The Search for Higgs Bosons of Minimal Supersymmetry at the LHC

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Abstract.

The prospects for discovering neutral Higgs bosons in the minimal supersymmetric model (MSSM) and in the minimal supergravity model (MSUGRA) at the LHC are investigated. Two special discovery channels are discussed: (i) the photon pair decay of the MSSM CP-odd Higgs boson, and (ii) the muon pair decays of neutral Higgs bosons and in the MSUGRA.

INTRODUCTION

In the minimal supersymmetric model (MSSM) [?], there are two Higgs doublets \( \phi_1 \) and \( \phi_2 \) coupling to fermions with \( t_3 = -1/2 \) and \( t_3 = +1/2 \) respectively [?]. After spontaneous symmetry breaking, there remain five physical Higgs bosons: a pair of singly charged \( H^\pm \), two neutral CP-even \( H^0 \) (heavier) and \( h^0 \) (lighter), and a neutral CP-odd \( A^0 \). The Higgs potential is constrained by supersymmetry such that all tree-level Higgs boson masses and couplings are determined by two independent parameters, commonly chosen to be mass of the CP-odd pseudoscalar \( m_A \) and ratio of the vacuum expectation values (VEVs) of Higgs fields \( \tan \beta \equiv v_2/v_1 \).

Extensive studies have been made for the detection of MSSM Higgs bosons at the CERN LHC [?,?,?,?]. Most studies have focused on the SM decay modes \( \phi \rightarrow \gamma \gamma \) (\( \phi = H^0, h^0 \text{ or } A^0 \)) and \( \phi \rightarrow ZZ \text{ or } ZZ^* \rightarrow 4l \) (\( \phi = H^0 \text{ or } h^0 \)). For \( \tan \beta \) close to one, the detection modes \( A^0 \rightarrow Zh^0 \rightarrow l^+l^−b\bar{b} \text{ or } l^+l^−\tau^+\tau^- \) [?] and \( H^0 \rightarrow h^0h^0 \rightarrow \gamma \gamma bb \) [?] may provide channels to simultaneously...
discover two Higgs bosons of the MSSM. For large $\tan \beta$, the $\tau \bar{\tau}$ decay mode \footnote{This important channel was not included in the CMS and the ATLAS technical proposals \cite{ref1,ref2}.} is a promising discovery channel for the $A^0$ and the $H^0$; neutral Higgs bosons might be observable via their $b\bar{b}$ decays \cite{ref1,ref2}. In some regions of parameter space, the rates for Higgs boson decays to SUSY particles are dominant. While these decays reduce rates for the standard modes, they might also open up new promising modes for Higgs detection \cite{ref1}. Recently, the muon pair decay mode was proposed \cite{ref1,ref2} to be a promising discovery channel for neutral Higgs bosons. For large $\tan \beta$, the muon pair discovery mode might be the only channel that allows precise reconstruction of Higgs masses at the LHC.

In this article, the prospects for discovering neutral Higgs bosons in the MSSM and in the minimal supergravity model (MSUGRA) at the LHC are investigated. Two special discovery channels are discussed: (i) the search for the MSSM CP-odd Higgs boson via its photon pair decay \cite{ref1}, and (ii) the detection of neutral Higgs bosons via their muon pair decays in the MSSM \cite{ref1} and in the MSUGRA \cite{ref1}.

**THE PHOTON PAIR DISCOVERY CHANNEL**

In this section, we present a realistic study for the observability of the MSSM CP-odd Higgs boson ($A^0$) via its photon pair decay mode \footnote{This important channel was not included in the CMS and the ATLAS technical proposals \cite{ref1,ref2}.} ($A^0 \rightarrow \gamma \gamma$) with the CMS detector performance \cite{ref1}. The cross section for the process of $pp \rightarrow A^0 \rightarrow \gamma \gamma + X$ is evaluated from the cross section $\sigma(pp \rightarrow A^0 + X)$ multiplied with the branching fractions of $A^0 \rightarrow \gamma \gamma$. We take $m_\tilde{q} = m_\tilde{g} = \mu = 1000$ GeV.

The irreducible backgrounds considered are, (i) $q\bar{q} \rightarrow \gamma \gamma$ and (ii) $gg \rightarrow \gamma \gamma$ (Box). In addition, we consider reducible backgrounds with at least one $\gamma$ in the final state, (i) $q\bar{q} \rightarrow g\gamma$, (ii) $gg \rightarrow g\gamma$, and (iii) $gg \rightarrow g\gamma$ (Box). In Figure 1, we present number of events for the signal and the background at the LHC versus $M_{\gamma\gamma}$.

We use PYTHIA 5.7 and JETSET 7.4 generators \cite{ref1} to simulate events at the particle level. The PYTHIA/JETSET outputs are processed with the CMSJET program \cite{ref1}. The resolution effects are taken into account by using the parameterizations obtained from the detailed GEANT \cite{ref1} simulations. The ECAL resolution is assumed to be $\sigma(E)/E = 5\%/\sqrt{E} + 0.5\%$ (CMS high luminosity regime). We require that every photon should have a transverse momentum ($p_T$) larger than 40 GeV and $|\eta| < 2.5$, and both photons must be isolated, i.e., (i) there is no charged particle with $p_T > 2$ GeV in the cone $R = 0.3$; and (ii) the total transverse energy $\sum E_{\text{cell}}$ is taken to be less than 5 GeV in the cone ring $0.1 < R < 0.3$. To be conservative, we assume no
rejection power against $\pi^0$’s with high $p_T$, i.e., all $\pi^0$’s surviving the cuts ($p_T$, isolation, etc.) are considered as $\gamma$’s.  

For each $m_A$ and $\tan \beta$, the values of mass window around the peak (within the range 2-6 GeV) and $p_T$ cut (50-100 GeV) were chosen to provide the best value of $N_S = S/\sqrt{B}$. For example, the best values of the mass window and $p_T$ cut for $m_A = 200$ GeV are 2 GeV and 60 GeV respectively, whereas these values equal to 4 GeV and 100 GeV for $m_A = 350$ GeV. Figures 2 shows the discovery contour for $pp \to A^0 \to \gamma\gamma$ at $\sqrt{s} = 14$ TeV, in the $(m_A, \tan \beta)$ plane, with an integrated luminosity $(L)$ of 100 fb$^{-1}$ and 300 fb$^{-1}$.

THE MUON PAIR DISCOVERY CHANNEL

The cross section of $pp \to \phi \to \mu\bar{\mu} + X$ ($\phi = A^0, H^0$, or $h^0$) is evaluated from the Higgs boson cross section $\sigma(pp \to \phi + X)$ multiplied with the branching fraction of the Higgs decay into muon pairs $B(\phi \to \mu\bar{\mu})$. The Higgs masses and couplings are evaluated with one loop corrections from the top and the bottom Yukawa interactions in the one-loop effective potential [?].

3) The background from the $\pi^0$ is overestimated, especially in the low mass $M_{\gamma\gamma}$ region.
In the MSSM, gluon fusion ($gg \to \phi$) is the major source of neutral Higgs bosons for $\tan \beta \lesssim 4$. If $\tan \beta$ is larger than about 10, neutral Higgs bosons are dominantly produced from $b$-quark fusion ($b\bar{b} \to \phi$)\footnote{\protect\cite{footnote}} because the $\phi b\bar{b}$ couplings are enhanced by $1/\cos \beta$. We have evaluated the cross section of Higgs bosons in $pp$ collisions $\sigma(pp \to \phi + X)$, with two dominant subprocesses: $gg \to \phi$ and $gg \to \phi b\bar{b}$. For $m_A \gtrsim 150$ GeV, the couplings of the lighter scalar $h^0$ to gauge bosons and fermions become close to those of the SM Higgs boson, therefore, gluon fusion is the major source of the $h^0$ even if $\tan \beta$ is large.

The QCD radiative corrections to $gg \to \phi$ was found to be large\footnote{\protect\cite{footnote}}, the same corrections to $gg \to \phi b\bar{b}$ are still to be evaluated. To be conservative, we take a K-factor of 1.5 and 1.0 for the contributions from $gg \to \phi$ and $gg \to \phi b\bar{b}$ respectively, to evaluate the cross section of $pp \to \phi + X$. For the dominant Drell-Yan background\footnote{\protect\cite{footnote},\protect\cite{footnote},\protect\cite{footnote}}, we have adopted the well known K-factor from reference\footnote{\protect\cite{footnote}}.

If the $b\bar{b}$ mode dominates Higgs decays, the branching fraction of $\phi \to \mu\bar{\mu}$ is about $m_\mu^2/3m_b^2$, where 3 is the color factor of the quarks. The QCD radiative corrections greatly reduce the decay width of $\phi \to b\bar{b}$\footnote{\protect\cite{footnote}}. For $\tan \beta \gtrsim 10$, the $b\bar{b}$ decay mode dominates, and the branching fraction of $B(\phi \to \mu\bar{\mu})$ ($\phi = A^0, H^0$, or $h^0$) is about $2 \times 10^{-4}$. For $m_A$ less than about 80 GeV, the $H^0$ decays dominantly into $h^0h^0$, $A^0A^0$ and $ZA^0$. 

**FIGURE 2.** The $5\sigma$ contour in the $(m_A, \tan \beta)$ plane, generated from a simulation with CMS performance, for $pp \to A^0 \to \gamma\gamma + X$ at the LHC with $L = 100$ fb$^{-1}$ and 300 fb$^{-1}$. 

![Diagram showing the 5\sigma contour in the $(m_A, \tan \beta)$ plane.](image-url)
Higgs Bosons of Minimal Supersymmetry

In Figs. 3(a) and 3(b), we present the cross section of the MSSM Higgs bosons at the LHC, \( pp \rightarrow \phi \rightarrow \mu\bar{\mu} + X \), as a function of \( m_A \) for \( \tan \beta = 15 \) and \( \tan \beta = 40 \). As \( \tan \beta \) increases, the cross section is enhanced because for \( \tan \beta > \sim 10 \), it is dominated by \( gg \rightarrow \phi b\bar{b} \) and enhanced by the \( \phi b\bar{b} \) Yukawa coupling. Also shown is the same cross section for the SM Higgs boson \( h^0_{SM} \) with \( m_{h^0_{SM}} = m_A \). For \( m_{h^0_{SM}} > 140 \) GeV, the SM \( h^0_{SM} \) mainly decays into gauge bosons; therefore, the branching fraction \( B(h^0_{SM} \rightarrow \mu\bar{\mu}) \) drops sharply.

**FIGURE 3.** The cross sections of \( pp \rightarrow A^0, H^0, h^0 \rightarrow \mu\bar{\mu} + X \) in fb at \( \sqrt{s} = 14 \) TeV, versus \( m_A \) for \( m_{\tilde{g}} = m_{\tilde{q}} = -\mu = 1 \) TeV, (a) \( \tan \beta = 15 \) and (b) \( \tan \beta = 40 \). Also shown is the cross section for the SM Higgs boson with \( m_{h^0_{SM}} = m_A \). The 5\( \sigma \) contours at the LHC with \( L = 300 \) fb\(^{-1} \) are shown for (c) \( m_{\tilde{g}} = m_{\tilde{q}} = -\mu = 1 \) TeV, and (d) \( m_{\tilde{g}} = m_{\tilde{q}} = -\mu = 300 \) GeV.

To study the observability for the muon pair decay mode, the dominant background from the Drell-Yan (DY) process, \( q\bar{q} \rightarrow Z, \gamma \rightarrow \mu\bar{\mu} \) is considered. We take \( \Delta M_{\mu\bar{\mu}} \) to be the larger of the ATLAS muon mass resolution (about 2\% of the Higgs bosons mass) \([?,?]\) or the Higgs boson width.\(^4\) The minimal cuts applied are (1) \( p_T(\mu) > 20 \) GeV and (2) \( |\eta(\mu)| < 2.5 \) for both the signal and background.

For \( m_A \gtrsim 130 \) GeV, \( m_A \) and \( m_H \) are almost degenerate while for \( m_A \lesssim 100 \) GeV, \( m_A \) and \( m_{A^0} \) are very close to each other \([?,?]\). Therefore, we sum

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\(^4\) The CMS mass resolution will be better than 2\% of \( m_\phi \) for \( m_\phi \lesssim 500 \) GeV \([?,?]\).