the Higgs boson decays into non-hadronic modes of $\gamma\gamma$, $WW^* \rightarrow \ell\nu\ell\nu$, $\tau\tau$, or even invisibly. The various QCD background processes are indeed reduced with the requirement of two energetic jets ($E_{\text{jet}} \geq 300 \text{ GeV}$) at large rapidities, with a substantial rapidity gap between the jets ($|\Delta\eta| \geq 4$), and that there be very little jet activity in the central region: no other jet must be reconstructed with a transverse energy in excess of 20 GeV. This central-jet-veto efficiency needs to be known to few % level and experimentally it is feasible at low-luminosity running condition of LHC ($10^{33}$ cm$^{-2}$ s$^{-1}$).

The next-to-leading order corrections of WBF is only $\sim 10\%$ of the leading order cross-section. Also the contribution to the $q\bar{q}H$ final state from gluon-fusion mode, after WBF-specific selection criteria, is expected to be only $\sim 10\%$. These aspects are suitable for the determination of the Higgs boson couplings when different modes of the Higgs boson production need to be distinguished in various decay final states.

The detection of WBF events demands hermetic calorimetry and the Very Forward (VF) Calorimeters of CMS extend up to $|\eta| \leq 5$. For about 65% of signal events at least one jet lie in VF with the above WBF-specific selection criteria. Trigger strategies have been extensively studied in CMS for various final state topologies where the selection thresholds are adjusted to keep reasonable efficiencies for signal channels while achieving large background rejection factors. The accuracy of the expected signal significance depends on the precision of the predicted background rate which sometimes can be measured directly from the data itself using accurately known final states.

### 3 Specific Studies in CMS

#### 3.1 $q\bar{q} \rightarrow q\bar{q}H, H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$

In addition to the common general features discussed above, the final state for this channel is characterised with two high-$p_T$ leptons and large missing transverse energy, $E_T^\text{miss}$. The potential background from $tt$ process has been studied with detailed detector simulation and reconstruction softwares of CMS. The spin correlation of the two Ws from the Higgs boson decay yields an opening angle between the two charged leptons which is smaller, on average, than for the background events. The resulting transverse mass, reconstructed from the leptons and $E_T^\text{miss}$, has a Jacobian peak at $m_H$ as presented in Fig. 3. This search can cover the Higgs boson mass range from 120 to 170 GeV/c$^2$ (Ref. [4]).

#### 3.2 $q\bar{q} \rightarrow q\bar{q}H, H \rightarrow \gamma\gamma$

This process has a low signal rate due to the small branching fraction ($\sim 10^{-3}$) for $H \rightarrow \gamma\gamma$, but much better signal-to-background ratio ($S/B \sim 1$ for $m_H = 115 - 140$ GeV/c$^2$) than in the gluon fusion mode ($S/B \sim 1/15$). This channel provides an interesting complementary final state for an early discovery (Ref. [5]) in the difficult low-mass region as illustrated in Fig. 4.

#### 3.3 $q\bar{q} \rightarrow q\bar{q}H, H \rightarrow \tau\tau$

This channel has been studied thoroughly in CMS (Ref. [6]). The trigger strategy involves $\tau$-identification algorithms based on calorimetric selection at Level 1, and on tracking isolations at High Level. The Higgs boson mass can be reconstructed from the measured momentum of the $\tau$ decay products and the $E_T^\text{miss}$, with the assumption that the latter originates entirely from the neutrinos of the $\tau$ decays and is therefore collinear with the parent $\tau$s. In the resulting distribution, shown in Fig. 5, the peak is clearly distinguishable from the QCD and EW background of $Z + 2$ jets which peaks at the Z mass.
Figure 3: Signal superimposed on background for $H \rightarrow WW^* \rightarrow l^+ l^- \nu \bar{\nu}$ for $m_H = 160 \text{ GeV/c}^2$ and 60 fb$^{-1}$.

Figure 4: Signal superimposed on background for $H \rightarrow \gamma \gamma$ with $m_H = 120 \text{ GeV/c}^2$ and 60 fb$^{-1}$.

3.4 $qq \rightarrow qqH_{\text{susy}}$

One of the neutral Higgs bosons of MSSM, $h$ or $H$, depending on the parameter values, can be searched through its $\tau \tau$ decay mode which alone spans a large region of parameter space even with limited luminosity of $\sim 30$ fb$^{-1}$ (Ref. [7]). Through WBF production, the channel $\tau \tau \rightarrow \ell + \text{jet} + E_T$ probes the regions $m_A \leq 120 \text{ GeV/c}^2$ with $H$ and $m_A \geq 150 \text{ GeV/c}^2$ with $h$ as shown in Fig. 6.

3.5 $qq \rightarrow qqH, H \rightarrow \text{Invisible}$

In a variety of scenarios beyond the SM, the Higgs boson can decay invisibly. In this case the transverse momenta of the tagging jets balance the $E_T$ due to the invisible Higgs boson. An upper threshold on the azimuthal angle between the two jets, in addition to the requirement of large $E_T$, reduce the potential background of QCD multijets, heavy-flavours, QCD and EW W/Z+2 jets types of events. A sensitivity for the invisible decay branching ratio of the Higgs boson as small as 12% can be obtained in CMS (Ref. [8]) with only 10 fb$^{-1}$ for $m_H \lesssim 200 \text{ GeV/c}^2$ assuming the vector boson couplings of the invisible Higgs boson to be the same as in SM.

4 Conclusion

The search for a low-mass Higgs boson in the SM as well as the neutral Higgs bosons in the MSSM can be enhanced by the weak boson fusion process with reasonably small integrated luminosity. The distinctive signatures of WBF allows to achieve a statistical significance similar to that of the gluon-fusion process during the initial low-luminosity phase of LHC.

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Figure 5: Reconstructed mass for SM $H \rightarrow \tau\tau$ with $m_H = 135\text{ GeV/c}^2$ and backgrounds superposed for 30 fb\(^{-1}\).

Figure 6: Expected 5\(\sigma\)-discovery range of the neutral scalar (h or H) MSSM Higgs bosons through WBF production in $m_A$-$\tan\beta$ parameter space.

References

References


