Study of Chargino-Neutralino pair production with decays via Standard Model W and Z bosons to 3 leptons targeting the off-shell boson region: Overview of lepton pair mass and missing transverse energy distributions

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Abstract

In this overview a study in progress of chargino-1-neutralino-2 pair production with decays via W and off-shell Z boson, to three leptons and missing transverse energy is presented. Two configurations for this decay are considered. In both cases chargino-1 and neutralino-2 are considered to be next to lightest supersymmetrical particle, or NLSP, in weak-scale R-parity conserving supersymmetry model with both NLSPs decaying to neutralino-1 (the lightest supersymmetrical particle, or LSP) and a W or Z bosons respectively. For one configuration both NLSP are wino-like and decay to a bino-like LSP; for the other both NLSP and LSP are higgsino-like. Two distributions of variables, missing transverse energy and mass of two leptons originating from the off-shell Z boson decay, are analysed and compared between the decay types. Furthermore, effects of classifying events into signal regions of interest based on optimised definitions for Bino-Wino configuration is presented for both decay types and compared. Preliminary conclusions of this study are presented at the end of this overview.

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1 Introduction

While the Standard model (SM) is a very effective theory, it contains multiple unresolved problems. One of such problems is the *hierarchy problem*[1], sometimes referred to as the *fine tuning problem*, requiring fantastically accurate corrections to the parameter μ_0 appearing in the Lagrangian to be made if no extensions to the Standard model are considered [1]. Introduction of a theoretical extension to the standard model in the form of a weak-scale Supersymmetry (SUSY) model in which R-parity is conserved solves this[2] problem [2].

In such model, supersymmetric particles are produced in pairs and decay into lighter states and due to R-parity invariance the lightest of such states produced at the end of the decay is stable. This stable particle is referred to as the *Lightest Supersymmetric Particle*, or *LSP*. In addition, due to cosmological constrains, LSP is expected to be electrically and colour neutral, and consequentially weakly interacting with matter, hence only detectable as missing transverse energy [2].

In this study, two types of a singular decay chain are considered and compared. The decay in question is a chargino $\widetilde{X}_1^{\pm}$ and neutralino $\widetilde{X}_2^0$ decay via leptonically decaying W and off-shell Z bosons into 2 $\widetilde{X}_1^0$ (LSP neutralino), 3 leptons with missing transverse energy. Bino-Wino and Higgsino-Higgsino configurations of this decay chain are investigated. Fig. 1 illustrates this decay chain. The following relationships $m_{\widetilde{X}_1^{\pm}} > m_{\widetilde{X}_1^0}$ and $m_{\widetilde{X}_2^0} > m_{\widetilde{X}_1^0}$ have also been assumed.

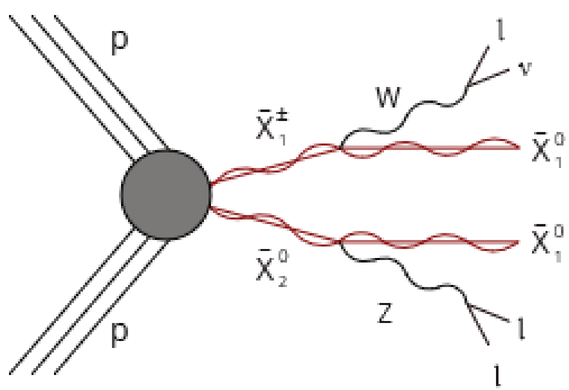


Figure 1: Illustrative diagram of $\widetilde{X}_1^{\pm}\widetilde{X}_2^0$ decay via leptonically decaying W and Z bosons

[1]There is enormous disagreement between "observed" value of μ (related to Higgs boson mass by $m_H^2 = \mu^2$) and its natural value once SM is embedded into more fundamental theory at higher energies [1]

[2]among many other

1.1 Chargino, neutralino and differences between Bino-Wino and Higgsino-Higgsino Configurations

In the discussed SUSY model, chargino ($\widetilde{X}_1^{\pm}$) and neutralinos ($\widetilde{X}_1^0$, $\widetilde{X}_2^0$), together commonly referred to as electroweakinos, are mass eigenstates formed as a result of a linear superposition of gauginos and higgsinos, SUSY partners to electroweak gauge and Higgs bosons. In some instances,[3] chargino and neutralinos can be approximated as a particular gaugino or higgsino state.

In this study two different decay types are considered. Bino-Wino (BW) configuration assumes that the LSP neutralino $\widetilde{X}_1^0$ is being modelled as being bino[4]-like, while the chargino and $\widetilde{X}_2^0$ form a wino[5]-like doublet and are a mass degenerate. Higgsino-Higgsino (HH) configuration implies that all three elecktroweakinos are modelled as higgsino-like and the relationship between electroweakinos is $m_{\widetilde{X}_1^0} + m_{\widetilde{X}_2^0} = 2m_{\widetilde{X}_1^{\pm}}$

BW case is considered more simplistic compared to the Higgsino-Higgsino case and is expected to be more common, however, as the current searches with Bino-Wino configuration have not yet yielded results, inclusion of the more complicated Higgsino-Higgsino case to the on going search for signs of weak-scale R-parity conserving supersymmetry could be considered.

1.2 Outline of the overview

This overview the on-going study is organised as follows: Section 2 describes the generation of data sets that have been used in this analysis as well as the production of the signal which would be expected to be detected with the detector. Section 3 is used to explain the definition and categorisation of the signal regions of interest, which are used in the analysis step for more detailed examination of the differences between the two configurations. Finally, Section 4 is dedicated to comparison of the Bino-Wino and Higgsino-Higgsino configurations through signal region of interest, mass of lepton pair originating from off-shell Z boson, and missing transverse energy distributions.

2 Data sets and production of simulated Signal

For this analysis 28 different data sets have been created using Monte Carlo generators (MadGraph5_aMC@NLO version 2.6.1 [4] for hard process, Pythia8-02-12-01 [5] for Showering, and MadSpin for decay behaviour). Each data set represents a unique *mass point*, a combination of the three elektroweakino masses with a specified process for $\widetilde{X}_1^{\pm}$ and $\widetilde{X}_2^0$ decay to two $\widetilde{X}_1^0$, three leptons, and E_T^{miss}. Decays with mass gap between $\widetilde{X}_1^{\pm}$ and $\widetilde{X}_1^0$ ranging from 10 GeV to 50 GeV with differing masses for $\widetilde{X}_1^{\pm}$, $\widetilde{X}_2^0$, and $\widetilde{X}_1^0$ are considered.

[3] see [3]

[4] Supersymmetric partner of the weak hypercharge gauge boson

[5] Supersymmetric partner of the weak SU(2) gauge boson

Each of these *mass point* has a specified branching ratio as well as a cross-section and contains exactly 10000 events. Furthermore, as the decay can happen with either $\widetilde{X}_1^+$ and $\widetilde{X}_1^-$, both of these instance have to be generated as separate data sets and later combined since in a real collision the observed hypothetical decay would be a superposition of $\widetilde{X}_1^+ + \widetilde{X}_2^0$ and $\widetilde{X}_1^- + \widetilde{X}_2^0$ decays. Hence, two data sets with the exactly the same masses for the three electroweakinos but differing decay processes are combined for this analysis.

2.1 Combination of data set pairs

In order to ensure precise combination of data, the events are normalised against the integrated luminosity of the full run 2 data set recorded with ATLAS detector L (in this study assumed to be 140 fb^{-1}) before they are combined. The scaling factor, *SF*, for each mass point is determined by

$$SF = \frac{L * cross\ section * branching\ ratio * filter\ efficiency}{total\ number\ of\ events} \quad (1)$$

where $filter\ efficiency$ is a variable denoting how many events generated by MadGraph are used by Pythia in the showering processes in the generation of the data set. Thus, each data set is scaled accordingly and added together with its pair partner to produce a proper simulated signal. Fig. 2 shows a graphical proof of this concept.

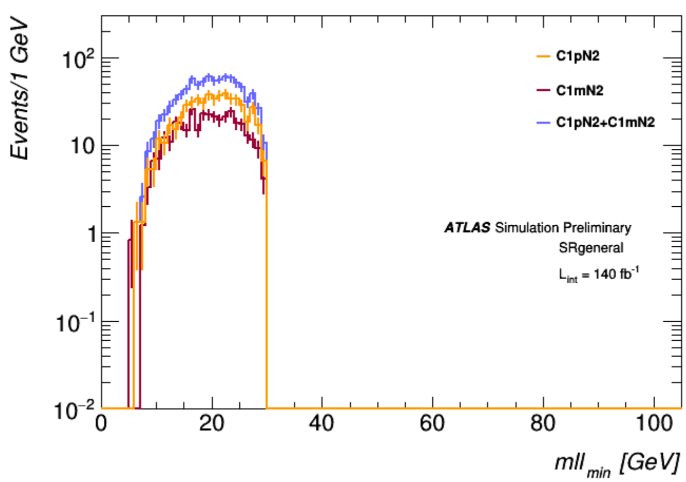


Figure 2: Proof of scaling and addition process validity using lepton pair mass distributions in data sets with 10000 events and $(m_{\widetilde{X}_1^\pm}, m_{\widetilde{X}_1^0})$ = (140,110) GeV. The events depicted have already been scaled according to Eq.1. The $\widetilde{X}_1^+ + \widetilde{X}_2^0$ process is indicated by C1pN2, where as C1mN2 is denoted by $\widetilde{X}_1^- + \widetilde{X}_2^0$ decay process.

3 Selection of Regions

For this study, four signal region of interest (SRi) have been selected for investigation. Each of these regions is defined and restricted through 9 shared selection cuts, which form a general signal region, and up to additional 7 unique selection cuts, further defining the four unique regions. The unique regions of interest definitions used in this study are based on those optimised for Bino-Wino configuration. The justification of such choice is based on the intent to see how much the not yet investigated configuration of Higgsino-Higgsino differs from the Bino-Wino case (searches currently being carried out).

3.1 Lepton Pair Mass: Assignment

Since the off-shell boson region is targeted in this study, the mass of the the lepton pair originating from the off-shell Z boson, mll, is considered to be one of the more important parameters in defining the signal regions in this analysis. In previous research papers tackling similar topics the approach of identifying such pairs was to select the two leptons who's combined mass is closest to the mass of the on-shell Z boson. However, as this study is aimed at chargino-neutralino pair production with W and off-shell Z boson leptonic decays, a different approach is used. The two leptons with the smallest combined mass from the three possible combinations are considered to come from off-shell Z boson decay. This smallest combined lepton pair mass is denoted by mll_{min} and shows a much more specific behaviour for this type of signals (see Fig. 3), which will later allow for better signal to background discrimination

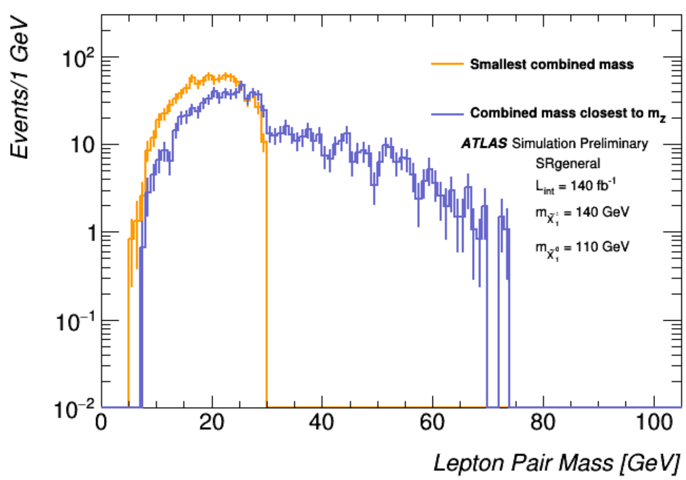


Figure 3: Comparison between pair of leptons with smallest combined mass versus pair of leptons with combined mass closest to the mass of Z-boson. Bino-Wino like event decay with $m_{\widetilde{X}_1^{\pm}} = 140$ GeV and $m_{\widetilde{X}_1^0} = 110$ GeV

3.2 Signal Regions

For an event to be considered to belong to any of the signal region of interest, the event must at least contain three leptons, of which two for a Opposite Sign Same Flavour (OSSF) lepton pair[6] which mass, mll_{min}, is smaller than the mass of Z boson. If these and another 6 constrain conditions, also known as selective cuts, are satisfied, the event is considered to belong to the General Signal Region (*SRgeneral*) and then further categorised into one of four unique signal regions of interest (uSRi) by its number of jets into either $0-jet$ or $n-jet$ SRi group, and missing transverse energy, E_T^{miss} into either *low* or *high* SRi group. Each unique signal region of interest also has additional selection cuts which also have to be satisfied, otherwise the event is ignored.

4 Analysis

4.1 Distribution of Regions

The effects of the selection cuts used to define the general signal region and the unique signal regions of interest are analysed by tracking what amount of all events each cut allows to pass through. To begin with, this overview analyses the distribution of events into regions of interest between Bino-Wino and Higgsino-Higgsino configurations. It is important to note that two addition regions indicating events containing 3 leptons and events containing 3 leptons with mll_{min} smaller than the on-shell Z boson mass have been included. These regions are denoted $3L$ and $3L\_minMll$ respectively.

In Fig. 4(c),(d) it can clearly be seen that the Higgsino-Higgsino events are primarily dominated by the *n-jet* group with negligent or small contributions from the *0-jet* group, where as the Bino-Wino events (Fig. 4(a),(b)) have a more balanced distribution, mainly dominated by events belonging to E_T^{miss} *low* SRi group and SRhigh-nj signal region of interest[7].

4.2 (Smallest combined mass) Lepton pair mass, mll_{min}

As discussed above, mll_{min} is one of the more important parameters when defining and constraining regions. When comparing mll_{min} behaviour in BW and HH cases a clear difference can be seen.

In Bino-Wino case (Fig. 5(a),(b)), the lepton pair mass distribution has a clear kinematic edge at the mass gap between the chargino and the LSP neutralino. This feature could hence be used to identify the mass gap between these electroweakinos with high accuracy. Furthermore, the distribution itself is skewed towards the kinematic edge. This effect becomes more visible as the mass gap is reduced.

In Higgsino-Higgsino configuration (Fig. 5(c),(d)), The distribution itself is far more symmetrical compared to the Bino-Wino case, is centred around the

[6] direct consequence of (off-shell) Z boson decay

[7] uSRi which belongs to the *n-jet* and E_T^{miss} *high* SRi groups

mass gap between the chargino and LSP neutralino value, and exhibits kinematic edge at the mass gap between the $\widetilde{X}_2^0$ and $\widetilde{X}_1^0$. This is an useful insight, as such kinematic edge behaviour could be used to distinguish the signal from the background in searches with Higgsino-Higgsino configuration. [8]

4.3 Missing Transverse Energy

Missing transverse energy, E_T^{miss}, is one the two variables which are used to define groups of signal regions of interests[9] and further separate these groups into unique signal regions. Understanding the behaviour differences of the distribution between Bino-Wino and Higgsino-Higgsino like events is vital in order to define proper selection cuts for the unique signal regions of interest to ensure that the analysis of discussed elektroweakino pair production is carried out efficiently.

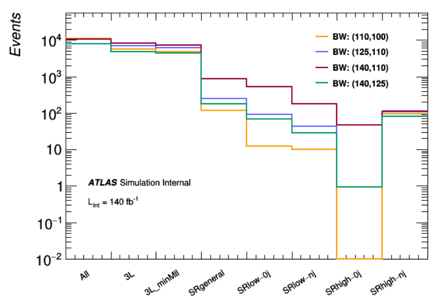
If E_T^{miss} would be investigated after the events have been classified (Fig. 6(a)-(e)), it is possible to distinguish three shape regions in both distributions: a "convex" region, centred around the mass gap between chargino and LPS neutralino, a "descend" region where the number of events is decreasing with increasing E_T^{miss} until E_T^{miss} = 200 GeV, and a "high E_T^{miss}" region pass the E_T^{miss} = 200 GeV. However, if the missing transverse energy distribution is analysed before any cuts are made (Fig. 7(a)-(e)), only one of the three features remains: the "convex" region, or rather a broad peak in the lower end of the distributions.

In Bino-Wino configuration, it can be clearly seen that this peak is located around the mass gap between the chargino and LPS neutralino with a slight offset towards the lower end of the spectrum. Furthermore, the width of the peak is increased with heavier chargino cases. In Higgsino-Higgsino configuration, a different behaviour is seen. The peak is highly suppressed and is not located an neither the mass gap between $\widetilde{X}_1^{\pm}$ and $\widetilde{X}_1^0$ or between $\widetilde{X}_2^0$ and $\widetilde{X}_1^0$, being centred round 60-80 GeV. Furthermore, mass of the chargino seems to have little to no effect on the general shape of the distribution.

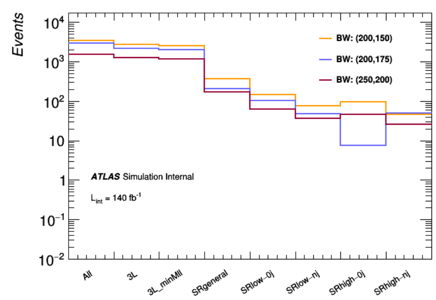
From the comparison of E_T^{miss} before and after the selections are made it is highly plausible the shape regions in the post selection distributions (Fig.6(a)-(e)) are artificially created due to the selections themselves. However, the peak towards the lower end of the spectrum is a true feature as it can also be observed in the distribution before the selections (Fig.7(a)-(e)). Furthermore, as the chargino mass is increased, this peak becomes more recognisable in the post selection distributions, whereas the fake effects become more suppressed.

[8] For example, in scenarios where a background signals can have mll_{min} greater than the mass gap between neutralinos.

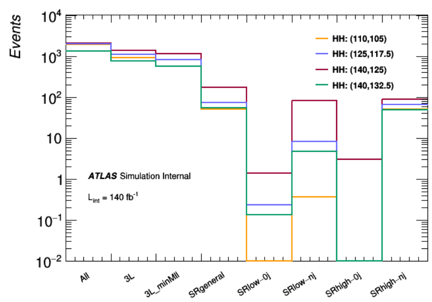
[9] the second parameter is number of jets, n_{jets}



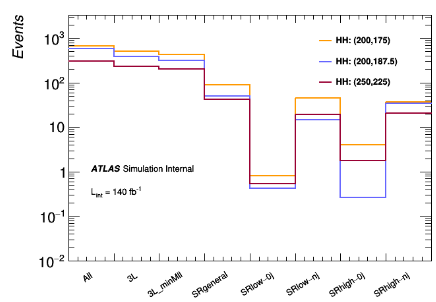
(a) BW $m_{\widetilde{X}_1^{\pm}} = 110, 125, 140\ GeV$



(b) BW $m_{\widetilde{X}_1^{\pm}} = 200, 250\ GeV$

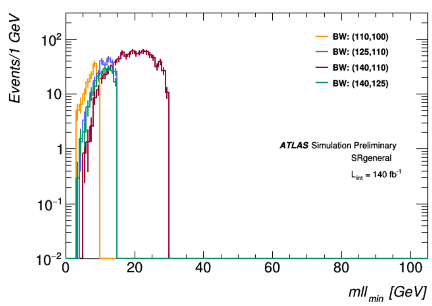


(c) HH $m_{\widetilde{X}_1^{\pm}} = 110, 125, 140\ GeV$

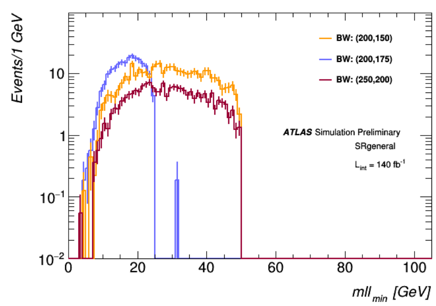


(d) HH $m_{\widetilde{X}_1^{\pm}} = 200, 250\ GeV$

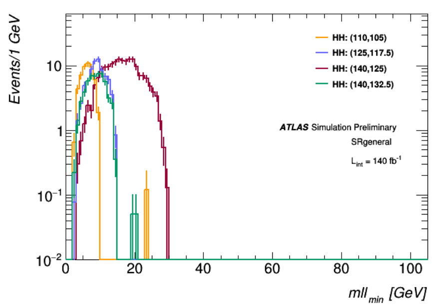
Figure 4: Distribution of Regions with Bino-Wino (a,b) and Higgsino-Higgsino (c,d) configurations.



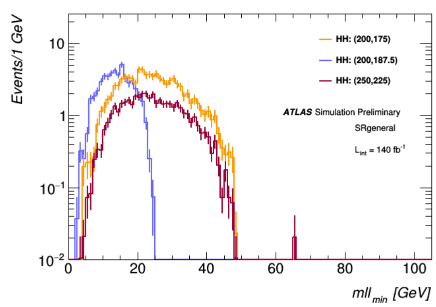
(a) BW $m_{\widetilde{X}_1^{\pm}} = 110, 125, 140\ GeV$



(b) BW $m_{\widetilde{X}_1^{\pm}} = 200, 250\ GeV$

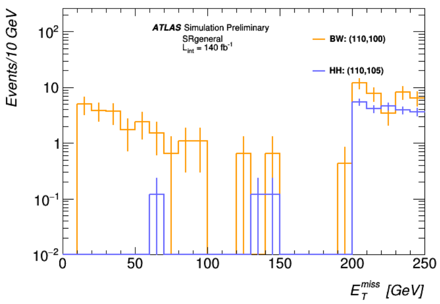


(c) HH $m_{\widetilde{X}_1^{\pm}} = 110, 125, 140\ GeV$

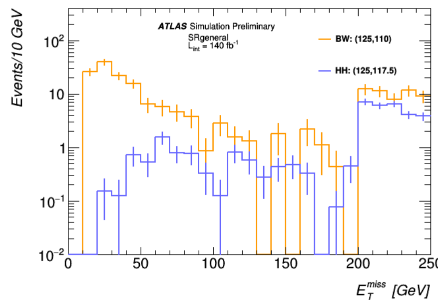


(d) HH $m_{\widetilde{X}_1^{\pm}} = 200, 250\ GeV$

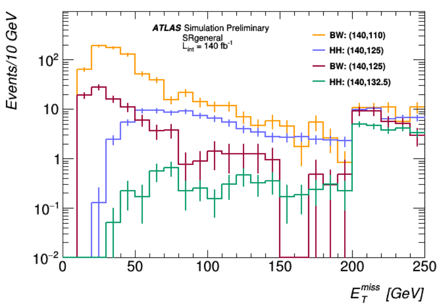
Figure 5: Distribution of of a lepton pair with the smallest combined mass with Bino-Wino (a,b) and Higgsino-Higgsino (c,d) configurations.



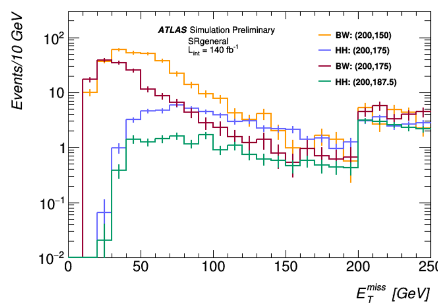
(a) $m_{\widetilde{X}_1^{\pm}} = 110\ GeV$



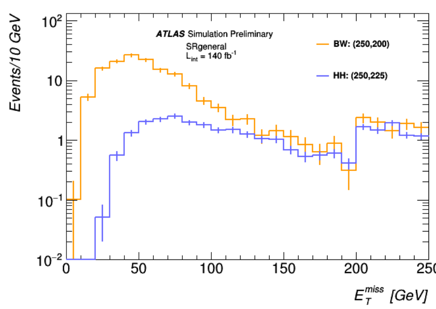
(b) $m_{\widetilde{X}_1^{\pm}} = 125\ GeV$



(c) $m_{\widetilde{X}_1^{\pm}} = 140\ GeV$

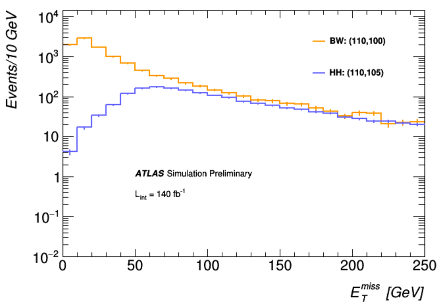


(d) $m_{\widetilde{X}_1^{\pm}} = 200\ GeV$

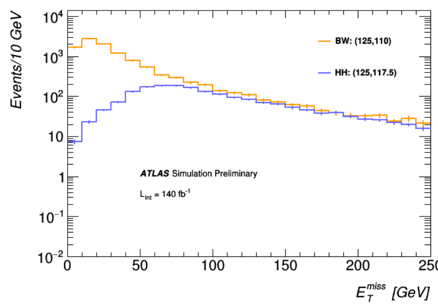


(e) $m_{\widetilde{X}_1^{\pm}} = 250\ GeV$

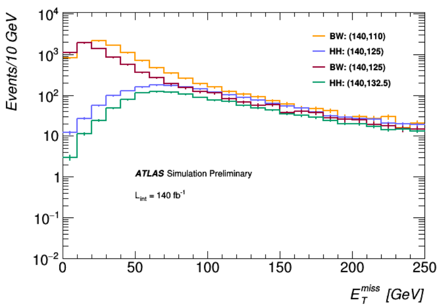
Figure 6: Missing Transverse Energy, E_T^{miss}, with Bino-Wino and Higgsino-Higgsino configurations. After selection cuts are made



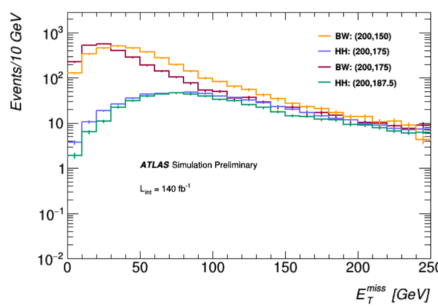
(a) $m_{\widetilde{X}_1^{\pm}} = 110\ GeV$



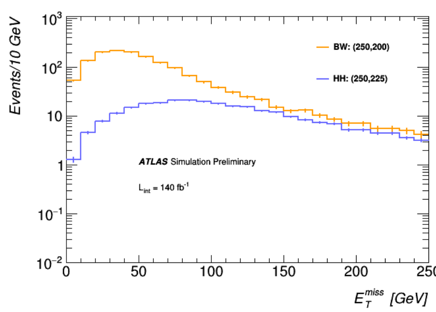
(b) $m_{\widetilde{X}_1^{\pm}} = 125\ GeV$



(c) $m_{\widetilde{X}_1^{\pm}} = 140\ GeV$



(d) $m_{\widetilde{X}_1^{\pm}} = 200\ GeV$



(e) $m_{\widetilde{X}_1^{\pm}} = 250\ GeV$

Figure 7: Missing Transverse Energy, E_T^{miss}, with Bino-Wino and Higgsino-Higgsino configurations. Before selection cuts are made

5 Conclusion

In this overview, comparison of two different decay types of chargino $\widetilde{X}_1^{\pm}$ and neutralino $\widetilde{X}_2^0$ decaying to into 2 LSP neutralino $\widetilde{X}_1^0$, 3 leptons and missing transverse energy via leptonically decaying W and off-shell Z bosons is presented. The distribution of signal region of interests, missing transverse energy, and lepton pair's mass have been chosen as the primary focus of the analysis carried out in this overview of the ongoing study. These variables have been chosen due to their importance to the theoretical background of this study (E_T^{miss}), importance as a differentiating factor for the discussed decay (mll_{min} defines lepton pair from off-shell Z boson), and ability to provide a general overview of the decay types (*Distribution of regions*).

As the definitions of signal region of interest used in this study are optimised for Bino-Wino configuration, it is not surprising that their application to Higgsino-Higgsino case is not optimal. However, comparison of the not yet explored Higgsino-Higgsino case in this fashion with currently searched Bino-Wino case, yielded important insight into what should be taken into account when the search is extended to include Higgsino-Higgsino configuration being discussed.

While the decay chain is the same, the Bino-Wino and Higgsino-Higgsino configurations produce fundamentally different results with differing behaviours for E_T^{miss} and mll_{min} distributions. If Higgsino-Higgsino configuration is to be used to expand the range of current searches in this field, the dominance of $n - jet$ regions should be investigated as well as optimised selection cuts of signal regions of interests for Higgsino-Higgsino case should be created and implemented.

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