Searches for electroweak production of higgsino with ATLAS

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Abstract. Fine-tuning arguments suggest the mass of the supersymmetric partner of the Higgs boson, the Higgsino, is not too far from the weak scale. In most beyond standard model scenarios the Higgsinos are almost mass degenerate, and the search for Higgsinos represents an experimental challenge due to the near mass-degeneracy resulting in soft decay products, and the low production cross section. This proceeding presents recent ATLAS results of analyses explicitly targeting the Higgsino with a variety of experimental techniques.

1. Introduction

Supersymmetry (SUSY) is one of the most promising extensions of Standard Model (SM) and it could explain both hierarchy and dark matter left open by the SM. SUSY introduces a symmetry between bosons and fermions associating to each fermion or boson SM particle respectively a boson or fermion superpartner. The Higgsino, being the fermion partner of the Higgs, mixes with the gauge boson partner (the Wino and Bino), forming the electroweakino. Electroweakinos are represented as mass eigenstates by $\tilde{\chi}^0_i (i = 1, 2, 3, 4)$ (neutralino) for neutral particles and $\tilde{\chi}^\pm_i (i = 1, 2)$ (chargino) for charged particles. In natural SUSY scenarios, the Higgsino mass is expected to be close to the weak scale [1]. As a result, the compositions of second lightest neutralino ($\tilde{\chi}^0_2$), the lightest chargino ($\tilde{\chi}^{\pm}_1$) and the lightest neutralino ($\tilde{\chi}^0_1$) are dominated by Higgsino. In this scenario, $\tilde{\chi}^0_2$ and $\tilde{\chi}^\pm_1$ are Next-to-Lightest SUSY Particle (NLSP) and $\tilde{\chi}^0_1$ is the Lightest SUSY Particle (LSP).

From an experimental point of view, there are some challenging aspects in the Higgsino search. We considered the simplified model reported in Refs. [2, 3] characterized by just a few parameters. For this search we consider scenarios where the mass gap between LSP and NLSP is assumed at the level $O(0.1) - O(10)$ GeV, which is the range predicted by natural SUSY scenarios [1]. Depending on the mass gap, different signal characteristics are expected. Here we focus on the searches for the following two scenarios: first we consider the case where the mass gap is of the order of a few GeV, in which leptons in the final state are expected to have very low momenta [4]. This scenario is parametrized by $m(\tilde{\chi}^0_2)$ and $\Delta m(\tilde{\chi}^0_2, \tilde{\chi}^0_1)$. Then we consider the case where the mass gap is of the order of a few hundred MeV, in which the chargino track is expected to “disappear” [5, 6]. The parameters used for this scenario are $m(\tilde{\chi}^{\pm}_1)$ and $\Delta m(\tilde{\chi}^{\pm}_1, \tilde{\chi}^0_1)$ or lifetime of $\tilde{\chi}^{\pm}_1$. The former case (soft lepton scenario) is overviewed in Section 2, the latter scenario (disappearing track scenario) is covered in Section 3. Figure 1 shows diagrams of those two scenarios. The analyses presented here are performed using 36.1 fb$^{-1}$ of proton-proton
Figure 1. Feynman diagrams representing two scenarios of Higgsino searches. (a) is for soft lepton scenario. (b) is for disappearing track scenario. Both diagrams assume an associated jet from initial state radiation.

collision data provided by the Large Hadron Collider (LHC) [7] at $\sqrt{s} = 13$ TeV and collected by the ATLAS detector [8] in 2015 and 2016.

2. Soft lepton

In the soft lepton scenario, the pair productions of $\tilde{\chi}^0 \tilde{\chi}^\pm$, shown in Figure 1(a), and $\tilde{\chi}^0 \tilde{\chi}^0$ are the main targets of the analysis. For those signals, the $\tilde{\chi}_2^0 \rightarrow Z^* \chi_1^0$, where $Z^*$ decays into $\ell \ell' \chi_1^0$ decay is a key for the search. The dilepton invariant mass $m_{\ell\ell}$ has its kinematic endpoint at the mass gap between $\chi_1^0$ and $\chi_2^0$, as shown in Figure 2. And it is used as a final discriminant.

Figure 2. $m_{\ell\ell}$ distribution of signal simulation [4]. Blue lines show the distribution of Higgsino simplified model, and red lines show it of wino-bino simplified model. Solid lines are from simulation, and dashed lines are from analytic calculation [9]. All model assume 20 GeV mass gap between $\chi_1^0$ and $\chi_2^0$ which corresponds to the endpoint of $m_{\ell\ell}$.

Figure 3. $E_{T}^{\text{miss}}/H_{T}^{\text{lep}}$ distribution of signal and total background after applying all signal region selections except for $E_{T}^{\text{miss}}/H_{T}^{\text{lep}}$ and for $m_{\ell\ell}$ [4]. Signals, especially for one assuming small mass gap indicated by blue dots, are distributed in higher $E_{T}^{\text{miss}}/H_{T}^{\text{lep}}$ region than backgrounds. The solid red line shows the definition of the signal region.

For those signals, the expected final states have a missing transverse momentum coming from two LSPs, and exactly two same flavor opposite charged leptons (electrons or muons). At
least one high momentum jet from initial state radiation (ISR) is additionally requested in the final states, resulting in a boosted $t$–$\bar{t}$ system so that the magnitude of missing transverse momentum ($E_T^{\text{miss}}$) is enhanced and can be exploited to trigger and select the event. In this analysis, the jet is required to have a transverse momentum ($p_T$) larger than 100 GeV. Major backgrounds for this search are $WW$, $ZZ$ (diboson background), $Z \to \tau\tau$, $tt$, single top (top background), and fake/non-prompt leptons. Diboson background, $Z \to \tau\tau$ background and top background are categorized as irreducible backgrounds, and they are evaluated using MC simulation. Fake/non-prompt leptons are categorized as reducible backgrounds, and they are evaluated with data-driven methods.

Because of the small mass gap, the two leptons in the final state are expected to have small momenta. Therefore, the event selection must accept relatively low $p_T$ leptons. Instead, in order to reduce backgrounds, the scalar sum of the lepton momenta ($H_T^{\text{lep}}$) is used for event selection. Especially for small values of the mass gap, $H_T^{\text{lep}}$ is expected to be smaller for signal events than for background events. The ratio $E_T^{\text{miss}}/H_T^{\text{lep}}$ is found to be useful to reduce diboson background events. As shown in Figure 3, signal events with small mass gap, such as 3 GeV, are distributed in a higher $E_T^{\text{miss}}/H_T^{\text{lep}}$ region than background events. This ratio is used for event selection with a threshold equal to max[5, $(15 - 2m_{\ell\ell}/(1 \text{ GeV}))$].

![Figure 4](image_url)  

**Figure 4.** Examples of kinematic distributions of observed data and expected backgrounds in control regions (CR) [4]. (a) is for $Z \to \tau\tau$ background. (b) is for top background. CRs are the region indicated by blue arrows. Both CRs are designed to enhance contribution of target background.

For the suppression of $Z \to \tau\tau$ background, an approximation of the invariant mass of a leptonically decaying $\tau$ lepton pair ($m_{\tau\tau}$) is used [10, 11, 12]. Events with $0 < m_{\tau\tau} < 160$ GeV are rejected. Top background is suppressed by $b$-jet veto. The normalization of $Z \to \tau\tau$ and top backgrounds is obtained by fitting to observed data in control regions (CRs) which are statistically independent from the signal region and designed to enrich the targeted background process. The CR for $Z \to \tau\tau$ background is defined by the requiring $60 < m_{\tau\tau} < 120$ GeV, where the purity of $Z \to \tau\tau$ is 83%, as shown in Figure 4(a). The CR for top background is required to have a $b$-tagged jet, and has a purity of 71%. The distribution of $E_T^{\text{miss}}/H_T^{\text{lep}}$ in the top CR is shown in Figure 4(b). Both CRs accept events with all possible flavor combinations to enhance statistics. Since it is difficult to find CR where the purity of diboson background is high enough, estimation of diboson background is not normalized using experimental data fitting, but checked in a proper validation region (VR).
Figure 5. Observed data and background estimation in the signal region [4]. Only the left side of the plot (SRee and SRµµ) is discussed in this proceedings. Uncertainties in the background estimates include both the statistical and systematic contributions, and \( \sigma_{\text{tot}} \) denotes the total uncertainty.

For fake/non-prompt leptons, estimation is done with data-driven method based on fake factors [13]. The estimation is validated using data in same-sign dilepton VR which has a large component of fake/non-prompt lepton contributions. Also the VR accepts events with all possible flavor combinations to increase the statistics. The estimated background is in good agreement with data in the same-sign dilepton VR.

Finally the \( m_{\ell\ell} \) distribution of estimated backgrounds is compared with experimental data in the signal region. As shown in Figure 5, no significant excess is observed in the data with respect to the SM prediction.

Figure 6 shows the 95% CL exclusion in the plane of \( m(\tilde{\chi}^0_2) \) and \( \Delta m(\tilde{\chi}^0_2, \tilde{\chi}^0_1) \). The new limit extends the LEP limit down to mass gap \( \Delta m(\tilde{\chi}^0_2, \tilde{\chi}^0_1) \approx 2.5 \) GeV, and reaches up to 145 GeV in \( m(\tilde{\chi}^0_2) \).

3. Disappearing track
In the disappearing track scenario, the production of \( \tilde{\chi}^0_1\tilde{\chi}^{\pm}_1 \), which is shown in Figure 1(b), is the main target of the analysis; due to compressed mass gap, \( \tilde{\chi}^{\pm}_1 \) is expected to have a long lifetime. Therefore, \( \tilde{\chi}^{\pm}_1 \) may leave some hits in the inner detector before decaying to pion and \( \tilde{\chi}^0_1 \), and the track of \( \tilde{\chi}^{\pm}_1 \) can be reconstructed. However, it is difficult to reconstruct the track of the pion from the \( \tilde{\chi}^{\pm}_1 \) decay due to its too low momentum. As a result, the reconstructed track of \( \tilde{\chi}^{\pm}_1 \) seems to be disappearing after its decay. Figure 7 shows an illustration of the disappearing track signature.

The reconstruction of such small number of hits, tracklet, is difficult if standard track reconstruction techniques are used. However, thanks to the new innermost tracking layer [15, 16], a tracklet traversing only in innermost part of detectors (pixel) can be reconstructed. After standard track processing, such tracklet is reconstructed using hits not associated to standard
Figure 6. Expected 95% CL exclusion sensitivity (blue dashed line) with $\pm 1\sigma_{\text{exp}}$ (yellow band) from experimental systematic uncertainties and observed limits (red solid line) with $\pm 1\sigma_{\text{theory}}$ (dotted red line) from signal cross-section uncertainties for simplified models of direct Higgsino production [4]. The gray region denotes the lower chargino mass limit from LEP [14].

Figure 7. Illustration of disappearing track [6].

tracks. This procedure improved the reconstruction efficiency especially for tracklet of signal particles decayed between pixel and SCT detectors, as shown in Figure 8.

Major backgrounds for this scenario are hadron scattering, photon emission, and fake tracklet. A standard track can be reconstructed as a tracklet if the hits produced after the pixel detector are not associated to the short track in pixel detector due to hadron scattering or photon emission. In addition, fake tracklets can arise as combinatorial background from random hits. Examples are shown in Figure 9.

The background is estimated using templates obtained from data. They are constructed independently for three background sources; hadrons plus electrons, muons, and fake tracklets. They are then fitted to data in the control regions. From a fit, yields of expected background events in the signal region is evaluated as $11.8 \pm 3.1$. The number of observed events in signal region is 9, which is compatible with the SM expectation. The distributions of tracklet $p_T$ is
Figure 8. Chargino reconstruction efficiency as a function of decay radius [6]. Green (red) dots show reconstruction efficiency with standard track reconstruction (tracklets reconstruction). The error bars show statistical uncertainties in the estimation. Blue line shows the distribution of decay radius for $\tilde{\chi}^\pm_1$ with a lifetime of 0.2 ns. The reconstruction efficiency is improved by tracklets especially between pixel and SCT.

Figure 9. Illustrations of expected backgrounds of tracklet [6]. (a) is hadron scattering. (b) is photon emission. (c) is fake tracklet.

Figure 10. Observed data and background estimation in the signal region [6]. As an example of expected signal spectrum, signal with $\tau_{\tilde{\chi}_1^\pm} = 0.2$ ns and $m_{\tilde{\chi}_1^\pm} = 400$ GeV is overlaid. The error band shows the uncertainty in the background prediction including both the statistical and systematic uncertainties.

shown in Figure 10.

Using profile-likelihood ratio methods, some combinations of signal mass and lifetime are excluded. Figure 6 shows the obtained limits and theoretical expectation (black dashed curve) assuming a pure Higgsino model. With pure Higgsino assumption, the limit reaches 152 GeV in $m(\tilde{\chi}_1^\pm)$. 
Figure 11. Expected (black dashed) and observed (red solid) 95% CL exclusion limit in the plane of (a) the chargino mass and its lifetime, and (b) the chargino mass and the mass gap between $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ [5]. The pink-coloured region is excluded. The yellow band shows the $1\sigma$ region of the expected limit. The black dot-dashed curve crossing over the exclusion line shows a theoretical prediction in the pure Higgsino scenario.

Figure 12. Exclusion limits at 95% CL for higgsino pair production $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^0\tilde{\chi}_1^0$, $\tilde{\chi}_2^+\tilde{\chi}_2^-$, and $\tilde{\chi}_2^0\tilde{\chi}_2^0$ with off-shell SM-boson-mediated decays to the lightest neutralino, $\chi_1^0$, as a function of the $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^0$ masses [17]. The production cross-section is for pure higgsinos.

4. Conclusions

In these proceedings, two scenarios of Higgsino search, soft lepton and disappearing track, have been presented, using 36.1 fb$^{-1}$ of proton-proton collision data provided by LHC at $\sqrt{s} = 13$ TeV and collected by the ATLAS detector in 2015 and 2016. No significant excess was observed in experimental data with respect to the SM expectation. The soft lepton search sets a new limit extending the LEP limit down to $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0) \simeq 2.5$ GeV and up to 145 GeV in $m(\tilde{\chi}_1^0)$. The search for disappearing track sets a new limit in compressed signal. With theoretical expectation assuming pure Higgsino model, the limit reaches 152 GeV in $m(\tilde{\chi}_1^0)$.

The two scenarios discussed here are complementary, the soft lepton scenario being sensitive to model parameters in the compressed region, and the disappearing track scenario being...
sensitive to parameters in the super-compressed region. The constraints derived for both interpretations are summarized in the same kinematic plane, shown in Figure 12.

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