Detecting MSSM Higgs bosons with muons at Very Large Hadron Colliders

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The prospects of discovering heavy neutral Higgs bosons in the minimal supersymmetric model via their decays into muon pairs are investigated for very high energy pp collisions. Promising results are found for the CP-odd pseudoscalar (A^0) and the heavier CP-even scalar (H^0) for reasonably large $\tan\beta \equiv v_2/v_1$. A pp collider with $\sqrt{s} = 28$ TeV can detect heavy Higgs bosons via muon pair decays significantly beyond the discovery potential of the LHC, and pp collisions at $\sqrt{s} = 100$ TeV will be able to discover heavy Higgs bosons in most of the $(M_A, \tan\beta)$ parameter plane except in the regions with $M_A \sim M_Z$ or $M_A \gtrsim m_t$.

1. Introduction

The Higgs sector of a supersymmetric theory must contain at least two $SU(2)$ doublets for anomaly cancellation. In the minimal supersymmetric standard model (MSSM), the Higgs sector has two doublets ϕ_1 and ϕ_2 that couple to the $t_3 = -1/2$ and $t_3 = +1/2$ fermions, respectively. After spontaneous symmetry breaking, there remain five physical Higgs bosons: a pair of singly charged Higgs bosons $H^\pm$, two neutral CP-even scalars H^0 (heavier) and h^0 (lighter), and a neutral CP-odd pseudoscalar A^0 [1].

The outstanding LHC discovery potential of the muon pair decay mode for neutral Higgs bosons was first demonstrated by Kao and Stepanov [2, 3]. This promising discovery channel at the LHC was later confirmed by Richter-Was et al. [4] and recently by the ATLAS collaboration [5], for the CP-odd pseudoscalar A^0 and the heavier CP-even scalar H^0. Although the $\mu\bar{\mu}$ channel has a small branching fraction than the $\tau\bar{\tau}$ decay, this can be compensated by the much better achievable mass resolution with muon pairs. For large $\tan\beta$, the muon pair discovery mode might be the only channel at the LHC that allows precise reconstruction of the A^0 and the H^0 masses in the MSSM and in the minimal supergravity model [6].

In this report, the prospects of discovering heavy neutral Higgs bosons in the minimal supersymmetric model via their decays into muon pairs at very large hadron colliders are investigated for pp collisions at $\sqrt{s} = 28$ TeV, 40 TeV, 100 TeV and 200 TeV. To study the observability of the muon discovery mode, we consider the dominant background from the Drell-Yan (DY) process, $q\bar{q} \to Z, \gamma \to \mu\bar{\mu}$. There are several physical processes in the Standard Model (SM) that generate sizeable muon pairs. However, there is only one dominant subprocess in the interesting mass range (50 GeV $\le M_{\mu\bar{\mu}} \le$ 1000 GeV), which is the DY muon pair production [2, 3]. The $b\bar{b}$ background can be reduced easily well below the DY process with isolation cuts on muons. The background from top quark pairs ($t\bar{t}$) is about 20 times smaller than the DY for $M_{\mu\bar{\mu}} \lesssim 150$ GeV and begins to compete with the DY for the higher $M_{\mu\bar{\mu}}$. The event rate from WW is 3-5 times lower than that from $t\bar{t}$. Both backgrounds from $t\bar{t}$ and WW could be reduced significantly with a cut on missing transverse energy. We assume that SUSY backgrounds from the lightest chargino pairs and from the second lightest neutralino decays could also be reduced significantly with a cut on missing transverse energy.

2. Cross section and branching fraction

The cross section of $pp \to \phi \to \mu\bar{\mu} + X$ ($\phi = A^0, H^0$, or h^0) is calculated for the two dominant subprocesses $gg \to \phi$ and $b\bar{b} \to \phi$ [7, 8, 9] and multiplied by the branching fraction of the Higgs

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decay into muon pairs $B(\phi \to \mu\bar{\mu})$. The parton distribution functions of CTEQ5L [10] are used to evaluate the $pp \to \phi + X$ cross section.

In the MSSM, gluon fusion ($gg \to \phi$) is the major source of neutral Higgs bosons for $\tan\beta$ less than about 4. If $\tan\beta$ is larger than about 10, neutral Higgs bosons in the MSSM are dominantly produced from b-quark fusion ($b\bar{b} \to \phi$). We choose the running mass $m_b(Q)$ or $m_t(Q)$ for the $\phi b\bar{b}$ or $\phi t\bar{t}$ coupling with $Q = M_\phi$, and evaluate the $b\bar{b}$ cross section from $\sigma(b\bar{b} \to \phi)$ then scale it with a factor parameterized from the cross sections in Ref. [8]. Since the Yukawa couplings of $\phi b\bar{b}$ are enhanced by $1/\cos\beta$, the production rate of neutral Higgs bosons is usually enhanced at large $\tan\beta$. For m_A larger than about 150 GeV, the couplings of the lighter scalar h^0 to gauge bosons and fermions become similar to those of the SM Higgs boson. Then gluon fusion is the major source of the h^0 even if $\tan\beta$ is large.

The QCD radiative corrections to the subprocess $gg \to \phi$ are substantial [11, 12]; the corrections to $gg \to \phi b\bar{b}$ are still to be evaluated. To be conservative, we take a K-factor of 1.5 for the contribution from $gg \to \phi$ and a K-factor of 1.0 for the contribution from $gg \to \phi b\bar{b}$. For the dominant Drell-Yan background we adopt the well known K-factor from reference [13].

With QCD radiative corrections to $\phi \to b\bar{b}$ [14, 15] the branching fraction of $\phi \to \mu\bar{\mu}$ is about $m_\mu^2/3m_b^2(M_\phi) \sim 2 \times 10^{-4}$ when the $b\bar{b}$ mode dominates Higgs decays, where 3 is a color factor of the quarks and $m_b(M_\phi)$ is the running mass at the scale $Q = M_\phi$. The branching fraction of $h^0 \to \mu\bar{\mu}$ is always about 2×10^{-4}. The branching fractions for $A^0 \to \mu\bar{\mu}$ and $H^0 \to \mu\bar{\mu}$ are always in the range $1.5 - 2.5 \times 10^{-4}$ when $\tan\beta \gtrsim 10$, even when A^0 and H^0 can decay into SUSY particles. For m_A less than about 80 GeV, the H^0 decays dominantly into h^0h^0, A^0A^0 and ZA^0.

In Figure 1, we present the cross section of the MSSM Higgs bosons $pp \to A^0 \to \mu^+\mu^- + X$ as a function of $\tan\beta$, for $M_A = 200$ GeV, $M_{\rm SUSY} = m_{\tilde{q}} = m_{\tilde{g}} = -A_t = -A_b = \mu = 1$ TeV, and $\sqrt{s} = 14$ TeV, 28 TeV, 40 TeV and 100 TeV. Contributions from three subprocess are shown: (i) $gg \to A^0$, (ii) $b\bar{b} \to A^0$, and (iii) $gg \to A^0 b\bar{b}$. Also shown is the cross section required for a 5σ signal. As $\tan\beta$ increases, the production cross section is enhanced because it is dominated by $b\bar{b} \to A^0$ for $\tan\beta \gtrsim 10$, and enhanced by the $A^0 b\bar{b}$ Yukawa coupling. At $\sqrt{s} = 28$ TeV with $M_A = 200$ GeV and $\tan\beta \gtrsim 40$, $gg \to A^0$ alone can generate enough $A^0 \to \mu\bar{\mu}$ for discovery.

3. Observability at very large hadron colliders

We define the signal to be observable if the $N\sigma$ lower limit on the signal plus background is larger than the corresponding upper limit on the background [16, 17], namely,

$$L(\sigma_s + \sigma_b) - N\sqrt{L(\sigma_s + \sigma_b)} > L\sigma_b + N\sqrt{L\sigma_b}$$

which corresponds to

$$\sigma_s > \frac{N^2}{L}\left[1 + 2\sqrt{L\sigma_b}/N\right]$$

Here L is the integrated luminosity, σ_s is the cross section of Higgs signal, and σ_b is the background cross section within a bin of width $\pm\Delta M_{\mu\bar{\mu}}$ centered at M_ϕ; $N = 2.5$ corresponds to a 5σ signal. We take the integrated luminosity L to be 100 fb^{-1}.

To study the observability of the muon discovery mode, we consider the background from the Drell-Yan process, $q\bar{q} \to Z, \gamma \to \mu\bar{\mu}$, which is the dominant background. We take $\Delta M_{\mu\bar{\mu}}$ to be the larger of the ATLAS muon mass resolution (about 2% of the Higgs bosons mass) [5] or the Higgs boson width. The CMS mass resolution will be better than 2% of m_ϕ for $m_\phi \lesssim 500$ GeV [3]. Therefore, the observability will be better for the CMS detector. The minimal cuts applied are (i) $p_T(\mu) > 20$ GeV and (ii) $|\eta(\mu)| < 2.5$ for both the signal and the 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_h are very close to each other [2]. Therefore, we add up the cross sections of the A^0 and the h^0 for $m_A \leq 100$ GeV and those of the A^0 and the H^0 for $m_A > 100$ GeV. The 5σ discovery contours are shown in Fig. 2 for the MSSM Higgs bosons in pp collisions at $\sqrt{s} = 14$ TeV, 28 TeV, 40 TeV, 100 TeV and 200 TeV, with an integrated luminosity $L = 100$ fb^{-1} for $M_{\rm SUSY} = m_{\tilde{q}} = m_{\tilde{g}} = -A_t = -A_b = \mu = 1$ TeV The QCD radiative corrections to background from the Drell-Yan process are included.

4. Conclusions

We have found promising results for detecting the CP-odd pseudoscalar (A^0) and the heavier CP-even scalar (H^0) Higgs bosons at high energy pp colliders. At $\sqrt{s} = 28$ TeV, a pp collider will be able to detect heavy Higgs bosons via muon pair decays significantly beyond the discovery potentail of the LHC, and the $gg \to \phi$ alone will be able to produce enough Higgs bosons for discovery if $\tan\beta$ is large. A very large hadron collider with pp collisions at $\sqrt{s} \gtrsim 100$ TeV will be able to discover heavy Higgs bosons in most of the $(M_A, \tan\beta)$ parameter plane even with $\tan\beta \sim 1$, except in regions with $M_A \sim M_Z$ or $M_A, M_H \gtrsim m_t$ and $\tan\beta \lesssim 15$.

In this report, we have chosen the mass scale $M_{\rm SUSY} = m_{\tilde{g}} = m_{\tilde{q}} = m_{\tilde{\ell}} = \mu = 1$ TeV such that both the A^0 and H^0 decay only into particles in the Standard Model. We note that there are regions of parameter space where rates for Higgs boson decays to SUSY particles are large and dominant. While these decays reduce the rates for the standard modes, making conventional detection of Higgs bosons more difficult, they also open up a number of new promising modes for Higgs detection [18, 19].

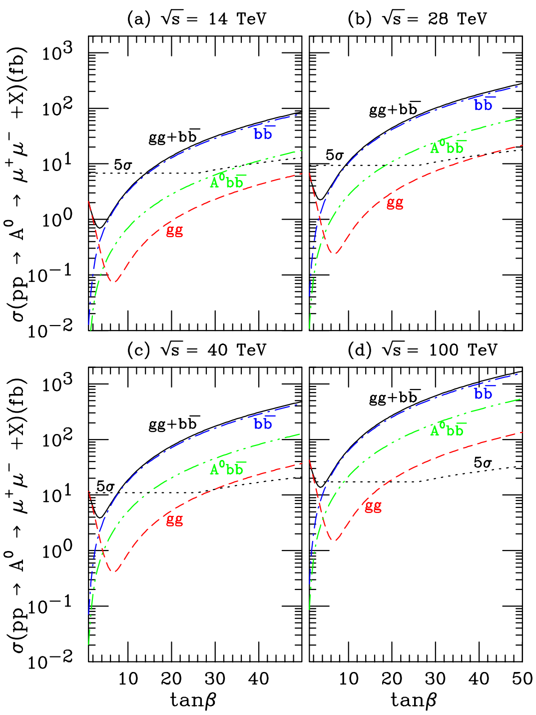

Figure 1: Cross section of $pp \to A^0 \to \mu^+\mu^- + X$ via $gg \to A^0$ (gg), $b\bar{b} \to A^0$ $(b\bar{b})$, and $gg \to A^0 b\bar{b}$.

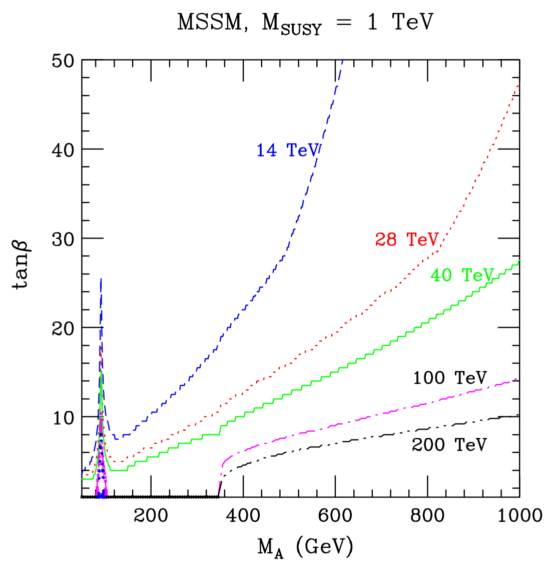

Figure 2: The 5σ contours in pp collisions for $L = 100$ fb^{-1}. The discovery region is above the 5σ contour.

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