TESTING SUPERSYMMETRY IN $AH^\pm$ ASSOCIATED PRODUCTION

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In the Minimal Supersymmetric Standard Model, the masses of the charged Higgs boson ($H^\pm$) and the CP-odd scalar ($A$) are related by $M^2_{H^\pm} = M^2_A + m^2_W$ at the Born level. Because the coupling of $W^- A H^\pm$ is fixed by gauge interaction, the Born level production rate of $q\bar{q}' \rightarrow W^\pm* \rightarrow AH^\pm$ depends only on one supersymmetry parameter – the mass ($M_A$) of $A$. We illustrate how to test the mass relation between $A$ and $H^\pm$ in case that the signal is found at the LHC. If the signal is not found, the product of the decay branching ratios of $A$ and $H^\pm$ predicted by the MSSM is bounded from above as a function of $M_A$.

One of the top priorities of current and future high-energy colliders, such as the Fermilab Tevatron and CERN Large Hadron Collider (LHC), is to probe the mechanism of the electroweak symmetry breaking. In the Standard Model (SM) of particle physics, this amounts to searching for the yet-to-be-found Higgs boson. It is also possible that the mechanism of electroweak symmetry breaking originates from new physics beyond the SM. Supersymmetry (SUSY) is one of the most commonly studied new physics models. The Higgs sector of the Minimal Supersymmetric Standard Model (MSSM) is known as a special case of the Two Higgs Doublet Model (THDM) with the type-II Yukawa interaction$^1$, and contains five physical scalar states, i.e., two CP-even ($h$ and $H$), a CP-odd ($A$) and a pair of charged Higgs bosons ($H^\pm$).

The coupling constants in the Higgs potential of the MSSM are determined by the gauge couplings due to the requirement of supersymmetry.

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Hence, at the Born level, the masses of $H^\pm$ and $A$ in the MSSM are related by the mass of the $W^\pm$ boson ($m_W$) as

$$M_{H^\pm}^2 = M_A^2 + m_W^2. \quad (1)$$

Furthermore, the coupling of $W^- A H^+$ is induced from the gauge invariant kinetic term of the Higgs sector:

$$L_{int} = \frac{g}{2} W^+_\mu (A\partial^\mu H^- - H^- \partial^\mu A) + \text{h.c.}, \quad (2)$$

and its strength is determined by the weak gauge coupling $g$.

Most production processes studied in the literature for testing the MSSM contain at least two SUSY parameters (such as $\tan \beta$ and $M_A$) in the search for supersymmetric Higgs bosons. Furthermore, the detection efficiency of the signal event depends on the assumed decay channels of the SUSY particles, hence, on the detailed choice of SUSY parameters. If the signal is not found after comparing experimental data with theory prediction, it is a common practice to constrain the product of the production cross section and the decay branching ratios of final state SUSY particles as a function of the multiple-dimension SUSY parameter space of the MSSM.

In Ref. 2, a novel proposal was made to study the $AH^\pm$ production process at hadron colliders via

$$q\bar{q}' \to W^{\pm*} \to AH^\pm. \quad (3)$$

In Fig. 1(a), we show the inclusive production rate of $AH^\pm$ as a function of $M_A$ for the Tevatron (a 1.96 TeV proton-antiproton collider) and the LHC (a 14 TeV proton-proton collider). Typically, the next-to-leading order QCD production rate is about 20% higher than the leading-order rate. The higher order ($\alpha_s^2$ or above) QCD correction is estimated to be about 10% at the Tevatron and less than a percent at the LHC, for $M_A = 120$ GeV, when the factorization scale is varied around the $AH^\pm$ invariant mass $\sqrt{s}$ by a factor of 2. The dominant one-loop electroweak corrections to the $q\bar{q}' \to AH^\pm$ process come from the loops of top ($t$) and bottom ($b$) quarks as well as stops ($\tilde{t}_{1,2}$) and sbottoms ($\tilde{b}_{1,2}$) due to their potentially large couplings to Higgs bosons. However, as shown in Ref. 3, the electroweak radiative corrections are found to be at most a couple of percent and smaller than

\[\text{We note that in general, a CP violating phase can enter the Higgs sector of the MSSM, so that the CP-even Higgs bosons can mix with the CP-odd Higgs scalar and the mass relation (1) does not hold any more. Here, we shall focus our study on the MSSM with a CP invariant Higgs sector.}\]
Figure 1. (a) The LO (dotted lines) and NLO QCD (solid lines) cross sections of the $AH^+$ and $AH^-$ pairs as a function of $M_A$ at the Tevatron (a 1.96 TeV $p\bar{p}$ collider), and the LHC (a 14 TeV $pp$ collider). The cross sections for $AH^+$ and $AH^-$ pair productions coincide at the Tevatron for being a $p\bar{p}$ collider. (b) Constraints on the product of branching ratios $B(A \rightarrow b\bar{b}) \times B(H^+ \rightarrow \tau^+\nu_\tau)$ as a function of $M_A$ for Case A and Case B, and $B(A \rightarrow b\bar{b}) \times B(H^+ \rightarrow t\bar{b})$ for Case C, at the LHC, where $\tau^+$ decays into $\pi^+\bar{\nu}_\tau$ channel.

the uncertainty in higher order (beyond the NLO) QCD corrections, parton distribution functions, or the accuracy of the experimental measurement.

This process possesses the following interesting properties.

- Its Born level production rate depends only on one SUSY parameter that can be determined by kinematic variables (e.g., the invariant mass of the $b\bar{b}$ pair from the decay of $A$).
- Its higher order production rate is not sensitive to detailed SUSY parameters through radiative corrections.
- Its final state particle kinematics can be properly modelled without specifying SUSY parameters. Hence, the detection efficiency of the signal can be accurately determined.
- If the signal is found, it can be used to distinguish the MSSM from its alternatives such as the THDM, by testing the MSSM mass relation Eq. (1)
- If the signal is not found, one can constrain the MSSM by limiting the product of decay branching ratios alone, without convoluting with the production cross section.

Either in the MSSM or the Type-II THDM, for a large $\tan\beta$ value, the dominant decay mode is $h, H, A \rightarrow b\bar{b}$ for the neutral Higgs bosons ($h, H, A$), and $H^+ \rightarrow \tau^+\nu$ for $m_{H^\pm} < m_t + m_b$. Due to the missing energy carried away by the final state neutrino, it is not possible to directly reconstruct
the mass of $H^+$ in the $\tau^+\nu$ mode. But, the transverse mass of $H^+$ can be reconstructed from the $\tau$ jet momentum and missing transverse energy. For $m_{H^+} \gtrsim 200$ GeV, the dominant decay mode is $H^+ \to t\bar{b}$, in which $M_{H^+}$ can be reconstructed after properly choosing the longitudinal momentum of the neutrino (with a two-fold solution) from $t$ decay.

To test whether such a signal can be detected at the LHC, we performed a Monte Carlo study at the parton level in Ref. 3. To cover both decay modes in our study, we consider the following three benchmark cases with $\tan \beta = 40$:

(A) $M_A = 101$ GeV (and $M_{H^+} < m_t + m_b$), and $H^+ \to \tau\nu$ being the dominant decay mode.
(B) $M_A = 166$ GeV (and $M_{H^+} \sim m_t + m_b$), and $H^+ \to \tau\nu$ being the dominant decay mode.
(C) $M_A = 250$ GeV and $H^+ \to t\bar{b}$ being the dominant decay mode.

We found that at the LHC this signal event can indeed provide useful information about the MSSM Higgs sector. If the $AH^+$ signal is not found in the decay mode of $\tau^+\nu$, then we can constrain the product of branching ratios $B(A \to b\bar{b}) \times B(H^+ \to \tau^+\nu_\tau)$ as a function of $M_A$, as shown in Fig. 1(b). This corresponds to Case A or Case B. In case C, for $M_{H^+} > m_t + m_b$, not finding the signal event implies an upper bound on $B(A \to b\bar{b}) \times B(H^+ \to t\bar{b})$ for a given $M_A$. Including the negatively charged channel $AH^-$ and the $\rho\nu$ decay mode of $\tau$ can tighten the above bounds roughly by a factor of $\sqrt{3}$. However, to have a more accurate conclusion, a full event generator with detector simulation should be used to repeat the analysis outlined in this paper.

From Fig. 1(a), we see that the $AH^+$ rate becomes very small (less than about 0.1 fb) at the LHC once $M_A$ is larger than 400 GeV. Hence, to cover the whole mass spectrum of the TeV scale MSSM, we need a high energy collider that can be sensitive to this process for $M_A$ approaching the TeV region. This could be one of the motivations for proposing a future Very Large Hadron Collider (VLHC), a 200 TeV proton-proton collider.

References
1. J.F. Gunion, et al., The Higgs Hunters Guide (Addison-Wesley).
2. S. Kanemura, C.–P. Yuan, Phys. Lett. B 530 (2002) 188.
3. Q.–H. Cao, S. Kanemura, C.–P. Yuan, hep-ph/0311083, to appear in Physical Review D.