Optimization of the event selection within the search for direct chargino pair production in 2-lepton OS final state and missing transverse momentum with the ATLAS detector

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Abstract

In 2011, a standard analysis was designed using 4.7 fb^{-1} of proton-proton-collision data at $\sqrt{s} = 7$ TeV recorded with the ATLAS experiment at the Large Hadron Collider (LHC) searching for chargino pair production decaying into final states with two opposite-sign leptons. As in 2012 LHC is running at a higher energy of $\sqrt{s}$ =8 TeV, an optimization of the event selection is presented using 1.043 fb^{-1} LHC data at $\sqrt{s} = 8$ TeV. In this report, three sets of improved event selections are developed and it is shown that each set of event selection serves to exclude more of the 38 SUSY models studied in this project than the standard analysis at the same background uncertainty.

Contents

1 Introduction

The Standard Model (SM) of particle physics is the most completely developed mathematical theory that describes elementary particles and interactions constituting the universe. Meanwhile, weak scale supersymmetry (SUSY), which is an extension to the SM, is at present the most highly developed framework for guiding and informing explorations of physics beyond the SM. It postulates for each known boson or fermion the existence of a particle whose spin differs by one-half unit from the SM partner. The introduction of these new particles provides solutions to the hierarchy problem and, if R-parity is conserved, a dark matter candidate in the form of the lightest supersymmetric particle(LSP). In the SUSY models studied in this report, R-parity conservation is assumed, hence SUSY particles are always produced in pairs. In a large fraction of the SUSY parameter space the LSP is the weakly interacting lightest neutralino, $\tilde{\chi}_1^0$.

Gluinos ($\tilde{g}$) and squarks ($\tilde{q}$) are the SUSY partners of gluons and quarks. Charginos ($\tilde{\chi}_i^\pm$, i = 1, 2) and neutralinos($\tilde{\chi}_j^0$, j = 1, 2, 3, 4) are the mass eigenstates formed from the linear superposition of the SUSY partners of the Higgses and electroweak gauge bosons: higgsinos, winos and the bino (collectively, gauginos). In a large fraction of the SUSY parameter space the LSP is the weakly interacting lightest neutralino, $\tilde{\chi}_1^0$, which is also true in the SUSY models studied in this project. The SUSY partners of the charged leptons are the selectron, smuon and stau, collectively referred to as charged sleptons ($\tilde{l}^\pm$). If the masses of the gluinos and squarks are greater than a few TeV and the weak gauginos and sleptons have masses of a few hundreds of GeV, the direct production of weak gauginos and sleptons may dominate the production of SUSY particles at the Large Hadron Collider (LHC). Such a scenario is possible in the general framework of the phenomenological minimal supersymmetric SM (pMSSM). Naturalness suggests that third generation sparticles, charginos and neutralinos should have masses of a few hundreds of GeV. Light sleptons are expected in gauge mediated and anomaly mediated SUSY breaking scenarios. Light sleptons could also play a role in helping SUSY to provide a relic dark matter density consistent with observations[1].

This report presents the optimization of event selection for direct chargino pair production with 2-lepton opposite sign (OS) final state(electrons, e, or muons, μ).

1.1 Direct Chargino Pair Production

SUSY samples used in this project are produced in a simplified model in pMSSM framework at given neutralino(LSP) mass and chargino mass. 38 SUSY scenarios are studied, which are all Monte Carlo (MC) simulated samples of the direct chargino pair production, where each chargino decays through $\tilde{\chi}_1^\pm \to l^\pm \nu \tilde{\chi}_1^0$, yielding a final state with two oppositely charged leptons, as shown in Fig. 1. The undetected $\tilde{\chi}_1^0$ gives rise to large missing transverse momentum in the event.

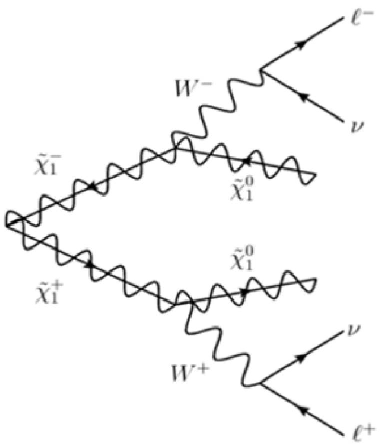


Figure 1: Feynman diagram for direct chargino pair production and subsequent decays.

In the 38 SUSY scenarios the masses of the squarks, gluinos and third generation supersymmetric partners of the fermions are large. All the 38 SUSY scenarios only differ in neutralino(LSP) mass and chargino mass. The neutralino mass and chargino mass used in every scenario are shown in Fig. 2, where every dot represents a SUSY scenario.

In Figure 2 three of the SUSY models are specified in colored circles, which in this report will always be used as examples in the plots. The three models are:

- blue: SUSY15, with chargino mass = 175.0 GeV, neutralino mass = 75.0 GeV, xsection = 0.5955330133
- green: SUSY22, with chargino mass = 250.0 GeV, neutralino mass = 100.0 GeV, xsection = 0.1402591020
- purple: SUSY39, with chargino mass = 550.0 GeV, neutralino mass = 450.0 GeV, xsection = 0.0031285346

These three scenarios will also be used to show difference in distributions between SUSY scenarios later in the report.

The xsections of the 38 SUSY scenarios range approximately from 3 pb, reaching below ~0.001pb, which are generally quite low compared to SM background processes. This is the main reason why finding SUSY signals or excluding SUSY scenarios is extremely challenging work.

1.2 SM Background

SM processes with 2-lepton OS final state are called background. In principle, if no deviation between background and data is observed SUSY scenarios can be excluded. In this project, MC simulated background samples are assumed to describe data sufficiently

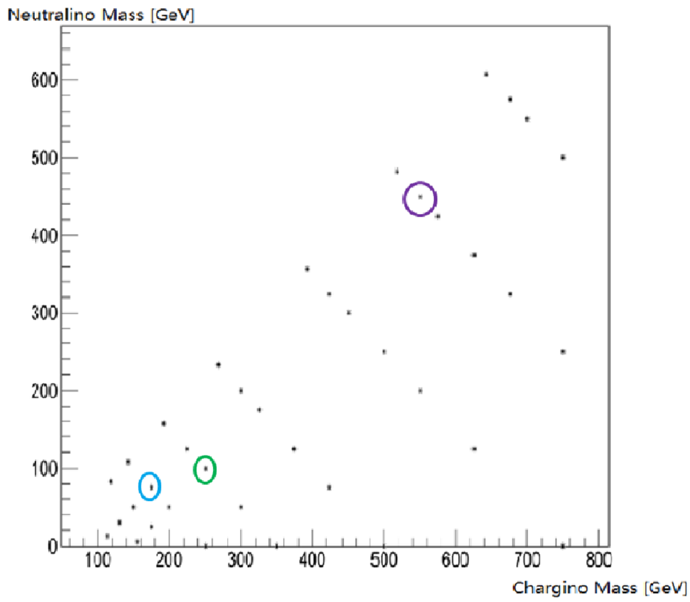


Figure 2: Chargino mass and neutralino mass used in the 38 SUSY scenarios.

well. Therefore, MC background samples and MC SUSY samples are used to develop event selection in order to increase signal/background ratio.
Six main MC simulated backgrounds with 2-lepton OS final state are used in this project:

- Z+jets: a Z boson decays into 2 same-flavor (SF) OS leptons.
- W+jets: a W boson decays into a lepton and a neutrino, where a jet is misidentifed as a lepton.
- Drell-Yan: a virtual photon or Z boson created from quark-antiquark annihilation decays into 2 SF OS leptons.
- Diboson: ZZ decay into 2 leptons and 2 neutrinos or dacay into 4 leptons where 2 leptons are not detected. WW decay into 2 leptons and 2 neutrinos. ZW decay into 3 leptons and a neutrino where 1 lepton is not detected.
- $t\bar{t}$: a top-antitop pair decays into 2 jets and 2 W bosons which further decay into 2 leptons and 2 neutrinos.
- Single top: a top quark decays into a jet and a W boson, where the jet is misidentified as a lepton.

1.3 Exclusion of SUSY scenarios

MC simulations of all SM backgrounds of 1.043 fb^{-1} at $\sqrt{s} = 8$ TeV are summed up to give a total background expectation. It is assumed that the 2012 LHC ATLAS data is described sufficiently well by MC simulation of background. The method to exclude SUSY scenarios is to perform the same event selection on MC of background and SUSY scenarios in signal regions where distributions of variables within SUSY scenarios have a different shape than SM background processes do, e.g. SUSY distribution might have a peak while background has a low, flat distribution. The purpose is to reject as few SUSY events as possible while discarding as many SM background events as possible allowing for a possible excess of SUSY over SM background events, thus being able to exclude or discover SUSY scenarios.

After the event selection, the number of events left are counted from a certain SUSY scenario and from background processes, yielding the expected number of events from the SUSY scenario and from background processes, which are denoted by s and b, respectively. Using s, b and a given background uncertainty denoted by db, the ROOT method RooStats::NumberCountingUtils::BionomialExpZ(s,b,db) is adopted, which returns the Gaussian significance z corresponding to the expected p-value for s=0 in a ratio of Poisson means. If the return value z > 1.64, the SUSY scenario is excluded at 95% CL.

2 The Standard Analysis of Search for SUSY Using 2-lepton OS Final State

The standard event selection was developed according to 2011 ATLAS data of 4.7 fb^{-1} at $\sqrt{s} = 7$ TeV. The standard analysis includes:

- Preselection: The event should contain exactly two oppositely charged leptons, where the transverse momentum of the leading lepton satisfies $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and that of the second leading lepton $p_{\mathrm{T}} > 10\,\mathrm{GeV}$. This preselection is performed in the beginning of every new set of cuts presented in this report.

- Cut1: remove Z mass peak and Drell-Yan peak in the m_{ll} distribution, where m_{ll} refers to the invariant mass of the sum of the 4-momentum of the two leptons. Namely, remove $m_{ll} < 20$ GeV and 81.2 GeV$< m_{ll} < 101.2$ GeV.

- Cut2: select events with 0 jet.

- Cut3: select events with $E_T^{miss,rel.} > 100$ GeV. The definition of the variable $E_T^{miss,rel.}$ will be explained later.

In the project the standard analysis is redone using data and MC of 1.043 fb^{-1} at $\sqrt{s} = 8$ TeV. Figure 3 shows the m_{ll} distribution and number of jets distribution for background and 3 SUSY scenarios after the preselection.

In the m_{ll} distribution, the Z peak and Drell-Yan peak are clearly seen. By removing the two peaks, many background events are discarded. In the number of jets distribution, both background and SUSY have most number of events with 0 jet. In the chargino pair production process studied in this project, no signal jets are expected in the final state.

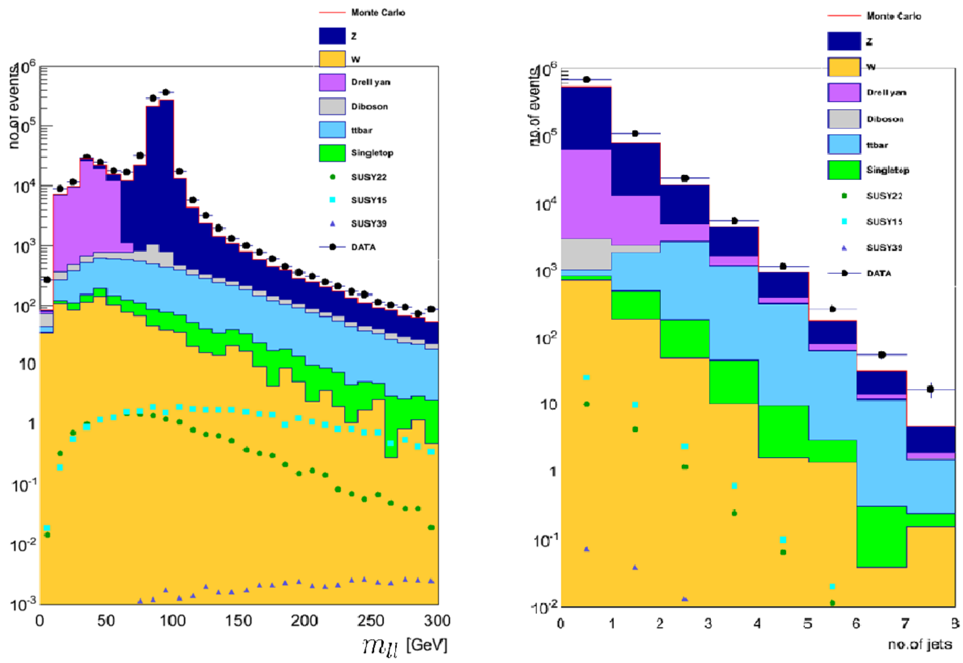


Figure 3: m_{ll} and number of jets distribution after the preselection. Different backgrounds are shown in different colors while the red line shows the sum of all SM background contributions. The black dots depict ATLAS data.

Therefore, events containing no jets are selected. These two cuts will also be applied in the optimization of event selection developed later.

The measurement of the missing transverse momentum two-vector, P_T^{miss}, and its magnitude, E_T^{miss}, is based on the transverse momenta of all electron and muon candidates, all jets, and all clusters of calorimeter energy with $|\eta| < 4.9$ not associated to such objects. The quantity $E_T^{miss,rel.}$ is defined as:

$$E_T^{miss,rel.} = \begin{cases} E_T^{miss} & if \Delta\phi_{l,j} \geq \pi/2 \\ E_T^{miss} \times \sin\Delta\phi_{l,j} & if \Delta\phi_{l,j} < \pi/2 \end{cases} \quad (1)$$

where $\Delta\phi_{l,j}$ is the azimuthal angle between the direction of P_T^{miss} and that of the nearest electron, muon or jet. In a situation where the momentum of one of the jets or leptons is significantly mis-measured, such that it is aligned with the direction of P_T^{miss}, only the E_T^{miss} component perpendicular to that object is considered. This is used to significantly reduce mis-measured E_T^{miss} in the processes such as $Z \to e^+e^-,\mu^+\mu^-$ [1]. Figure 4 shows the $E_T^{miss,rel.}$ distribution after performing cut1 and cut2. For the standard analysis, cut3 select events with $E_T^{miss,rel.}$>100GeV, thus removing many background events.

After performing the standard analysis, z value for each of the 38 individual scenarios is calculated for $1.043 fb^{-1}$ at $\sqrt{s} = 8$ TeV. Considering that the standard analysis

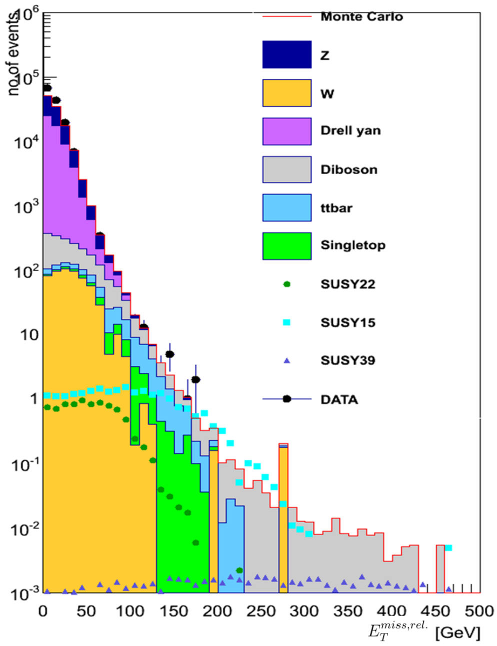


Figure 4: $E_T^{miss,rel.}$ distribution after cut1 and cut2. Different backgrounds are shown in different colors while the red line shows the sum of all SM background contributions. The black dots depict ATLAS data.

was designed to be suited for $4.7fb^{-1}$ of data at $\sqrt{s} = 7$ TeV, the standard analysis is also performed for $4.7fb^{-1}$ at $\sqrt{s} = 8$ TeV for better comparison. Any SUSY scenario whose z value is greater than 1.64 is excluded at 95% CL. The exact z values are not listed here for the sake of avoiding redundancy. The z values are calculated assuming four different background uncertainties of 20%, 50%, 60% and 70%. The number of excluded SUSY scenarios for $4.7fb^{-1}$ is 1, 0, 0, and 0, respectively, and for $1.043fb^{-1}$ is 0, 0, 0, 0. The z values for $4.7fb^{-1}$ at $\sqrt{s} = 8$ TeV are shown in Fig. 5 with 50% background uncertainty, where no SUSY scenario is excluded, and with 20% background uncertainty, where 1 SUSY scenario is excluded. Figure 5 shows that the SUSY scenario that can be excluded generally lies in the low chargino mass and low neutralino mass region.

3 Optimization of the event selection of the 2-lepton OS SUSY search

3.1 The 1^{st} set of event selection

In the 1^{st} set of event selection, cut1 and cut2 of the standard analysis are adopted. A new signal region(SR) is defined exploiting the "stransverse" mass variable, m_{T2}, to

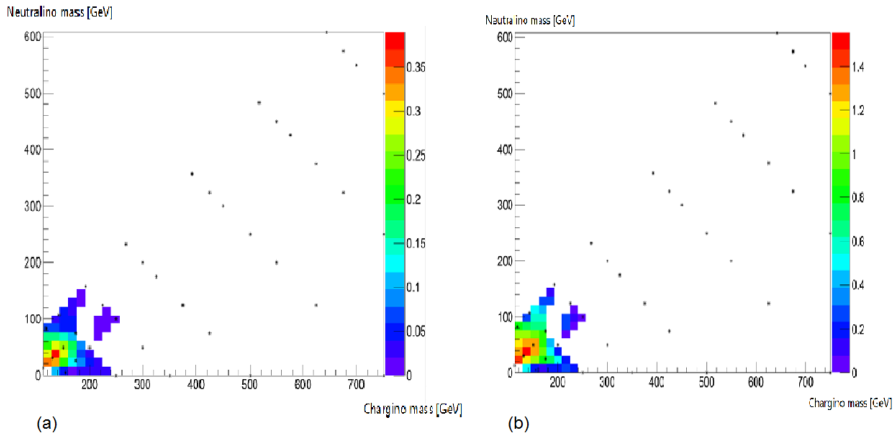


Figure 5: z value of the standard analysis displayed in color for every SUSY scenario, with 50% background uncertainty, (a), where no SUSY scenario is excluded, and 20% background uncertainty, (b), where 1 SUSY scenario is excluded.

provide sensitivity to chargino pair production. This variable is defined as:

$$m_{T2} = \min_{q_{\mathrm{T}}+r_{\mathrm{T}}=P_{\mathrm{T}}^{miss}} \left[\max\left(m_{\mathrm{T}}(p_{\mathrm{T}}^{l_1}, q_{\mathrm{T}}), m_T(p_{\mathrm{T}}^{l_2}, r_{\mathrm{T}})\right)\right] \tag{2}$$

where $P_{\mathrm{T}}^{l_1}$ and $P_{\mathrm{T}}^{l_2}$ are the transverse momenta of the two leptons, and q_{T} and r_{T} are two vectors which satisfy $q_{\mathrm{T}} + r_{\mathrm{T}} = P_{\mathrm{T}}^{miss}$. m_{T} indicates the transverse mass, $m_{\mathrm{T}} = \sqrt{2E_{\mathrm{T,p}}^{l_1} E_{\mathrm{T,q}}(1-\cos\phi)}$, where E_{T} is the transverse energy of a particle and ϕ the angle between the two particles in the transverse plane. The minimisation is performed over all possible decompositions of P_{T}^{miss} [1]. Figure 6 shows the m_{T2} distribution after cut1 and cut2.

For cut3, events with $m_{\mathrm{T2}} > 100$ GeV are selected. $m_{\mathrm{T2}} > 90$ GeV and $m_{\mathrm{T2}} > 110$ GeV are also tested. $m_{\mathrm{T2}} > 100$ GeV is found to generally yield higher z values for SUSY scenarios.

The 1^{st} set of event selection is set to be as follows:

- Cut1: remove Z mass peak and Drell-Yan peak in the m_{ll} distribution.
- Cut2: select events with 0 jet.
- Cut3: select events with $m_{T2} > 100$ GeV.

Using this set of alternative event selection, the z value for $1.043 fb^{-1}$ at $\sqrt{s} = 8$ TeV is calculated for each of the 38 individual scenarios assuming four different background

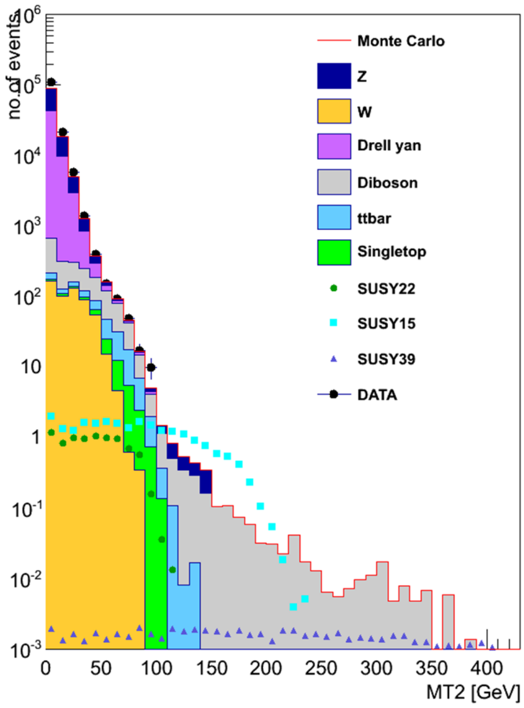


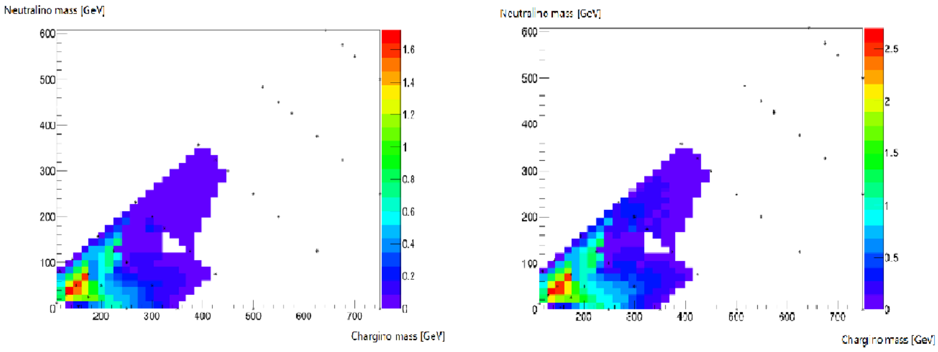
Figure 6: m_{T2} distribution after cut1 and cut2.

uncertainties of 20%, 50%, 60% and 70%. The number of SUSY scenarios excluded at 95% CL is 4, 1, 1 and 1, respectively. Figure 7 shows the z values for all SUSY scenarios with 50% background uncertainty, where 1 SUSY scenario is excluded, and with 20% background uncertainty, where 4 SUSY scenarios are excluded.

3.2 The 2^{nd} set of event selection

For the 2^{nd} set of event selection, cut1 and cut2 of standard analysis are adopted again. Then the variable p_{T}^{ll} is examined. In this report, p_{T}^{ll} refers to the transverse momentum of the sum of the 4-momentum of the two leptons.

Figure 8 shows the p_{T}^{ll} distribution after cut1 and cut2. It is seen in Fig. 8 that different SUSY scenarios show different p_{T}^{ll} distributions. SUSY22 has a p_{T}^{ll} peak value around 60 GeV, and the number of events drops down quickly on both sides of the peak. Thus for SUSY scenarios which have similar p_{T}^{ll} distribution as SUSY22,it would be a good cut to keep the events around the peak, thus removing much background. A different p_{T}^{ll} cut will be developed later to suit SUSY scenarios which have similar p_{T}^{ll} distribution as SUSY15 or SUSY39. The difference is further displayed in Fig. 9, which shows the $m_{T2} \sim p_{\mathrm{T}}^{ll}$ distribution. Different ways of p_{T}^{ll} cuts are tested, including m_{T2}-dependent p_{T}^{ll} cuts with triangle or rectangle shape on Fig. 9. The cut is chosen to be keeping events between $40\,\mathrm{GeV} < p_{\mathrm{T}}^{ll} < 150\,\mathrm{GeV}$.



(a) (b)

Figure 7: z value displayed in color for every SUSY scenario using the 1^{st} set of new cuts, with 50% background uncertainty, (a), where 1 SUSY scenario is excluded, and with 20% background uncertainty, (b), where 4 SUSY scenarios are excluded.

A high m_{T2} cut should always be applied as it has proven to define a good SR while developing the 1^{st} set of event selection. This can be also seen in Fig. 10, which shows the m_{T2} distribution after cut1 and cut2 of the standard analysis and 40 GeV $< p_{\mathrm{T}}^{ll} <$150 GeV cut. Different cuts of m_{T2} greater than 90 GeV, 100 GeV, 110 GeV, 120 GeV and 130 GeV have been tested and the best cut is m_{T2} >100 GeV.

Since a high $E_T^{miss,rel.}$ cut has shown to also define a good SR in the standard analysis, a high $E_T^{miss,rel.}$ cut is tested after the m_{T2} cut. Figure 11 shows the $E_T^{miss,rel.}$ distribution after $m_{T2} >$ 100 GeV cut. Different cut values of 90GeV, 100GeV, 110GeV, 120 GeV and 130 GeV have been tested. The cut is chosen to be $E_T^{miss,rel.} >$ 100GeV.

The 2^{nd} set of event selection is set to be as follows:

- Cut1: remove m_Z peak and Drell yan peak in the m_{ll} distribution.
- Cut2: select events with 0 jet.
- Cut3: select events with 40 GeV $< p_{\mathrm{T}}^{ll} <$ 150 GeV.
- Cut4: select events with m_{T2} >100 GeV.
- Cut5: select events with $E_T^{miss,rel.} >$ 100 GeV.

Using this set of alternative event selection, the z values are calculated for $1.043 fb^{-1}$ at $\sqrt{s} = 8\,\mathrm{TeV}$ assuming four different background uncertainties of 20%, 50%, 60% and

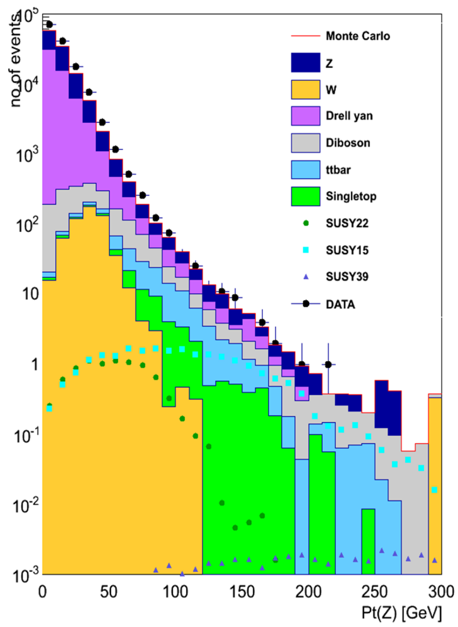


Figure 8: p_{T}^{ll} distribution after cut1 and cut2.

70%. The number of SUSY scenarios excluded at 95% CL is 4, 3, 2 and 2, respectively. Figure 12 shows the z values for all SUSY scenarios, with 50% background uncertainty, where 3 SUSY scenarios are exclude, and with 20% background uncertainty, where 4 SUSY scenarios are exclude.

3.3 The 3^{rd} set of event selection

For the 2^{nd} set of event selection, cut3 of selecting events with 40 GeV $< p_{\mathrm{T}}^{ll} <$ 150 GeV is designed for SUSY scenarios with similar p_{T}^{ll} distribution as SUSY22 model. This is not an ideal cut for SUSY scenarios like SUSY15 or SUSY39, where the number of events does not drop rapidly in high p_{T}^{ll} region. To illustrate this point, Fig. 13 shows the cut efficiency of 40 GeV $< p_{\mathrm{T}}^{ll} <$ 150 GeV cut as a profile for all 38 SUSY scenarios. The cut efficiency is defined as cut efficiency = (number of events before the cut - number of events after the cut)/(number of events before the cut). The cut efficiency shows the fraction of all events that are lost by performing this event selection. The efficiency of this cut for SM background is 0.967.

Figure. 13 clearly shows that for SUSY scenarios in low chargino and nertralino mass region the selection efficiency is low while for other SUSY scenarios, including SUSY39, the cut efficiency remains high. Therefore a different p_{T}^{ll} cut is chosen in the 3^{rd} set of new cuts selecting events with $p_{\mathrm{T}}^{ll} >$ 50 GeV, dropping the rejection of high p_{T}^{ll} region.

m_{T2} and $E_T^{miss,rel.}$ cuts are then performed after $p_{\mathrm{T}}^{ll} >$ 50 GeV. Different cut values are tested in the same way as in the 2^{nd} set of new cuts. And the best combination is

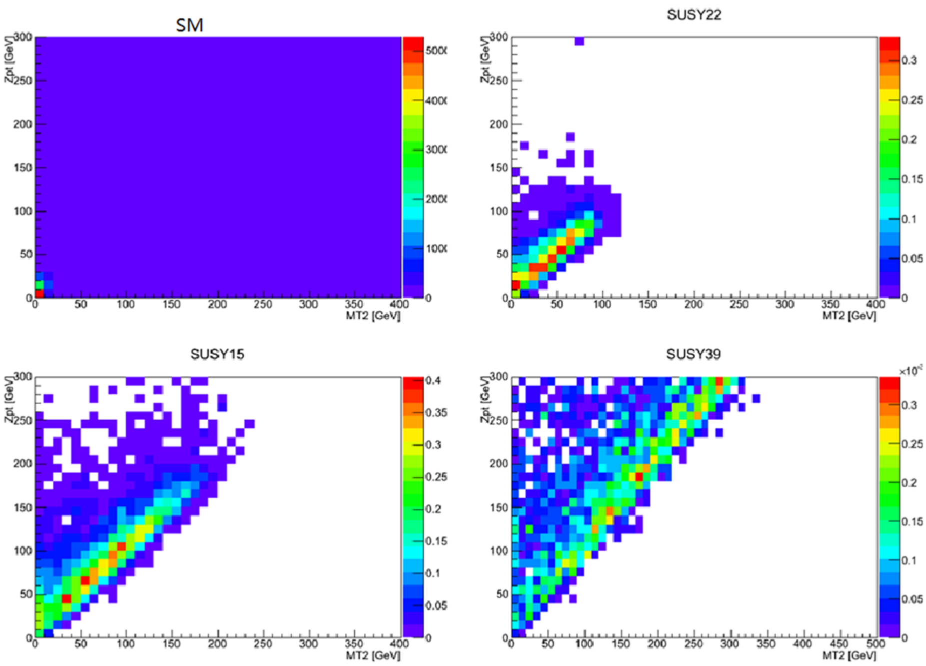


Figure 9: $m_{T2} \sim p_{\mathrm{T}}^{ll}$ distribution after cut1 and cut2, with SM background on the top left corner.(For SM background, the color plot only helps to show that the red peak lies in the low m_{T2} and low p_{T}^{ll} region.Actually the vast blue area is filled with almost no events.)

found to be selecting events with $m_{T2} > 120$ GeV and $E_T^{miss,rel.} > 120$ GeV.

The 3^{rd} set of event selection are set to be as follows:

- Cut1: remove Z mass peak and Drell-Yan peak in the m_{ll} distribution.
- Cut2: select events with 0 jet.
- Cut3: select events with $p_{\mathrm{T}}^{ll} > 50$ GeV.
- Cut4: select events with m_{T2} >120 GeV.
- Cut5: select events with $E_T^{miss,rel.}$ >120 GeV.

Again, using this set of alternative cuts, the z values are calculated for $1.043 fb^{-1}$ at $\sqrt{s} = 8\,\mathrm{TeV}$ assuming four different background uncertainties of 20%, 50%, 60% and 70%. The number of SUSY scenarios excluded is 2, 1, 1 and 1, respectively. Figure 14 and Figure 15 show the z values in color for all SUSY scenarios, with 20% and 50% background uncertainty, respectively.

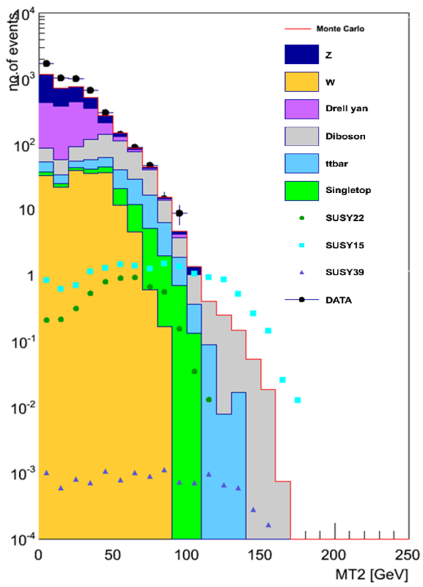


Figure 10: m_{T2} distribution after 40 GeV$< p_{\mathrm{T}}^{ll} <$150 GeV cut.

4 Summary

In this report, the standard event selection when searching for direct chargino pair production in 2-lepton OS final state and missing transverse momentum is redone using $4.7 fb^{-1}$ of $\sqrt{s} = 8$TeV data. Only one SUSY scenario out of the 38 SUSY scenarios studied in this project can be excluded at 95% CL assuming 20% background uncertainty. Three sets of event selections are tested for $1.043 fb^{-1}$ of $\sqrt{s} = 8$ TeV data resulting in the exclusion of additional SUSY scenarios at 95% CL.

As an outlook, by the end of the year 2012 LHC will have collected a much greater data sample corresponding to an integrated luminosity of approximately 20.0 fb^{-1}. Therefore, the standard analysis and optimized event selections are also carried out using 20.0 fb^{-1} of $\sqrt{s} = 8$ TeV MC samples showing again that more data allows the exclusion of additional SUSY scenarios. All results of the number of SUSY scenarios that may be excluded are given in Fig. 16.

It is thus concluded, that an optimized event selection for the search for direct chargino pair production in 2-lepton OS final state and missing transverse momentum as detailed in this report is profitable for new data collected at a center-of-mass energy of $\sqrt{s} = 8$ TeV and proves to exclude further SUSY scenarios in comparison to the standard analysis.

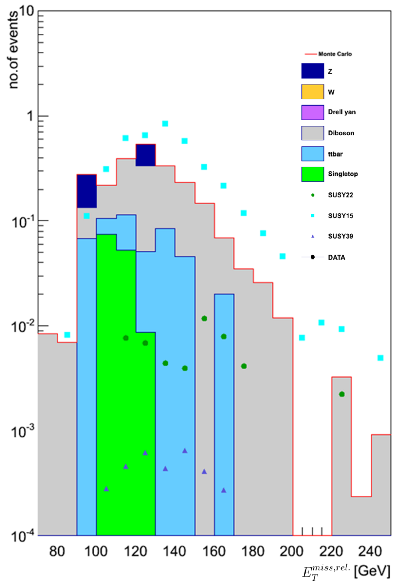


Figure 11: $E_T^{miss,rel.}$ distribution after m_{T2} cut.

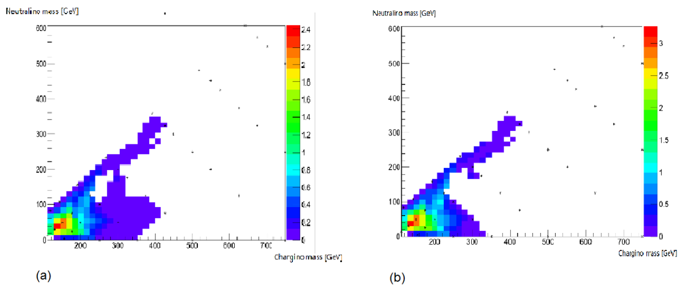


Figure 12: z value displayed in color for every SUSY scenario using the 2^{nd} set of new cuts, with 50% background uncertainty, (a), where 3 SUSY scenario is excluded, and with 20% background uncertainty, (b), where 4 SUSY scenarios are excluded.

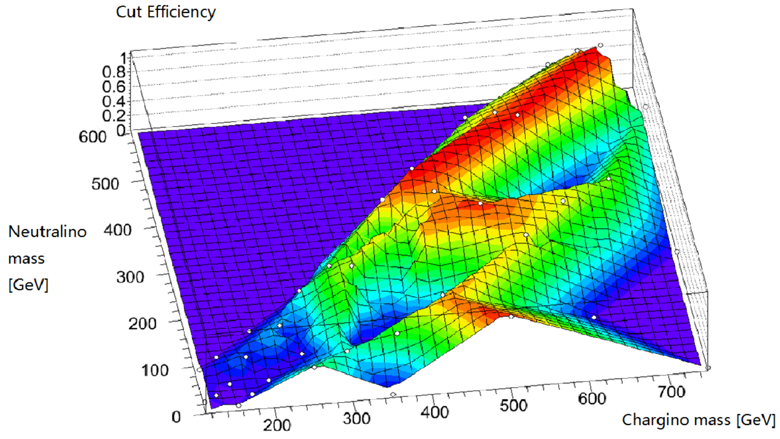


Figure 13: The efficiency of 40 GeV $< p_{\mathrm{T}}^{ll} <$ 150 GeV cut as a profile for all SUSY scenarios.

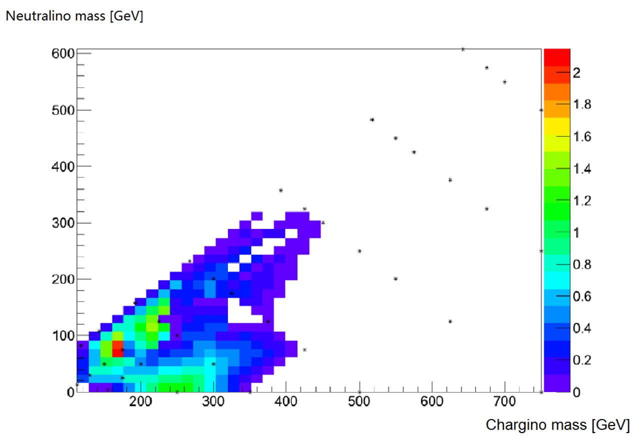


Figure 14: z value displayed in color for every SUSY model using the 3^{rd} set of event selection, with 20% background uncertainty. 2 SUSY scenarios are excluded.

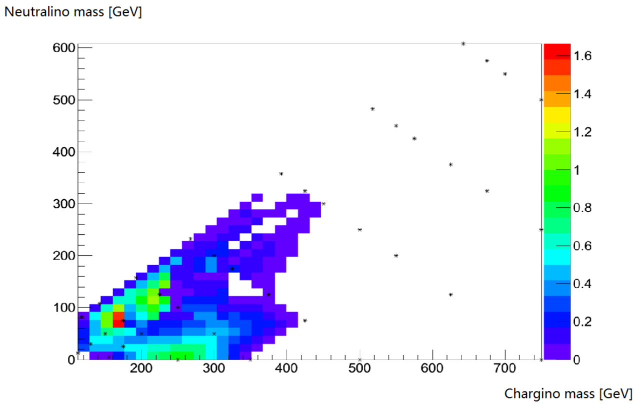


Figure 15: z value displayed in color for every SUSY model using the 3^{rd} set of event selection, with 50% background uncertainty. 1 SUSY model is excluded.

No. of SUSY models excluded with 95% CL	20% background uncertainty	50% background uncertainty	60% background uncertainty	70% background uncertainty
8 TeV , 4.7 fb^{-1}				
Standard Analysis	1	0	0	0
8TeV , 1.043 fb^{-1}				
Standard analysis	0	0	0	0
1^{st} set of new cuts	4	1	1	1
2^{nd} set of new cuts	4	3	2	2
3^{rd} set of new cuts	2	1	1	1
8TeV , 20.0 fb^{-1}				
Standard analysis	1	0	0	0
1^{st} set of new cuts	7	3	2	2
2^{nd} set of new cuts	6	4	4	3
3^{rd} set of new cuts	8	3	2	2

Figure 16: Summary of the number of SUSY scenarios that may be excluded after performing the standard analysis and optimized event selection assuming background uncertainty of 20%,50%,60% and 70% for varied integrated luminosities.

References

[1] ”The ATLAS Collaboration,Search for direct slepton and gaugino production in final states with two leptons and missing transverse momentum with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ TeV”, CERN-PH-EP-2012-216

[2] ”S. Martin, A Supersymmetry Primer”, (1997), hep-ph/9709356.

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