Variation of the cross section for $e^+e^- \to W^+H^-$ in the Minimal Supersymmetric Standard Model

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We study the loop-induced process $e^+e^- \to W^+H^-$ in the Minimal Supersymmetric Standard Model (MSSM). This process allows the charged Higgs boson to be produced in e^+e^- collisions when its mass is larger than half the center-of-mass energy, so that $e^+e^- \to H^+H^-$ is kinematically forbidden. By scanning over the MSSM parameters subject to experimental constraints we examine the range of values possible for this cross section. We find that, in regions of parameter space where this cross section is large enough to be of interest, the contributions from supersymmetric particles typically increase the cross section by 50–100% compared to the non-supersymmetric two Higgs doublet model result. Choosing a few typical MSSM parameter sets, we show the regions in the $m_{H^\pm}$–$\tan\beta$ plane in which at least 10 $W^\pm H^\mp$ events would be produced at the e^+e^- collider for $m_{H^\pm} \geq \sqrt{s}/2$. We also show that including radiative corrections to the MSSM Higgs sector has only a small effect on the cross section.

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I. INTRODUCTION

In our recent paper [1] we computed the cross section for $e^+e^- \to W^+H^-$ in the Minimal Supersymmetric Standard Model (MSSM). This process, which first arises at the one loop level, offers the possibility of producing the charged Higgs boson with mass above half the e^+e^- collider center-of-mass energy, when $e^+e^- \to H^+H^-$ is kinematically forbidden. The cross section for $e^+e^- \to W^+H^-$ is largest at relatively low values of $\tan\beta$, and is enhanced over its value in the non-supersymmetric two Higgs doublet model (2HDM) [2, 3] by the contributions of light supersymmetric (SUSY) particles in the loop [1]. This is the most promising process considered to date for producing the charged Higgs boson with mass above $\sqrt{s}/2$ in e^+e^- collisions at low to moderate $\tan\beta$ values (above the lower bound of $\tan\beta \geq 2.4$ from the CERN LEP-2 Higgs search [4]). This region of low to moderate $\tan\beta$ is exactly where the CERN Large Hadron Collider will have difficulty discovering the heavy MSSM Higgs bosons [5, 6, 7].

In this paper we examine the behavior of the W^+H^- cross section when the MSSM parameters are varied, taking into account the present experimental constraints on the SUSY particle masses from direct searches. In the Higgs sector, the strongest constraint comes from the lower bound on the mass of the lighter CP-even Higgs boson h^0 from searches at LEP [4]. Because the LEP search for h^0 relied primarily upon the production process $e^+e^- \to Zh^0$ for $m_{A^0} \gtrsim 120$ GeV,[1] the LEP constraint depends on the effective coupling of h^0 to Z boson pairs, parameterized by the effective mixing angle $\alpha_{\rm eff}$ that diagonalizes the higher-order corrected CP-even Higgs mass matrix.

For given values of $m_{H^\pm}$ and $\tan\beta$, the MSSM prediction for m_{h^0} receives very large radiative corrections of several tens of GeV [8], primarily due to loops involving top quarks and their supersymmetric partners. Obviously, these radiative corrections must be taken into account if the experimental constraint on m_{h^0} is to be used to constrain the MSSM parameter space.

The radiative corrections to the MSSM Higgs boson masses appear directly in the calculation of the $e^+e^- \to W^+H^-$ cross section via Feynman diagrams [1, 2] with Higgs bosons in the loop. The mixing angle α that diagonalizes the tree-level CP-even Higgs mass matrix and affects the Higgs couplings[2] must also be replaced by $\alpha_{\rm eff}$ after radiative corrections are included. Formally, these corrections are of two-loop and higher orders; however, because their effects are large (especially on m_{h^0}), their impact should be examined.

This paper is organized as follows. In Sec. II we examine the numerical effects on the $e^+e^- \to W^+H^-$ cross section of including the radiative corrections to the masses and mixing angle of the MSSM Higgs bosons in the calculation. In Sec. III we explore the possible variation of the $e^+e^- \to W^+H^-$ cross section as a function of the MSSM parameters, subject to the experimental lower bounds on the Higgs and SUSY particle masses and to the constraint on the ρ parameter. We also examine the reach in the $m_{H^\pm}$–$\tan\beta$ plane for some specific SUSY parameter sets. In Sec. IV we summarize our conclusions.

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[1] For lower values of m_{A^0}, the process $e^+e^- \to h^0A^0$ is also important at LEP.

[2] For details of the MSSM Higgs sector, see Ref. [9].

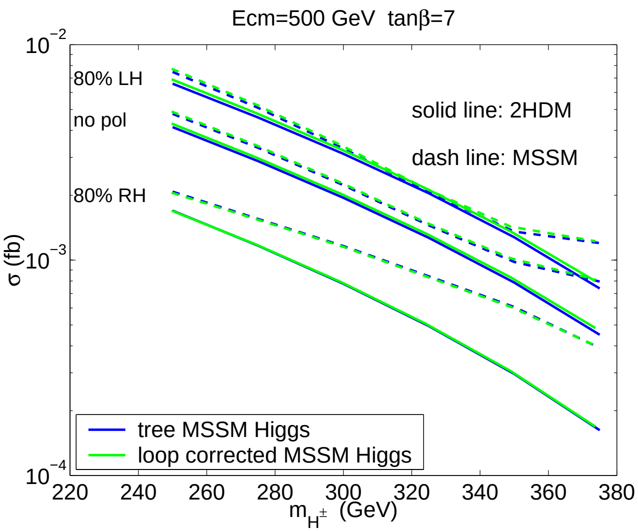

FIG. 1: Cross section for $e^+e^- \to W^+H^-$ as a function of $m_{H^\pm}$ for $\tan\beta = 7$ and $\sqrt{s} = 500$ GeV in the 2HDM (solid lines) and the full MSSM (dashed lines), with tree-level (dark/blue lines) and radiatively corrected (light/green lines) values for the MSSM Higgs masses and mixing angle. The SUSY parameters are chosen to be $M_{\rm SUSY}^{tb} = 1000$ GeV for the top and bottom squarks, $M_{\rm SUSY} = 200$ GeV for the rest of the squarks and the sleptons, $\mu = -200$ GeV, $2M_1 = M_2 = 200$ GeV, $M_{\tilde g} = 800$ GeV, and $A_t = A_b = 2M_{\rm SUSY}^{tb}$. For this choice of SUSY parameters, the radiatively corrected m_{h^0} is above the LEP lower bound. The lines from top to bottom are the cross sections for 80% left-polarized, unpolarized, and 80% right-polarized electrons. Positrons are assumed unpolarized.

II. RADIATIVE CORRECTIONS TO THE HIGGS SECTOR

In Ref. [1] we presented numerical results for the cross section for $e^+e^- \to W^+H^-$ in the MSSM, computed using the tree-level relations for the MSSM Higgs masses and mixing angle. Here we investigate numerically the effect of including the full radiative corrections to the MSSM Higgs masses and mixing angle. As shown in Fig. 1, the effect on the cross section is quite small, about 5% or less. In Fig. 1 we use the values of m_{h^0}, m_{H^0}, $m_{H^\pm}$, and $\alpha_{\rm eff}$, for given choices of m_{A^0}, $\tan\beta$ and the SUSY parameters, computed with the program FeynHiggs [10], which includes the complete one-loop and leading two-loop Higgs sector radiative corrections in the Feynman-diagrammatic approach. The MSSM parameters are given in the figure caption.[3]

[3] The kinks in the MSSM cross section at $m_{H^\pm} \simeq 350$ GeV are due to a chargino and neutralino in the loop going on shell. For our choice of SUSY parameters, one chargino has a mass of 257 GeV and one neutralino has a mass of 97 GeV.

III. VARIATION OF THE CROSS SECTION WITH MSSM PARAMETERS

In this section we explore the possible variation of the $e^+e^- \to W^+H^-$ cross section as a function of the MSSM parameters. The SUSY contributions to this cross section come mainly from loop diagrams involving top/bottom squarks and charginos/neutralinos. The diagrams involving top/bottom squarks are potentially large due to the large third-generation Yukawa couplings, but their contribution decouples like $1/m_{\tilde t,\tilde b}^2$, where $m_{\tilde t,\tilde b}$ are the masses of the top/bottom squarks [1]. The size of the top/bottom squark contributions is controlled mainly by $M_{\rm SUSY}^{tb}$ (the soft-SUSY-breaking mass that appears in the diagonal entries of the top and bottom squark mass matrices), which sets the overall top/bottom squark mass scale, and μ, $A_{t,b}$, and $\tan\beta$, which control the top and bottom squark mixing and their couplings to Higgs bosons. Generally, the m_{h^0} constraint forces $M_{\rm SUSY}^{tb}$ to be relatively large, so that the contribution of top and bottom squarks to the cross section is suppressed. We take $A_t = 2M_{\rm SUSY}^{tb}$ to maximize m_{h^0} for a given $M_{\rm SUSY}^{tb}$, so that lower values of $M_{\rm SUSY}^{tb}$ are allowed by the h^0 mass constraint. The diagrams involving charginos/neutralinos can also be large, and decouple more slowly, like $1/m_{\tilde\chi}$, where $m_{\tilde\chi}$ stands for the relevant chargino or neutralino mass [1]. The size of the chargino/neutralino contributions is controlled mainly by the gaugino and Higgsino mass parameters M_1, M_2 and μ, which control the chargino/neutralino masses and mixing, and $\tan\beta$, which also affects their mixing. There are additional contributions from box and t-channel diagrams involving charginos/neutralinos and selectrons/sneutrinos, and diagrams involving loops of sleptons and of the first two generations of squarks that couple to the charged Higgs boson through the supersymmetric D-terms [1]; however, these diagrams are less important. In what follows we include the radiative corrections to the Higgs masses and mixing angle using FeynHiggs [10].

We begin by scanning over the MSSM parameters in the following ranges: $2.4 \leq \tan\beta \leq 60$, 50 GeV $\leq M_{\rm SUSY}^{tb} \leq 1000$ GeV for the top and bottom squarks, and 50 GeV $\leq |\mu| \leq 1000$ GeV, with both positive and negative μ. We focus on varying the μ parameter because the $e^+e^- \to W^+H^-$ cross section depends on μ in a rather complicated way: μ affects the chargino/neutralino mass spectrum and mixings as well as the top/bottom squark mixings and couplings to Higgs bosons. We take $A_t = A_b = 2M_{\rm SUSY}^{tb}$. We fix the remaining parameters to be $2M_1 = M_2 = 200$ GeV, $M_{\tilde g} = 800$ GeV, and $M_{\rm SUSY} = 200$ GeV for the sleptons and the first two generations of squarks. The dependence of the cross section on M_1, M_2 and $M_{\rm SUSY}$ is quite simple: when these parameters are large, the diagrams involving the corresponding superparticles decouple. The gluino mass $M_{\tilde g}$ only enters our calculation in the two-loop corrections to the Higgs masses and mixing angle,

$\tilde{\nu}$	$\tilde{\ell}$	$\tilde{t}_1$	$\tilde{b}_1$	$\tilde{\chi}_1^0$	$\tilde{\chi}_1^\pm$
43 GeV	95 GeV	95 GeV	85 GeV	36 GeV	84.6 GeV

TABLE I: Lower bounds on the SUSY particle masses used in our calculation.

so that varying it has a negligible effect on the cross section. For the charged Higgs mass, we scan over 250 GeV $\leq m_{H^\pm} \leq$ 400 GeV for $\sqrt{s}$ = 500 GeV, and 500 GeV $\leq m_{H^\pm} \leq$ 900 GeV for $\sqrt{s}$ = 1000 GeV.

We discard any points that yield SUSY particle masses below the experimental lower bounds, as summarized in Table I. These bounds are model dependent; we have used the bounds quoted in Ref. [11] for the minimal supergravity scenario, which is reasonably close to our choice for the MSSM parameters. We also discard any points for which h^0 is too light. We take the experimental bound from LEP [12] on the mass of h^0 as a function of the cross section for $e^+e^- \to Zh^0$, which is equal to the corresponding Standard Model cross section times $\sin^2(\beta-\alpha_{\rm eff})$. For $\sin^2(\beta-\alpha_{\rm eff})$ values close to 1, LEP excludes m_{h^0} values up to 114 GeV [12]. After the dominant two-loop radiative corrections to m_{h^0} [10] have been included, the remaining theoretical uncertainty due to uncalculated higher order corrections is estimated to be about ± 3 GeV [13]. To take into account this theoretical uncertainty, we reduce the experimental m_{h^0} bound by 3 GeV; *e.g.*, we require $m_{h^0} > 111$ GeV for $\sin^2(\beta-\alpha_{\rm eff}) \simeq 1$. We then apply this reduced experimental bound to m_{h^0} as a function of $\sin^2(\beta-\alpha_{\rm eff})$ computed for each point using FeynHiggs [10]. Finally, we discard any points that give too large a SUSY contribution to the ρ parameter [14]; we require $|\Delta\rho_{\rm SUSY}| < 0.002$ [15].[4]

The results of the parameter scans are shown in Figs. 2 (with $\sqrt{s}$ = 500 GeV) and 3 (with $\sqrt{s}$ = 1000 GeV). We show the total $e^+e^- \to W^+H^-$ cross section in the full MSSM ($\sigma_{\rm SUSY}$) normalized to the cross section in the 2HDM[5] ($\sigma_{\rm 2HDM}$) as a function of the total MSSM cross section (left plots) and as a function of $\tan\beta$ (right plots). For both $\sqrt{s}$ = 500 and 1000 GeV, the relative enhancement due to the SUSY contributions is largest when the total cross section is small and when $\tan\beta$ is large. The SUSY contribution is also much more significant at $\sqrt{s}$ = 1000 GeV than at 500 GeV.

At large $\tan\beta \gtrsim 20$, a SUSY enhancement of the cross section by a factor of 50 or more is possible. However, for such large values of $\tan\beta$, the 2HDM cross section is extremely small [1, 2, 3], so that even such a large enhancement factor will not typically bring the cross section up to an observable level [1]. At low $\tan\beta \lesssim 5$, the SUSY contributions typically enhance the cross section over that in the 2HDM by up to 50% at $\sqrt{s}$ = 500 GeV, and by up to an order of magnitude at 1000 GeV. For some SUSY parameter points at $\sqrt{s}$ = 500 GeV, the cross section can also be reduced at low $\tan\beta$ by up to 30%; such points are less common at 1000 GeV. At $\sqrt{s}$ = 500 GeV, for a total cross section above 0.01 fb (corresponding to 10 $W^\pm H^\mp$ events in 500 fb^{-1}) the SUSY contributions typically enhance the 2HDM cross section by up to about 50%, with enhancements of 20-30% at the largest cross section values. At $\sqrt{s}$ = 1000 GeV, the SUSY enhancements are much larger. Cross sections above 0.005 fb (corresponding to 10 $W^\pm H^\mp$ events in 1000 fb^{-1}) can arise predominantly due to the SUSY contributions, even when the 2HDM cross section is very small; in this case the SUSY enhancement can be as large as a few orders of magnitude. When the 2HDM cross section itself is above 0.005 fb, the SUSY enhancements are typically of order 100%.

In order to illustrate the reach of the $e^+e^- \to W^+H^-$ production process, we choose a "typical" set of SUSY parameters (see the caption of Fig. 4) that obey the constraints from direct searches and the ρ parameter, and consider two values of the μ parameter, μ = 200 and 500 GeV. For this set of parameters, we show contours in Fig. 4 in the $m_{H^\pm}$–$\tan\beta$ plane below which 10 or more $W^\pm H^\mp$ events will be produced in the e^+e^- collider data sample. As a typical collider run plan, we assume that 500 fb^{-1} would be collected at $\sqrt{s}$ = 500 GeV and that 1000 fb^{-1} would be collected at $\sqrt{s}$ = 1000 GeV. We plot 10-event contours for the 2HDM (solid lines) and for the MSSM with μ = 200 GeV (dashed lines) and 500 GeV (dot-dashed lines). We consider an unpolarized e^- beam (light/green lines) and an 80% left-polarized e^- beam (dark/blue lines). In all cases we assume the e^+ beam is unpolarized.

For $\sqrt{s}$ = 500 GeV (the left panel of Fig. 4), the 10-event reach in the 2HDM is $m_{H^\pm} \lesssim 327$ GeV and $\tan\beta \lesssim$ 4.6 with unpolarized beams, which increases to $m_{H^\pm} \lesssim$ 355 GeV and $\tan\beta \lesssim 5.8$ if the e^- beam is 80% left-polarized. In the full MSSM the reach is larger. For the SUSY parameters considered here, the dependence on the μ parameter is small at this center-of-mass energy; for either value of μ, the 10-event reach is $m_{H^\pm} \lesssim 345$ GeV and $\tan\beta \lesssim 5.0-5.3$ with unpolarized beams. This increases to $m_{H^\pm} \lesssim 375$ GeV and $\tan\beta \lesssim 6.3-6.6$ if the e^- beam is 80% left-polarized.

For $\sqrt{s}$ = 1000 GeV (the right panel of Fig. 4), the

[4] In principle, one could also impose the constraints from the measurement of $b \to s\gamma$, which receives MSSM contributions from diagrams involving charged Higgs or chargino exchange, especially at large $\tan\beta$ values. However, because $b \to s\gamma$ is a flavor-changing decay, the constraints that it places on the MSSM parameter space depend strongly on the presence or absence of additional non-minimal flavor structure in the model. Similarly, one could discard any points that yield an unacceptable amount of neutralino dark matter. However, introducing a very small amount of R-parity violation can remove the dark matter constraint while having a negligible effect on the collider phenomenology. In order to maintain generality, then, we have not applied the $b \to s\gamma$ or dark matter constraints.

[5] For the 2HDM cross section calculations in Figs. 2 and 3 we use the MSSM radiatively corrected Higgs masses and mixing angle in order to isolate the effects of the SUSY loop diagrams.

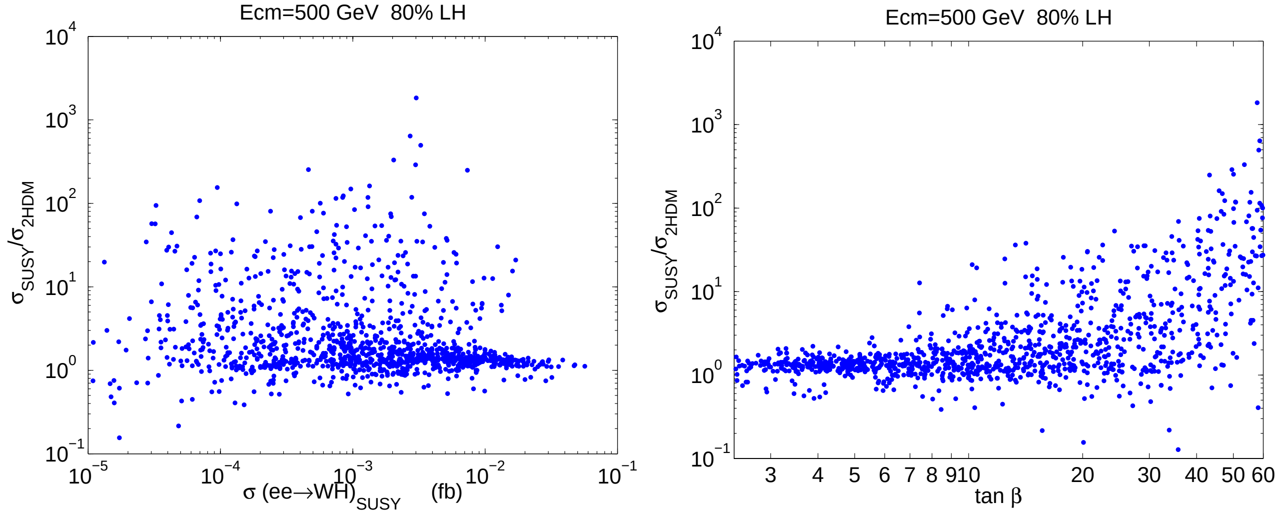

FIG. 2: Cross section in the full MSSM compared to that in the 2HDM as a function of the total cross section (left) and $\tan\beta$ (right), for $\sqrt{s} = 500$ GeV and an 80% left-polarized e^- beam. The positrons are unpolarized. The MSSM parameters are given in the text.

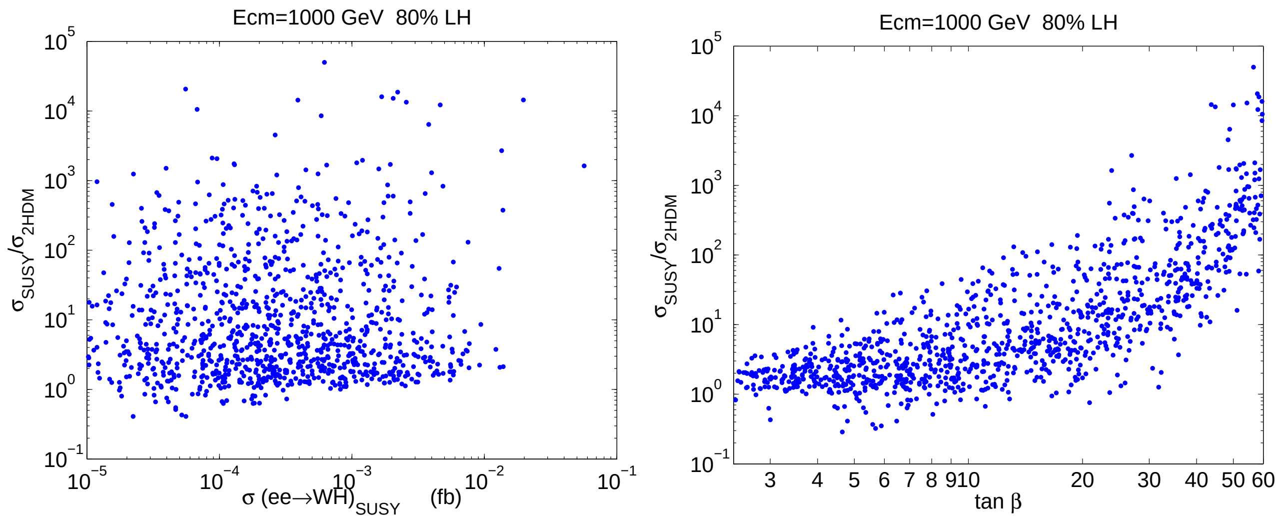

FIG. 3: The same as Fig. 2 but for $\sqrt{s} = 1000$ GeV.

2HDM cross section is too small to give 10 or more events for $m_{H^\pm} > \sqrt{s}/2$ and $\tan\beta > 2.4$ with unpolarized beams. However, if the e^- beam is 80% left-polarized, the cross section increases so that the 10-event reach in the 2HDM becomes $m_{H^\pm} \lesssim 535$ GeV and $\tan\beta \lesssim 2.8$. The full MSSM yields a significantly larger reach, producing at least 10 events in some regions even for unpolarized beams. For this center-of-mass energy, the dependence on μ is much more dramatic. For unpolarized beams, the 10-event reach is $m_{H^\pm} \lesssim 520$ GeV and $\tan\beta \lesssim 2.7$ for $\mu = 200$ GeV, which increases to $m_{H^\pm} \lesssim 585$ GeV and $\tan\beta \lesssim 3.6$ for $\mu = 500$ GeV. With an 80% left-polarized e^- beam, the 10-event reach is $m_{H^\pm} \lesssim 575$ GeV and $\tan\beta \lesssim 3.6$ for $\mu = 200$ GeV, which increases to $m_{H^\pm} \lesssim 650$ GeV and $\tan\beta \lesssim 5$ for $\mu = 500$ GeV.

IV. CONCLUSIONS

We examined the possible range of values for the cross section for $e^+e^- \to W^+H^-$ in the MSSM as a function of the MSSM parameters, after imposing the experimental constraint on the ρ parameter and the lower bounds on the masses of the SUSY particles and the lighter CP-even Higgs boson h^0. We found that for $\sqrt{s} = 500$ GeV, the cross sections in the MSSM tend to cluster around the 2HDM result when the cross section is near its maximal value, which occurs at low $\tan\beta$. In particular, for cross sections above 0.01 fb (corresponding to 10 $W^\pm H^\mp$ events in 500 fb^{-1}), SUSY enhancements of $\lesssim 50\%$ are typical; a few parameter points also exist at which the SUSY contributions can suppress the cross section by

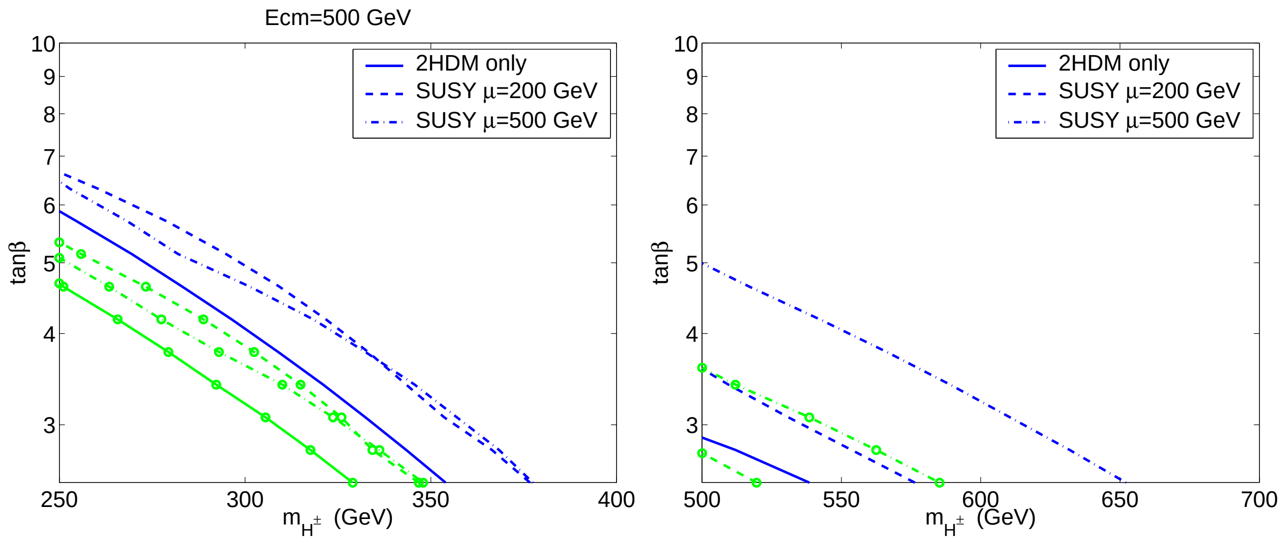

FIG. 4: Ten-event contours for $e^+e^- \to W^\pm H^\mp$ for $\sqrt{s} = 500$ GeV with 500 fb^{-1} (left) and $\sqrt{s} = 1000$ GeV with 1000 fb^{-1} (right). The SUSY parameters are chosen to be $M_{\rm SUSY}^{tb} = 1000$ GeV for the top and bottom squarks, $M_{\rm SUSY} = 200$ GeV for the rest of the squarks and the sleptons, $2M_1 = M_2 = 200$ GeV, $M_{\tilde{g}} = 800$ GeV, $A_t = A_b = 2M_{\rm SUSY}^{tb}$, and $\mu = 200$ GeV (dashed lines) and 500 GeV (dot-dashed lines). The radiative corrections to the MSSM Higgs boson masses and mixing angle have been included for both the 2HDM contours (solid lines) and the MSSM contours. For the 2HDM Higgs sector radiative corrections we have taken $\mu = 200$ GeV; taking $\mu = 500$ GeV changes the cross section by less than 1%. Light (green) lines show the unpolarized cross section and dark (blue) lines show the cross section with an 80% left-polarized e^- beam. The e^+ beam is unpolarized.

20-30%. For $\sqrt{s} = 1000$ GeV, the MSSM cross sections are much more widely scattered about the 2HDM result. In particular, for cross sections above 0.005 fb (corresponding to 10 $W^\pm H^\mp$ events in 1000 fb^{-1}), the SUSY enhancements can be much larger, with typical enhancements of order 100% for the case of relatively large 2HDM cross sections.

We also examined in detail the reach in $m_{H^\pm}$ and $\tan\beta$, focusing on the dependence on the μ parameter and electron beam polarization. At $\sqrt{s} = 1000$ GeV, increasing the μ parameter from 200 to 500 GeV with other SUSY parameters held fixed increases the 10-event reach by about 70 GeV in $m_{H^\pm}$, and by about 1 unit in $\tan\beta$. At $\sqrt{s} = 500$ GeV, the μ dependence is much weaker. For either value of μ, using an 80% left-polarized e^- beam increases the reach compared to using unpolarized beams by about 30 GeV in $m_{H^\pm}$ at $\sqrt{s} = 500$ GeV and by twice that at $\sqrt{s} = 1000$ GeV; at either center-of-mass energy the reach in $\tan\beta$ increases by about 1 unit. Because the cross section is quite sensitive to the SUSY parameters, this process can be used not only to produce $H^\pm$ at low $\tan\beta$, but also to test and/or constrain the MSSM [16].

Finally, we found that using the radiatively corrected MSSM Higgs boson masses and mixing angle in the cross section calculation instead of the tree-level masses and mixing angle has only a small numerical effect on the cross section.

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