DESY Summerstudent program 2018
Report

Investigation of the current LHC sensitivity to heavy Higgs decays into gauginos in the MSSM

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Content

1 Introduction

In this DESY summerstudent project report, I present an investigation of current searches for Supersymmetry (SUSY) at the LHC at CERN. I analyze whether current searches by ATLAS and CMS, which are sensitive to the direct production of electroweakinos (EWino), i.e. neutralinos and charginos, are also sensitive to heavy Higgs bosons decaying into EWinos. I focus on the Minimal Supersymmetric Standard Model (MSSM), which is the minimal extension of the Standard Model (SM) that realizes supersymmetry (SUSY).

To start with this sensitivity analysis, I use predefined two-dimensional benchmark scenarios, since otherwise the MSSM parameter space is too large to analyze due to too many free parameters. A benchmark scenario usually has a parameter space, that is in agreement with previous observations and discoveries. In my benchmark scenario m_h^{mod+} the mass of the CP-odd Higgs boson M_A as well as $\tan(\beta) = \frac{v_1}{v_2}$, the ratio of the vacuum expectation values of the two Higgs doublets in the MSSM, are free parameters.

Since no supersymmetric particle has been discovered so far, experimental results have been presented as upper limits on the number of signal events for various collider signatures. These signatures typically assume that the lightest supersymmetric particle (LSP), χ_1^0, is stable and leaves missing transverse energy in the detector. The heavier neutralinos and charginos decay into the LSP under the emission of Z or W boson, which can decay into leptons. A detectable signature for the EWino production is therefore composed of multiple leptons plus missing transverse energy $\not{E}_T$.

In this project I study the implications of LHC multilepton plus $\not{E}_T$ searches for EWino production for the benchmarks scenario. We first only consider direct EWino production, and then study how the exclusion changes if the heavy Higgs boson decays to EWinos is considered in addition.

2 Theoretical Background

2.1 The MSSM

The Standard Model (SM) of particle physics is a powerful theoretical framework which describes very successfully the building blocks of matter and their fundamental interactions. It features the Higgs mechanism, which provides mass to most elementary particles in a gauge-invariant way via spontaneous symmetry breaking. The discovery of the Higgs boson was a big success for the theory. However, the Standard Model cannot be the full theory of particle physics, as it is not able to explain several physics phenomena, such as the nature of dark matter (DM), or the inconsistency of the hierarchy problem.

The Minimal Supersymmetric Standard Model (MSSM) is the minimal extension of the Standard Model that realizes Supersymmetry. The advantage of the MSSM in comparison to the SM is that it elegantly solves the hierarchy problem and features a DM candidate. Fig. 2.1 shows the particles of the MSSM. On the left side the particles of the Standard Model are shown and on the right side their supersymmetric partners.

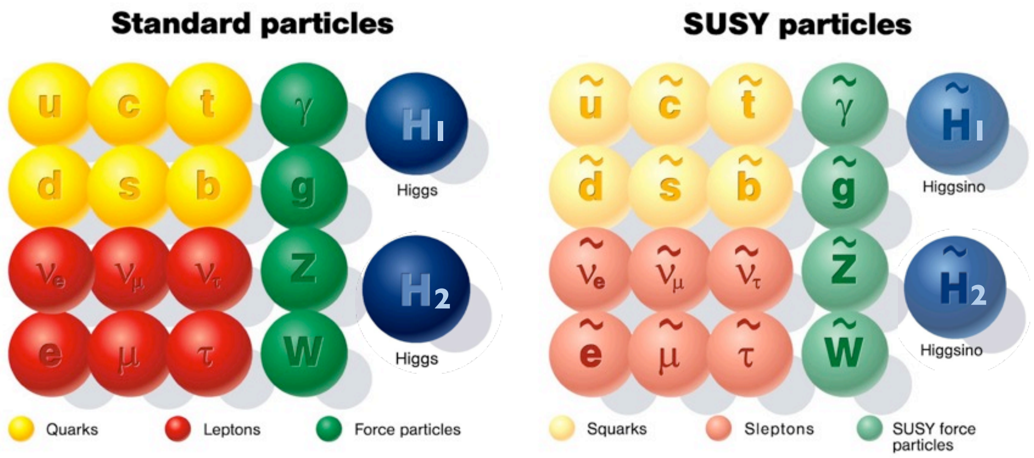

Figure 2.1: Standard model particles and their supersymmetric partners [1].

The supersymmetric partners of the fermions (spin = $\frac{1}{2}$) are bosons (spin = 0) while the supersymmetric partners of the bosons are fermions. Furthermore, the SM Higgs sector is extended by a second Higgs doublet, resulting in 5 physical Higgs bosons: the light CP-even Higgs boson **h**, the heavy CP-even Higgs boson **H**, the CP-odd Higgs boson **A** and the charged Higgs bosons $\mathbf{H}^{\pm}$.

The photino $\tilde{\gamma}$ and zino $\tilde{Z}$ mix with the neutral higgsinos of the supersymmetric Higgs doublets. The resulting mass eigenstates are called neutralinos,

$$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0. \tag{1}$$

The two charged winos $\tilde{W}$ mix with the charged higgsinos of the two supersymmetric Higgs doublets to the charginos

$$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{\pm}. \tag{2}$$

The mixing depends on the gaugino mass parameters M_1, M_2, the higgsino mass parameter μ, the ratio of the vacuum expectation values of the two Higgs doublets $\tan\beta$ for neutralinos, and on $M_2, \mu, \tan\beta$ for charginos. The neutralinos and charginos are sorted by their masses, with χ_1^0 being the lightest.

2.2 The benchmark scenario m_h^{mod+}

The MSSM has a large amount of free parameters, which makes it very difficult to analyze the complete parameter space. Therefore, benchmark scenarios were introduced, in which all parameters are fixed except for two parameters that describe the Higgs sector at tree-level. The parameters are chosen in order to be consistent with current searches and observations. In this project, the $\mathbf{m_h^{mod+}}$, [2] is chosen as the benchmark scenario. It was defined in 2013 under the then applied results and state of research. The Higgs-like particle, discovered at the LHC in 2012, can be interpreted as the light Higgs boson h of the $\mathbf{m_h^{mod+}}$. The two parameters μ and M_2, that contribute to the mixing of the neutralinos and charginos, have the same value of 200 GeV. The bino mass parameter M_1 is set to $M_1 \approx \frac{M_2}{2}$.

The scenario $\mathbf{m_h^{mod+}}$ is defined by the following parameters:

$\mathrm{m}_t = 173.2$ GeV	$\mathrm{M}_{SUSY} = 1000$ GeV	$\mu = 200$ GeV
$\mathrm{M}_2 = 200$ GeV	$\mathrm{X}_t^{OS} = 1.5 M_{SUSY}$	$\mathrm{X}_t^{MS} = 1.6 M_{SUSY}$
$\mathrm{A}_b = A_\tau = A_t$	$\mathrm{m}_{\tilde{g}} = 1500$ GeV	$\mathrm{M}_{\tilde{l}_3} = 1000$ GeV.

The small value of the wino mass parameter, M_2, and the higgsino mass parameter, μ, of 200 GeV yield small masses for the EWinos: $M_{\tilde{\chi}_2^0} \approx M_{\tilde{\chi}_1^\pm} \approx$ 156 GeV and with $M_1 \approx \frac{M_2}{2}$, $M_{\tilde{\chi}_1^0} \approx 88$ GeV.

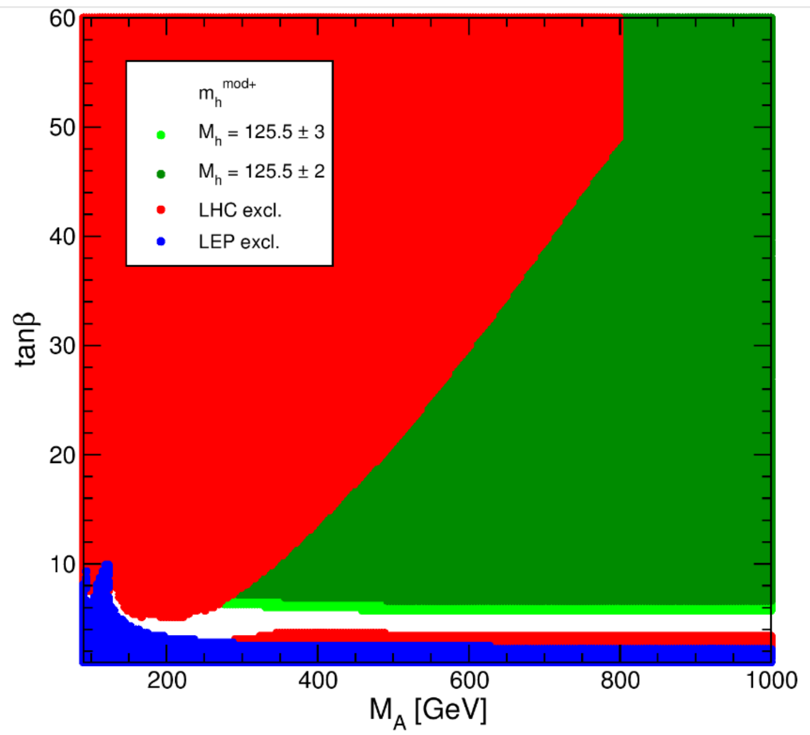

Figure 2.2: Exclusion limit on the benchmark scenario

Fig.2.2 shows the exclusion of the $\mathbf{m_h^{mod+}}$ benchmark scenario in the $(M_A, \tan\beta)$ plane. As shown in red, searches for the production of $H/A \to \tau\bar{\tau}$ at the LHC exclude high $\tan\beta$ values, as well as low M_A values. In blue is the LEP exclusion shown, in green the parameter space consistent with the mass of the discovered Higgs boson at the time of 2013.

3 Programs

In this section I give a short introduction to the programs and computer tools in this project. The order and interaction of the tools can be seen in figure 3.1.

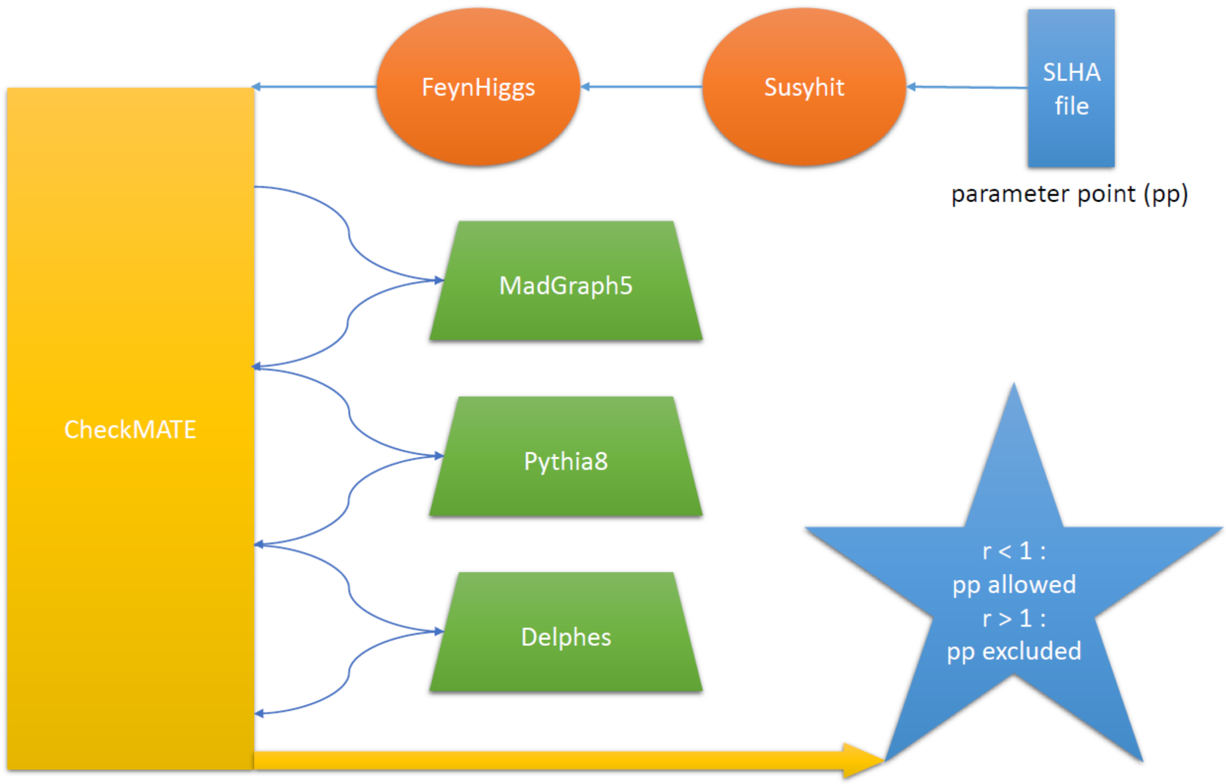

Figure 3.1: Evaluation scheme to determine if a parameter point is allowed or excluded by current searches at the LHC, CERN.

The overlying program CheckMATE [3] provides the information whether a specific parameter point of the benchmark scenario is allowed or excluded by current searches at the LHC. CheckMATE therefore needs the input parameter file in the format of the SUSY Les Houches Accord (SLHA) [4], a specific file structure, where the data is structured in various blocks, which provides an interface between spectrum calculators, decay packages and event generators. Further details about the structure of the SLHA files can be found in [4]. From the input parameters of a parameter point the program packages SUSY-HIT [5] and FeynHiggs [6, 7, 8, 9, 10, 11, 12] calculate the entire mass and decay spectrum of the Higgs and SUSY particles.

CheckMATE then calls MadGraph-5 to generate events for the direct EWino production processes, and gives these events to Pythia-8, which is responsible for hadronization and showering of the events. The fast detector simulator Delphes is the final step of CheckMATE. The data is then compared with several ATLAS and CMS searches for Supersymmetry. At first, the most sensitive analysis is determined, and in the following the r value calculated, which gives the information whether the parameter point is allowed or excluded at a 95% confidence level by the most sensitive analysis. The ratio is defined as:

$$r = \frac{signal\ events}{95\%\,Confidence\ level\ limit\ on\ signal}. \tag{3}$$

If $r \leq 1$, the parameter point is still allowed and if $r > 1$, the parameter point is excluded.

4 Results and Discussion

The aim of this project can be subdivided into two questions:

1. Do LHC EWino searches exclude the m_h^{mod+} scenario?
2. What happens if the additional contribution from heavy Higgs decays to EWinos is taken into account?

To answer these questions we estimate the r value, as defined in 3 with the tool CheckMATE 2. The number of signal events for the first part considers the number of events in the direct EWino production:

Number of signal events (1.) : estimated from direct EWino production (pp > EWinos).

For the second question, additionally to the direct EWino production, the heavy Higgs boson production is taken into account, where the heavy Higgs bosons further decay into EWinos:

N. signal events (2.) : estimated from direct EWino production + heavy Higgs (pp > EWinos + pp > heavy Higgs, heavy Higgs > EWinos).

If the current LHC searches are sensitive to the heavy Higgs production, it is expected that the number of signal events (and thus the r-value) increases with respect to the result from the first part. For a fixed value of $M_A = 352$ GeV, I investigate six parameter points for different $\tan\beta$ values. Per parameter point $500,000$ events are generated. In order to achieve higher statistics, three runs are added up to $1,500,000$ events per parameter point.

4.1 Direct EWino production

At the LHC, current searches target the direct production of the EWinos in the following production modes:

$$pp \to \tilde{\chi}_1^+ \tilde{\chi}_1^-, \tag{4}$$
$$pp \to \tilde{\chi}_2^0 \tilde{\chi}_2^0, \tag{5}$$
$$pp \to \tilde{\chi}_1^\pm \tilde{\chi}_2^0. \tag{6}$$

Fig. 4.1 shows the $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ production mode, Eq. (6), with successive decay to a W and a Z boson.

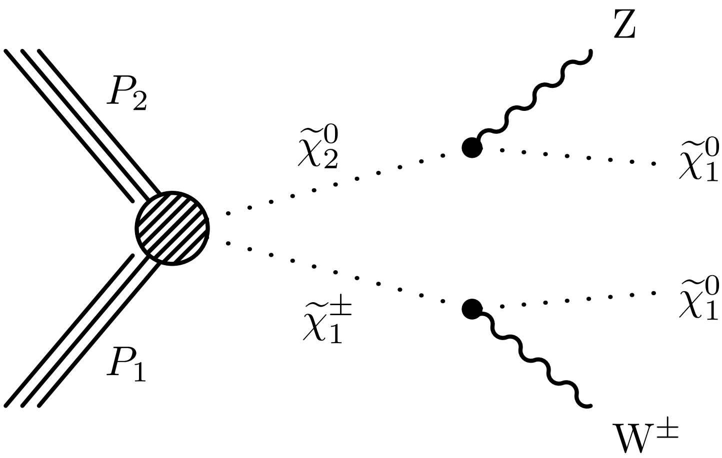

Figure 4.1: Production of $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^{\pm}$ in proton proton collisions in the MSSM. Figure taken from [13].

The second lightest neutralino, $\tilde{\chi}_2^0$, decays into $\tilde{\chi}_1^0$ under the emission of a Z boson. The chargino $\tilde{\chi}_1^{\pm}$ also decays into the LSP, $\tilde{\chi}_1^0$, under the emission of $W^{\pm}$. $\tilde{\chi}_1^0$ is stable and therefore only leaves $\not{E}_T$ in the detector. The Z and $W^{\pm}$ bosons can both decay into two leptons, of which are three charged. For this production mode is the searched for in the three charged leptons plus $\not{E}_T$.

In general, a promising search for the direct EWino production is the multi-lepton + $\not{E}_T$ channel.

4.2 Heavy Higgs decaying into EWinos

In this project I consider the production of the heavy Higgs via gluon fusion in the LHC proton proton collisions. I furthermore consider that the heavy Higgs bosons H and A decay into EWinos. Since the heavy Higgs boson itself is charge-neutral, only neutral states can be created, i.e. combinations of $\tilde{\chi}_i^0$, or one positive and one negative $\tilde{\chi}_j^{\pm}$. It is interesting to see the branching ratios for the different decay modes. With the masses, as defined in the used benchmark scenario, the heavy Higgs boson H mostly decays to $\tilde{\chi}_1^+$ $\tilde{\chi}_1^-$ and

$\tilde{\chi}_1^0\ \tilde{\chi}_3^0$. Fig. 4.2 shows these branching ratios in the $(M_A, \tan\beta)$ plane for the CP-even Higgs boson H.

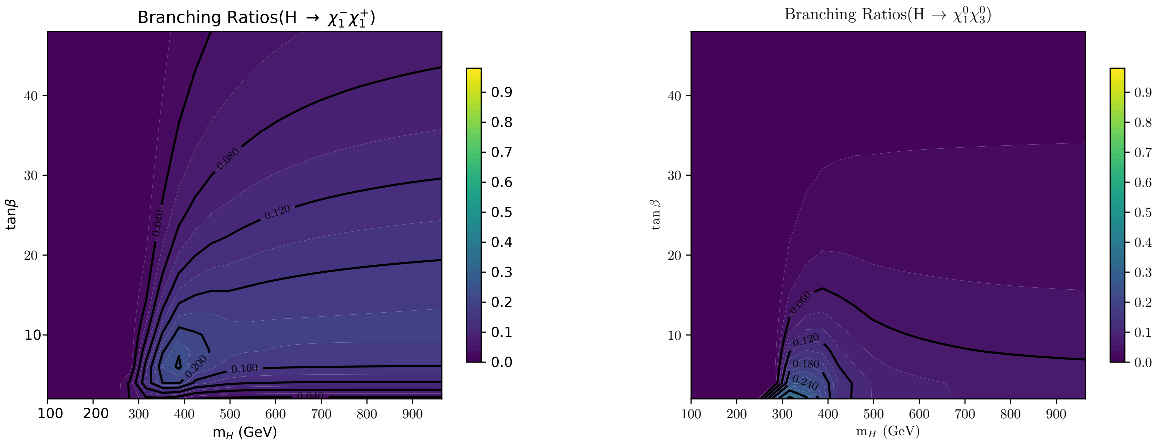

Figure 4.2: Branching ratios for the dominant decays of the heavy CP-even Higgs boson H to EWinos, shown in the $(M_A, \tan\beta)$ plane.

The heavy Higgs boson A mostly decays to $\tilde{\chi}_1^+\ \tilde{\chi}_1^-$ and $\tilde{\chi}_1^0\ \tilde{\chi}_2^0$. Fig. 4.2 shows the branching ratios in the $(M_A, \tan\beta)$ plane for the pseudoscalar Higgs boson A.

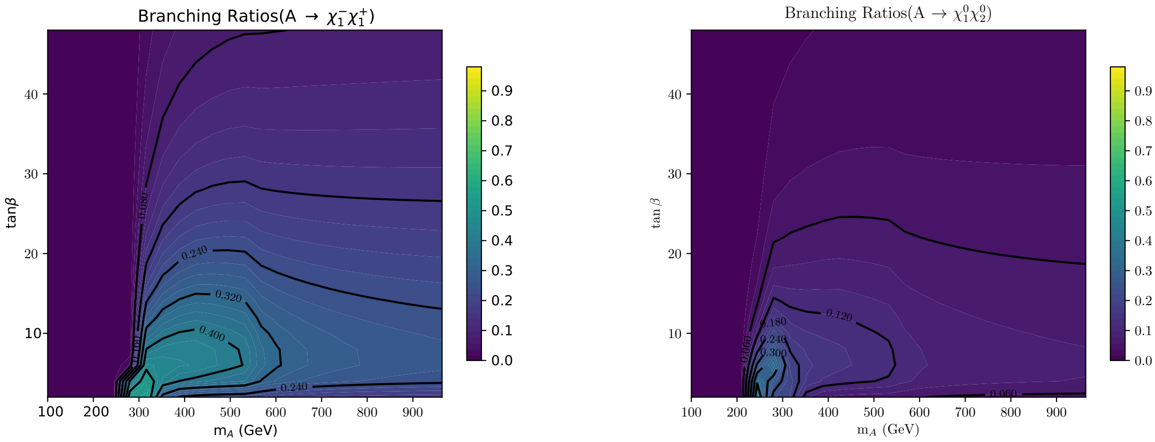

Figure 4.3: Branching ratios for the dominant decays of the pseudoscalar Higgs boson A to EWinos, shown in the $(M_A, \tan\beta)$ plane.

The highest branching ratios can be found around the parameter point $\tan\beta = 10$, and $M_A = 350$ GeV. I therefore choose this parameter point as a starting point for my investigation.

The heavy Higgs boson (H, A) decay modes into EWinos with the highest branching ratios (Fig. 4.2 and Fig. 4.3) lead to a promising collider signature of 2 leptons plus missing transverse energy (emitted W and Z bosons can both decay into two leptons + $\not{E}_T$ from LEP). While doing the analysis, it emerged that the most sensitive analysis actually uses a 4 lepton plus missing transverse energy signal region. Therefore, the decay modes with the highest branching ratios are not contributing to the most sensitive analysis. However, I found two contributing heavy Higgs decay modes to EWinos (of higher mass rank i/j) that can provide a 4 lepton plus missing transverse energy final state. These are $H \to \tilde{\chi}_2^0\tilde{\chi}_3^0$ and $A \to \tilde{\chi}_2^0\tilde{\chi}_2^0$. The corresponding branching ratios are shown in Fig. 4.4.

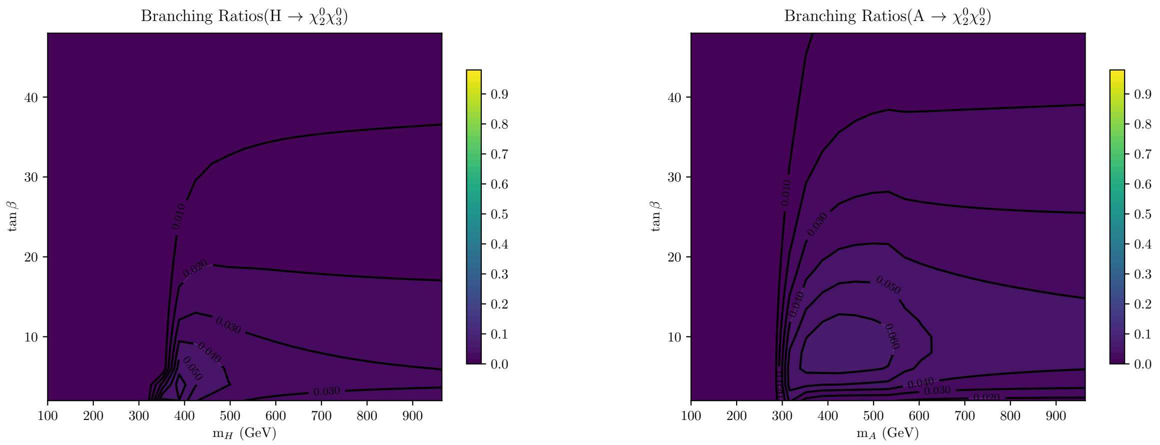

Figure 4.4: Free parameter plane $\tan\beta$ in dependence of m_A for the gaugino production providing 4 lepton plus missing transverse energy as collider signature.

4.3 Results

The analysis "Search for electroweak production of charginos and neutralinos in multilepton final states in pp collision data at $\sqrt{s}$=13 TeV" [13] by CMS, using 36 fb^{-1} of data, turned out to be the most sensitive study to the EWino production in the m_h^{mod+} benchmark scenario.

With the tool CheckMATE six points in the $\tan\beta$ range from 2 to 50, for a fixed value of $M_A = 352$ GeV, are tested against current searches at the LHC. In Fig. 4.5 the r value (as defined in Section 3) of these six parameter points is shown as a function of $\tan\beta$.

The two points of $\tan\beta = 2$ and $\tan\beta = 34$ seem already excluded, as their r value is > 1. The other four points are still allowed, although three could be excluded within their uncertainty.

I conclude that, in answer to the first question, the LHC EWino searches are not yet fully excluding the mod_h^{mod+} scenario. The results are just at the edge of being excluded, with 5 of 6 points being excluded within one standard deviation.

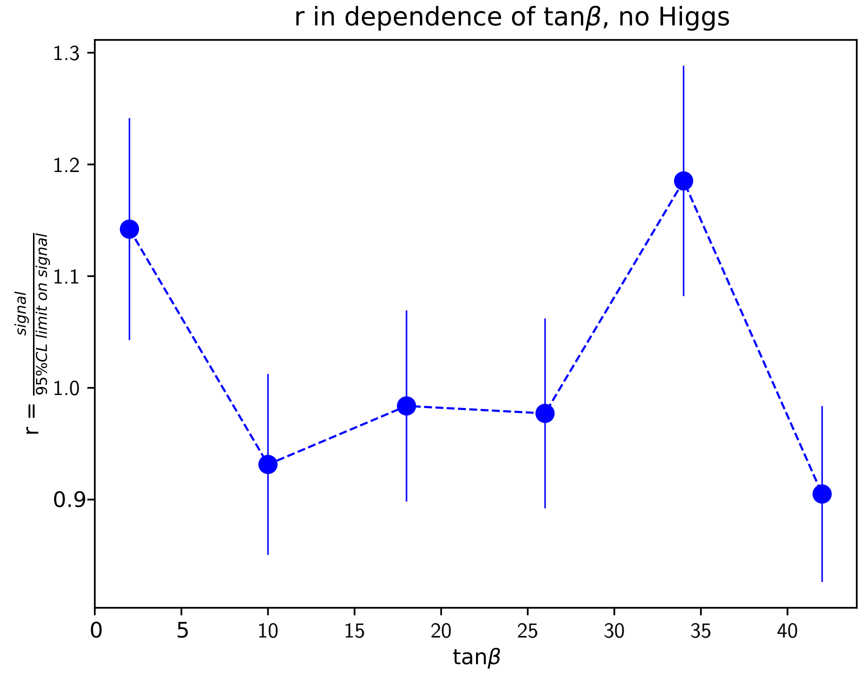

Figure 4.5: Estimated r values for different $\tan\beta$ points, considering the direct EWino production at M_2=352GeV.

Fig. 4.6 shows the same parameter points as in Fig. 4.5, but considers in addition to the direct EWino production the gluon fusion production of the heavy Higgs bosons H and A, which then decay into EWinos. We can observe an upwards trend of the r-value. More precisely, five of the six tested points have an r-value above 1 and are therefore excluded. Because of the general trend, I conclude, in answer to the second question, that LHC searches are indeed sensitive to the heavy Higgs bosons H and A decays to EWinos. However, there is to say that there are in general still strong statstical fluctuations and more events need to be generated in order to make detailed quantitative statements.

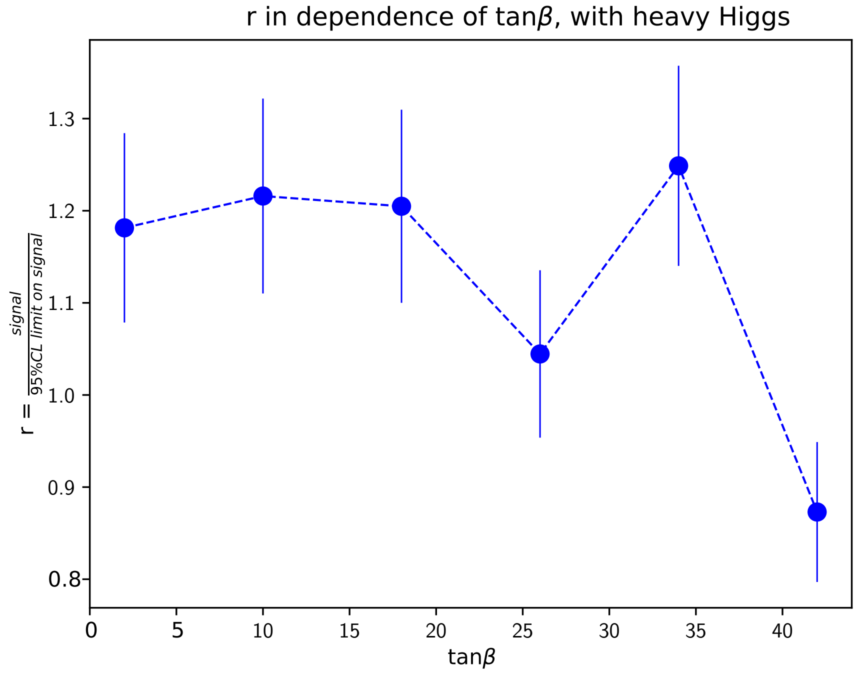

Figure 4.6: Estimated r values for different $\tan\beta$ points at M_2=352GeV, considering the direct EWino production plus the heavy Higgs production, which decay into EWinos.

5 Conclusion and Outlook

In this report I investigated the sensitivity of current LHC searches to MSSM heavy Higgs bosons decaying to EWinos. I was studying the m_h^{mod+} benchmark scenario of the MSSM, which contains two Higgs doublets. The first question was, if current LHC EWino searches exclude the m_h^{mod+} scenario, the second, what happens if the additional contribution from heavy Higgs decays to EWinos is taken into account?

At first I explored the branching ratios of the heavy Higgs bosons decaying to EWinos in order to find an interesting value for the pseudoscalar Higgs mass, $M_A = 352$ GeV. I considered 6 points in the $\tan\beta$ range from 2 to 50. Generating 3 times 500 000 events per point with the tools CheckMate, MadGraph-5 and Pythia-8 for the direct EWino production, two of the $\tan\beta$ points were found to be already excluded. When additionally taking the heavy Higgs production to the direct EWino production into account, 5 of the 6 selected parameter points are excluded. In comparison to the direct EWino production there is an upwards trend to see. But in general there is to say that there are still sizable fluctuations, despite a large number $(1, 500, 000)$ of events were generated per point.

To conclude, the first question can be answered that the LHC searches are not yet fully excluding the direct EWino production in the mod_h^{mod+} scenario. By taking the heavy Higgs decays to EWinos additionally to the direct EWino production into account, the results show that the LHC searches are sensitive to the heavy Higgs bosons H and A, and that more parameter points are excluded.

For the next steps it would be important to include the next-to-leading-order cross sections for both direct EWino and heavy Higgs boson production, which should lead to an increase of the r-value for both processes. With this, I anticipate that the m_h^{mod+} scenario is fully excluded.

6 Bibliography

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