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Search for direct pair production of higgsinos by reinterpretation of the disappearing track analysis with 36.1 fb^{-1} of $\sqrt{s}$ = 13 TeV data collected with the ATLAS experiment

The ATLAS Collaboration

This note presents a search for direct production of higgsinos in which the lightest chargino, $\tilde{\chi}_1^{\pm}$, is nearly mass-degenerate with the lightest and the next-to lightest stable neutralinos, $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$. A small mass difference $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_{1,2}^0) \sim 300$ MeV corresponds to $c\tau \sim 0.05$ ns and gives rise to a disappearing track signature. The search is performed using proton-proton collision data recorded by the ATLAS detector at the Large Hadron Collider in 2015 and 2016, corresponding to 36.1 fb^{-1} of integrated luminosity at $\sqrt{s} = 13$ TeV. The disappearing track analysis was previously established targeting the direct electroweak pure-wino pair production. This note focuses on the reinterpretation of the previous analysis for pure-higgsino production.

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1 Introduction

Supersymmetry (SUSY) models, including the Minimal Supersymmetric extension of the Standard Model (MSSM) [1–6], predict superpartners of the Standard Model (SM) particles that differ from their SM partners by a half unit of spin. In R-parity conserving SUSY models [7], the lightest supersymmetric particle (LSP) must be stable, and can be a good candidate of the dark matter. SUSY particles are pair produced in R-parity conserving models. R-parity conservation is an assumption through this note. Supersymmetric partners of the electroweak gauge bosons and the Higgs bosons, collectively referred to as electroweakinos, have weak eigenstates (bino, winos, higgsinos) that mix to form neutral mass eigenstates called neutralinos and charged mass eigenstates called charginos. When the lightest neutralino is the LSP, and it is an almost pure-wino or higgsino state, the mass-splitting between the LSP and the lightest chargino, $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$, is predicted to be of order 100 MeV, and the lightest chargino becomes long-lived. The lifetime of the chargino in the pure-wino (pure-higgsino) LSP scenarios is expected to be approximately 0.2 (0.05) ns, such that the chargino may reach the detector before decaying. In such scenarios, the chargino decays with approximately 95% branching ratio ($\mathcal{B}$) into the LSP and a soft pion, where the pion has a typical transverse momentum (p_{T}) of ~300 MeV. Since the LSPs escape detection and the pion from the chargino decay has too low momentum to be observed, such events can be identified experimentally from the distinctive 'disappearing' chargino track(s). The search [8] for a disappearing-track signature using $\sqrt{s}$ = 13 TeV pp-collision data collected in 2015 and 2016 was performed by the ATLAS collaboration setting a limit on the chargino mass of 460 GeV for the pure-wino LSP scenario. In this note, we present a reinterpretation of the search for the pure-higgsino LSP scenario.

2 Signal model

'Natural' models of SUSY [9–11] suggest a light higgsino LSP. In such scenarios, a typical $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ varies from a few hundred MeV to several tens of GeV depending mainly on the mass scales for the weak SUSY eigenstates. A mass-splitting of a few GeV may be probed by dedicated searches [12] requiring low-momentum leptons (soft-leptons), typically $p_{\mathrm{T}} \sim$ 4–5 GeV, that arise from highly off-shell W/Z bosons. However, probing a mass-splitting of a few hundred MeV is difficult for soft-lepton searches. Furthermore, the chargino becomes rather long-lived in this regime. The disappearing track search, which was originally designed for the long-lived wino LSP scenario with a few hundred MeV mass-splitting, is sensitive to the higgsino with a few hundred MeV mass-splitting and is complementary to the soft-lepton seaches.

2.1 Pure-higgsino phenomenology

In the limit of the pure higgsino $\tilde{\chi}_1^0$, namely the decoupling limit of the masses of gauginos, the mass-splitting is derived by the electroweak-loop contribution. The mass-splitting of $\Delta m(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ vanishes, but a non-zero mass-splitting of $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ remains due to radiative corrections [13]. For a higgsino mass parameter (μ) greater than 1 TeV, the mass-splitting is approximately 355 MeV, and it gets smaller as μ decreases. The mass-splitting is, for example, 257 MeV at μ =100 GeV. The lifetime of the chargino ($c\tau$) is almost uniquely determined by the mass-splitting [14]:

$$c\tau[\mathrm{mm}] \sim 7 \times \left[\left(\frac{\Delta m\left(\tilde{\chi}_1^\pm, \tilde{\chi}_{1,2}^0\right)}{340\,\mathrm{MeV}}\right)^3 \sqrt{1 - \frac{m_\pi^2}{\Delta m\left(\tilde{\chi}_1^\pm, \tilde{\chi}_{1,2}^0\right)^2}}\right]^{-1}, \tag{1}$$

where m_π denotes the charged pion mass. Only the chargino decay via a charged pion ($\tilde{\chi}_1^\pm \to \pi^\pm \tilde{\chi}_{1,2}^0$) is considered in Eq. 1. The contribution of leptonic decays ($\tilde{\chi}_1^\pm \to \ell^\pm \nu \tilde{\chi}_{1,2}^0$, where ℓ is a muon or an electron) to the total decay width is found to be small[1]. The lifetime of the chargino varies from 0.03 to 0.07 ns, corresponding to $c\tau$ in the range from 8 mm to 20 mm, in the pure-higgsino scenario for a Lorenz factor of order unity. This allows the chargino to leave a few hits in the pixel layers.

2.2 Signal sample

Pure-higgsino signal samples were generated with MG5_aMC@NLO 2.3.3 at leading order (LO), considering $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$, $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ production modes, and including up to two extra partons. They were then interfaced to Pythia 8.212 [15] for parton showering and hadronisation. The CKKW-L merging scheme [16] was applied to combine tree-level matrix elements with parton showers. The scale parameter for merging was set to a quarter of the mass of the higgsino LSP. The A14 [17] set of tuned parameters with simultaneously optimised multi-parton interaction and parton shower parameters was used together with the NNPDF2.3LO [18] parton distribution function (PDF) set.

The chargino was forced to decay not in Pythia but instead in the Geant4 [19] simulation, in order to precisely simulate the response of the chargino interaction through the inner detector. The decay branching ratio of the chargino was fixed and set to $\mathcal{B}(\tilde{\chi}_1^\pm \to \pi^\pm \tilde{\chi}_{1,2}^0) = 95.5\%$, $\mathcal{B}(\tilde{\chi}_1^\pm \to e^\pm \nu \tilde{\chi}_{1,2}^0) = 3\%$, and $\mathcal{B}(\tilde{\chi}_1^\pm \to \mu^\pm \nu \tilde{\chi}_{1,2}^0) = 1.5\%$ [13], as the search does not depend much on the branching ratios over the range of mass-splittings considered in this model. The mass-splitting between the chargino and the LSP was set for the pure higgsino, which varies from 257 to 355 MeV in $\mu > 100$ GeV. The mean lifetime was set to 0.3 ns for any chargino mass, and events were then reweighted by decay time to any lifetime.

Signal cross-sections were calculated to next-to-leading order (NLO) in the strong couplings, adding the resummation of soft gluon emission at next-to-leading-logarithm accuracy (NLO+NLL) [20–22] using Resummino 2.0.1 [23, 24]. The nominal cross-section and its uncertainty were taken from an envelope of cross-section predictions using different PDF sets and factorisation and renormalisation scales, as described in Ref. [25]. The signal uncertainty on the acceptance was also evaluated by varying factorization and renormalization scales, merging scales, and parton shower tunings.

3 ATLAS detector and data collection

The ATLAS detector [26] is a multipurpose particle detector with nearly 4π coverage in solid angle around the collision point.[2] It consists of an inner tracking detector (ID), surrounded by a superconducting solenoid

[1] The leptonic decay contribution to the total decay width varies from 3% to 7% depending on the $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ in the pure-higgsino regime.

[2] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points

providing a 2 T axial magnetic field, a system of calorimeters, and a muon spectrometer (MS) incorporating three large superconducting toroid magnets. The ID consists of a pixel detector and a strip semiconductor tracker (SCT) covering the pseudorapidity region of $|\eta| < 2.5$, surrounded by a transition radiation tracker (TRT). During the LHC shutdown between Run 1 (2010–2012) and Run 2 (2015–present), a new innermost layer of silicon pixels was added [27], which improved the track impact-parameter resolution, vertex-position resolution and b-tagging performance [28]. The pixel detector spans the radius range from 30 to 120 mm, the SCT from 300 to 520 mm, and the TRT from 560 to 1080 mm.

This search is based on a dataset collected in 2015 and 2016 at a collision energy of $\sqrt{s} = 13$ TeV. The data contain an average number of simultaneous pp interactions per bunch crossing, or "pile-up", of approximately 23.7 across the two years. After the application of beam, detector and data-quality requirements, the total integrated luminosity is 36.1 fb^{-1} with an associated uncertainty of 3.2%. The uncertainty is derived following a methodology similar to that detailed in Ref. [29] from a preliminary calibration of the luminosity scale using a pair of x–y beam separation scans performed in August 2015 and June 2016.

The events were recorded with a trigger logic that accepts events with the magnitude of missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$) above a given threshold, which varies from 70 to 110 GeV depending on a period of time in 2015 and 2016.

4 Summary of analysis

The analysis used in this note for the pure-higgsino reinterpretation is identical to the one detailed in Ref. [8], besides the fact that the pure-higgsino signal model is considered in this note. The experimental signature of this search is characterised by large $E_{\mathrm{T}}^{\mathrm{miss}}$, a high-$p_{\mathrm{T}}$ initial-state-radiation (ISR) jet, and a short track with no associated SCT hits. Short tracks, which are referred to as tracklets hereafter, are reconstructed after the standard track reconstruction with ID hits not associated to standard tracks and a looser requirement of the number of associated hits. Tracklets are seeded by pixel-detector hits and extended to the SCT and TRT detectors. In particular, tracklets which have only pixel-detector hits are called pixel tracklets.

Signal events are selected using a set of kinematic requirements. At least one pixel tracklet which satisfies a set of quality requirements as detailed in Ref. [8] is required. Events that have an isolated lepton (electron or muon) with $p_{\mathrm{T}} > 10$ GeV are rejected. Events are also required to have at least one jet with $p_{\mathrm{T}} > 140$ GeV and $E_{\mathrm{T}}^{\mathrm{miss}} > 140$ GeV. In order to further suppress the multijet background, the difference in azimuthal angle ($\Delta\phi$) between the direction of missing momentum and each of the up to four highest-p_{T} jets with $p_{\mathrm{T}} > 50$ GeV is required to be larger than 1.0.

The dominant irreducible background after the kinematic selection arises from a lepton from the W+jets or $t\bar{t}$ production process that is scattered with a large angle and is reconstructed as a pixel tracklet. Also hadrons undergoing hadronic interactions and leptons with significant bremsstrahlung radiation can be reconstructed as pixel tracklets. Another category of the reducible background is from fake tracklets which are reconstructed from random combinations of hits.

upwards. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. The transverse momentum, p_{T}, is defined with respect to the beam axis (x–y plane).

Table 1: Number of observed events and predicted background events, together with the yield of expected signal for a benchmark point $(m_{\tilde{\chi}_1^\pm}, \tau_{\tilde{\chi}_1^\pm})$ = (160 GeV, 0.05 ns) in the signal region with a requirement of pixel-tracklet $p_T > 100$ GeV. The observed and expected background yields, but not the signal yield, are taken from Ref. [8]. For a comparison, the number of expected signal events for the pure wino LSP model with $(m_{\tilde{\chi}_1^\pm}, \tau_{\tilde{\chi}_1^\pm})$ = (400 GeV, 0.2 ns) is also shown.

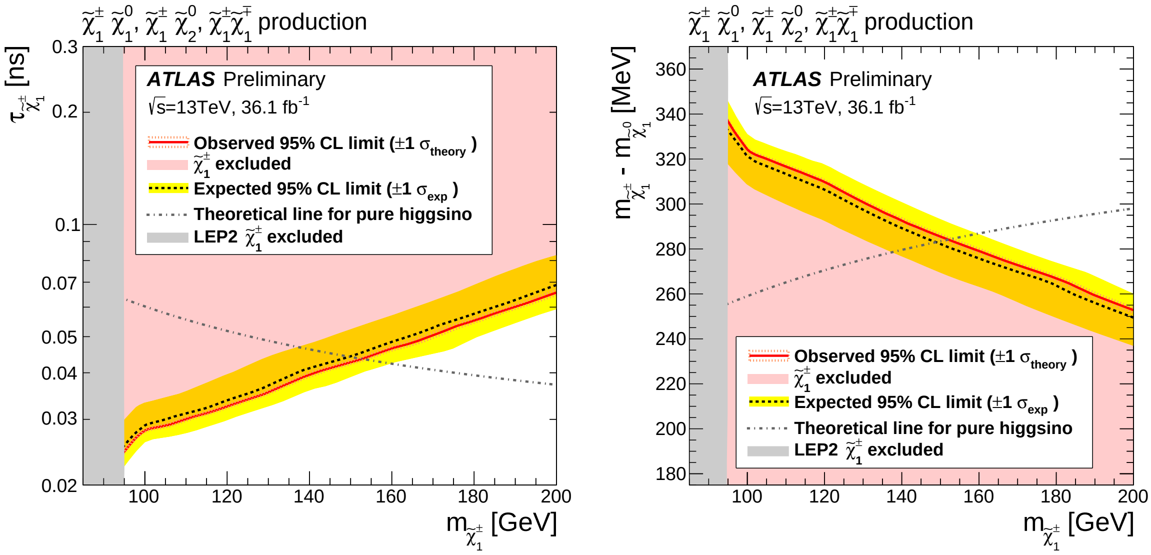
Number of observed events		
	9	
Number of expected events		
Hadron+electron background	6.1	± 0.6
Muon background	0.15	± 0.09
Fake background	5.5	± 3.3
Total background	11.8	± 3.1
Number of expected signal events for the higgsino LSP model with $(m_{\tilde{\chi}_1^\pm}, \tau_{\tilde{\chi}_1^\pm})$ = (160 GeV, 0.05 ns)		
	10.3	± 2.1
Number of expected signal events for the wino LSP model with $(m_{\tilde{\chi}_1^\pm}, \tau_{\tilde{\chi}_1^\pm})$ = (400 GeV, 0.2 ns)		
	13.5	± 2.1

A likelihood fit is performed in the pixel-tracklet p_T distribution to determine yields of backgrounds using the following data-driven templates: the sum of hadrons and electrons, muons, and fake tracklets, following the procedure as described in Ref. [8]. The hadron and electron components are combined as the shapes of their p_T spectra are similar. For the exclusion limit, the signal templates for the pure-higgsino LSP model are also constructed for each chargino mass and lifetime, by smearing the generator-level p_T distribution of charginos with the measured q/p_T resolution, where q is the electric charge.

5 Results

Table 1 shows the number of observed events and the predicted number of SM background events in the signal region with a requirement of the pixel-tracklet $p_T > 100$ GeV to enhance signal events from the fit. The number of observed events and the expected background event yields are taken from Ref. [8]. No data excess is found in the signal region.

As no excess is observed, exclusion limits are set based on profile-likelihood fits for the higgsino pair production models by following the CL_s prescription [30]. Figure 1 shows the model-dependent exclusion limits in the $(m_{\tilde{\chi}_1^\pm}, \tau_{\tilde{\chi}_1^\pm})$ and $(m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_1^\pm})$ planes, where $\tau_{\tilde{\chi}_1^\pm}$ is the lifetime of the chargino. When the lifetime of the chargino is translated to the mass-splitting $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ and vice versa, the full decay width of the chargino is properly considered including the leptonic decay modes. Chargino masses up to 152 GeV are excluded in the pure higgsino LSP model at 95% confidence level (CL).



(a) (b)

Figure 1: 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-splitting between the chargino and the LSP. The pink-coloured region is excluded. The yellow band shows the 1σ region of the expected limit. The grey region is a limit obtained by the LEP [31]. The black dot-dashed curve crossing over the exclusion line shows a theoretical prediction in the pure-higgsino scenario.

6 Conclusion

The reinterpretation of the disappearing track search previously established for the long-lived wino LSP was performed targeting the pure-higgsino signature. The search is based on *pp* collision data collected by the ATLAS experiment at the LHC in 2015 and 2016 at $\sqrt{s}$ = 13 TeV, corresponding to an integrated luminosity of 36.1 fb^{-1}. No significant excess is observed over the estimated SM backgrounds. Exclusion limits at 95% CL are derived for direct production of higgsinos. Chargino masses up to 152 GeV are excluded in the pure-higgsino LSP model.

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