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Probing compressed mass spectra in electroweak supersymmetry with Recursive Jigsaw Reconstruction

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ABSTRACT: The lack of evidence for the production of colored supersymmetric particles at the LHC has increased interest in searches for superpartners of the electroweak SM gauge bosons, namely the neutralinos and charginos. These are challenging due to the weak nature of the production process, and the existing discovery reach has significant gaps in due to the difficulty of separating the supersymmetric signal from SM diboson events that produce similar final states and kinematics. We apply the Recursive Jigsaw Reconstruction technique to study final states enriched in charged leptons and missing transverse momentum, focusing on compressed topologies with direct production of charginos and neutralinos decaying to the lightest neutral supersymmetric particle through the emission of W and Z bosons. After presenting prototype analysis designs for future LHC runs, we demonstrate that its detectors have the potential to probe a significant amount of unexplored parameter space for chargino-neutralino associated production within the next few years, and show that the very challenging successful search for chargino pair production with compressed spectra might be possible by the end of the LHC lifetime.

KEYWORDS: Supersymmetry Phenomenology

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1 Introduction

Although the Standard Model (SM) of particle physics provides a successful explanation for a multitude of phenomena, it is considered an effective field theory of an underlying model valid at higher energies. Supersymmetry [1–8] (SUSY) refers to an invariance under generalized space-time transformations linking bosons and fermions. For each Standard Model particle, it is postulated that there exists a partner with spin differing by one-half unit, and other quantum numbers unchanged. Evidence of supersymmetric particles with masses at the electroweak-TeV scale is a sought-after experimental outcome, providing an explanation for the stabilization of the Higgs mass and potential gauge coupling unification.

R-parity conserving SUSY phenomenology demands an even number of superparticles in each interaction. Consequently, in collider experiments, super-partners would be pair-produced, providing in the final state two stable lightest supersymmetric particles (LSPs). As the LSP interacts only weakly, escaping the detector, it assumes the characteristics compatible with a dark matter candidate. At the Large Hadron Collider (LHC) the missing transverse momentum, $\vec{\cancel{E}}_T$, can infer the presence of unmeasured weakly interacting particles. As the momentum in the transverse plane is conserved, any missing momentum can be assumed to arise from missing particles including the LSPs.

Reconstruction techniques suffer from the lack of information related to the multiplicity and the masses of the particles not interacting with the detector. The difficulty is exacerbated in situations when the momenta of the weakly interacting particles are

low. This is the case for supersymmetric spectra in which the difference in mass between the pair-produced parent superparticles, $\tilde{P}$, and the LSPs is low. Scenarios with a small mass-splitting are referred to herein as *compressed* [9].

In the compressed regime, visible and invisible decay products have low transverse momenta, as the center-of-mass system of the parent superparticles does. In this scenario, the efficacy of typical variables [10] exploited to distinguish signal from background, based on large object transverse momenta and missing transverse energy, is limited.

One can gain indirect sensitivity by observing the reaction of the LSP pair to a probing force. The initial state radiation (ISR) from the interacting partons is the natural probe provided in the laboratory of a hadron collider. The ISR can boost the sparticles produced in these reactions and, in turn, endow their decay products with its momentum.

The Recursive Jigsaw Reconstruction technique has been used by the ATLAS collaboration to probe supersymmetric scenarios in cases involving the production of colored superpartners of SM particles [11]. In the compressed regime, a general basis of kinematic observables designed for the analysis of events with initial state radiation can be used independently of the topology investigated. In this study, we focus on applications of this technique to final states in the electroweak SUSY sector.

Electroweakinos are a linear combination of the fermionic partner of the gauge bosons and the two Higgs bosons. Neutral higgsinos and gauginos mix to form four eigenstates of mass called neutralinos ($\tilde{\chi}_i^0$ with $i = 1, 2, 3$ or 4), while charged winos and higgsinos form two eigenstates of mass referred to charginos ($\tilde{\chi}_i^\pm$ with $i = 1$ or 2). Herein, one assumes the lightest neutralino is the LSP and focuses on cases with small mass difference between it and the $\tilde{\chi}_1^\pm$ and/or $\tilde{\chi}_2^0$.

Compressed scenarios involving electroweakinos have been studied in detail elsewhere in the literature [12–18], and they are common in supersymmetric theory. For example, in naturalness-inspired models [19], the higgsino components are light, hence extremely small mass splittings are expected for the lower eigenstates of mass of higgsino-like charginos and neutralinos. At the same time, the masses of the wino components, appearing in the one-loop corrections to the Higgs mass, are expected to be limited. Dedicated techniques, as the monojet analysis, can be used for probing the extremely compressed regime.

Mass differences between the parent superparticle and the LSP, $\Delta M = M_{\tilde{P}} - M_{\tilde{\chi}_1^0}$, between 15 GeV and 75 GeV are probed in this work. The lightest chargino and the next-to-lightest neutralino are assumed the next-to-LSP of the theory, with the branching fractions for the decay modes $\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0$ assumed to be 100%. Final states arising from intermediate sleptons are not considered. For a mass splitting below the W -boson mass, two-body decays are kinematically suppressed, and we generate three-body decays involving off-shell bosons and assume other mediators do not contribute.

2 The simplified compressed decay tree

Recursive Jigsaw Reconstruction (RJR) [20] is a HEP technique based on the imposition of a decay tree mimicking the signal topology investigated. A series of algorithms, referred to as jigsaw rules, are applied to solve final state ambiguities due to unknown kinematic

Figure 1. The simplified decay tree diagram for the analyses of compressed signal topologies in events with an ISR-system.

degrees of freedom, when weakly interacting particles are present, and combinatoric challenges, due to the presence of indistinguishable visible particles from a detector prospective. The result is an estimate of the relevant reference frames and, hence, the definition of a complete basis of kinematic variables. These observables are sensitive to the masses and decay angles of the resonances appearing in the chosen tree, and can be used to distinguish signatures of new physics from the SM background.

In RJR involving compressed scenarios, the simplified decay tree shown in figure 1 is used for analyzing topologies with initial state radiation. A transverse view of the event is considered, namely all the z -momenta of the visible objects are set to zero.

We follow the procedure outlined in [21]. The estimate for the center-of-mass system of the whole reaction, SUSY + ISR, is labeled by CM; ISR is the system assigned to the radiation from the initial state, S is the signal or sparticle system decaying to visible and invisible products: the V and I systems. In each event, the missing transverse momentum is assigned to the I-system, while a jigsaw rule specifies the reconstructed objects hypothesized to come from the decay of sparticles, and assigned to the V-system, with respect to those associated with ISR. Jigsaw rules are implemented using the RestFrames software package [22].

Topology independent observables include:

- $R_{\text{ISR}} \equiv \frac{|\vec{p}_{\text{I},T}^{\text{CM}} \cdot \vec{p}_{\text{ISR},T}^{\text{CM}}|}{p_{\text{ISR},T}^{\text{CM}}}$: variable sensitive to the mass ratio between LSP and parent superparticle.
- $p_{\text{ISR},T}^{\text{CM}}$: magnitude of the vector-sum of the jets transverse momenta of the ISR-system evaluated in the CM frame.
- $\Delta\phi_{\text{ISR},\text{I}}$: transverse opening angle between the ISR-system and the I-system, evaluated in the CM frame.

In final states with two LSPs and no other weakly interacting particles, the observable R_{ISR} can be written in the laboratory frame as

$$R_{\text{ISR}} \sim \frac{|\vec{E}_T \cdot \hat{p}_T^{\text{ISR}}|}{p_T^{\text{ISR}}} \sim \frac{M_{\tilde{\chi}_1^0}}{M_{\tilde{P}}} + \mathcal{O}\left(\frac{p_{\tilde{\chi}_1^0}^{\tilde{P}}}{2M_{\tilde{P}}}\right) \left(\frac{\sqrt{(p_T^{\text{ISR}})^2 + m_{\tilde{P}\tilde{P}}^2}}{p_T^{\text{ISR}}}\right) \sin \Omega. \quad (2.1)$$

This approximation is valid for the extremely compressed scenarios, hence in the limit of a low-momentum of the LSP in the parent superparticle rest frame ($p_{\tilde{\chi}_1^0}^{\tilde{P}}$) with respect to the parent superparticle mass ($M_{\tilde{P}}$). In eq. (2.1), $m_{\tilde{P}\tilde{P}}$ is the true mass of the S-system and $\sin \Omega$ is a quantity which is zero on average. The observable scales with the mass ratio $\frac{M_{\tilde{\chi}_1^0}}{M_{\tilde{P}}}$ and width of order $\frac{p_{\tilde{\chi}_1^0}^{\tilde{P}}}{2M_{\tilde{P}}}$ in the limit $p_T^{\text{ISR}} \gg m_{\tilde{P}\tilde{P}}$. When visible decay objects are not reconstructed in the V-system, or additional neutrinos in the final state contribute to the missing transverse momentum, R_{ISR} is expected to assume values between the mass ratio and unity, while the last term in eq. (2.1) decreases.

3 Compressed electroweakino production in leptonic channels

Simulated Monte Carlo (MC) samples of Standard Model backgrounds and SUSY signals are used to study distributions of the performance of the RJR observables. The SM background processes expected to be the largest contributions have been generated elsewhere [23]. These samples are proton-proton collisions at $\sqrt{s} = 14$ TeV generated with MadGraph 5 [24]. The parton shower and hadronization is performed with Pythia 6 [25] followed by a detailed detector simulation with Delphes 3 [26]. The parameterization incorporates the performance of the existing ATLAS [27] and CMS [28] experiments. Jets are reconstructed by the anti- k_T clustering algorithm [29] with $R = 0.5$ and $p_T^{\text{min}} = 20$ GeV, implemented with the FastJet [30] package. The simulation procedure involves generation of events at leading order in bins of the scalar sum of the generator level particles transverse momenta, with jet-parton matching and corrections for next-to-leading order (NLO) contributions [31].

The same procedure and parametrization are used to generate the signal samples. The topologies considered are associated chargino-neutralino production and chargino pair production assuming degenerate masses, $M_{\tilde{\chi}_1^\pm} = M_{\tilde{\chi}_2^0}$, $M_{\tilde{\chi}_1^+} = M_{\tilde{\chi}_1^-}$, in the range $100 \text{ GeV} \leq M_{\tilde{P}} \leq 500 \text{ GeV}$. The compressed regime is probed: the mass splittings considered are in the range $15 \text{ GeV} \leq \Delta M \leq 75 \text{ GeV}$.

The cross sections for pure wino chargino pair production and chargino-neutralino associated production at $\sqrt{s} = 13$ TeV at NLL can be found elsewhere [32, 33], with relative uncertainties in the range $4.5\% \lesssim \Delta\sigma \lesssim 9\%$ for the masses investigated. We estimate the NLL cross sections at $\sqrt{s} = 14$ TeV, evaluating the NLO cross sections for the wino-like electroweakino pair production at 13 and 14 TeV with MadGraph, and assuming the same NLL/NLO k -factors for the corrections. The resulting NLL cross sections are shown in figure 2a and used as inputs for the analysis of the simplified supersymmetric topologies. This procedure provides small corrections ($\lesssim 5\%$) from the k -factors, and it is a check for

Figure 2. Estimated NLL cross sections for pure wino chargino pair production (blue curve) and chargino-neutralino associated production (red curve) at $\sqrt{s} = 14$ TeV (a). Feynman diagrams for electroweakino productions in final states with missing transverse momentum and three charged leptons (b) and two charged leptons (c).

the matched MadGraph cross sections and their potential dependences on the cutoff scales chosen.

The focus of this work is on the leptonic decay channels of off-shell W and Z bosons, as depicted in the Feynman diagrams in figure 2b and figure 2c. Leptonic final states from charmonium and bottomonium are expected to be negligible in the phase space probed.

Focusing on electrons and muons as visible decay products provides several advantages. Firstly, the signal-to-background ratio increases progressively with lepton multiplicity in the final state. Secondly, the channels result in clean final states with high efficiencies for the lepton reconstruction. Although the minimum value for reconstructed lepton p_T of 10 GeV is assumed in this study, recent work by the CMS collaboration has demonstrated improvements in the efficiency of identification of *soft* isolated electrons and muons (down to ~ 3 –4 GeV) [34], where dedicated triggers are described.

Moreover, for our purposes, all the leptons are identifiable as reconstructed objects produced via sparticle decays and assigned to the V-system, while all the jets can be assigned to the ISR-system with no ambiguity. A minimal value of the transverse momentum of the ISR-system, in concert with $\cancel{E}_T$, can elicit an increase in the transverse momenta of the decay products of the SUSY system. For compressed scenarios, the lack of combinatoric ambiguity allows us to leverage the RJR technique without requiring a restrictive event selection based on a huge value of the ISR transverse momentum.

The two phenomenological studies, treated separately, are presented in the next two sections emphasizing the role of the RJR observables for discriminating compressed electroweakino signals with respect to the individual SM processes. In appendices B and C two examples of cut-flows are shown in table 3 and figure 16, and table 4 and figure 17 respectively, for the overall SM background and two benchmark signal samples.

3.1 Chargino-neutralino associated production in final states with three leptons and missing transverse momentum

The signal samples are the simplified topologies as in figure 2b generated within the mass ranges $125 \text{ GeV} \leq (M_{\tilde{\chi}_1^\pm} = M_{\tilde{\chi}_2^0}) \leq 500 \text{ GeV}$, with five mass splittings $\Delta M = M_{\tilde{P}} -$

Figure 3. Distributions of $R_{\text{ISR}} = \frac{|\tilde{p}_{1,T}^{\text{CM}} \tilde{p}_{\text{ISR},T}^{\text{CM}}|}{p_{\text{ISR},T}^{\text{CM}}}$ (a) and $p_{\text{ISR},T}^{\text{CM}}$ (b) for events that have satisfied the preselection criteria. All the contributions are scaled with an integrated luminosity of 300 fb^{-1} at $\sqrt{s} = 14 \text{ TeV}$.

$M_{\tilde{\chi}_1^0} = 15, 25, 35, 50$ and 75 GeV . Event-by-event a basis of RJR variables is extracted and analyzed to probe compressed spectra for a projection of $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$. To the previous variables, additional transverse observables for this study include:

- M_T^V is the transverse mass of the V-system.
- $M_{\ell+\ell-}$ is the transverse mass of the two same flavor opposite sign leptons in final states where the third lepton has different flavor (corresponding to $M_{T,e+e-}$, when the third lepton is a muon, and $M_{T,\mu+\mu-}$, when the third lepton is an electron).
- $\Delta\phi_{\text{CM},\text{I}}$ is the transverse opening angle between the CM-system and the I-system.

Three leptons (electrons and muons) are required in the final state with $p_T > 10 \text{ GeV}$, while at least one jet, with $p_T > 20 \text{ GeV}$, is associated with the ISR-system. A minimal value for the missing transverse momentum, $\cancel{E}_T > 50 \text{ GeV}$, is the last preselection requirement.

Figure 3 shows the distributions of R_{ISR} and $p_{\text{ISR},T}^{\text{CM}}$ after preselection criteria are imposed. All of the relevant Standard Model backgrounds are stacked together and categorized into five groups. The dominant contributions are associated WZ production and $t\bar{t}$ processes with an additional vector boson. The overlaid dashed curves refer to four chargino-neutralino production samples with different masses and mass splittings.

The observable R_{ISR} provides a remarkable signal-to-background discrimination in the absence of more stringent selection criteria as shown in figure 3a. The assignment of the different objects in the compressed tree is performed with no ambiguity, and it is not necessary to focus on the high ISR regime in order to improve the observable resolution for the signal samples. Notice that R_{ISR} can assume larger values than unity when some objects are forced in the V-system. The observable is expected to be peaked for values beyond $M_{\tilde{\chi}}/M_{\tilde{P}}$ due to the additional contribution to $\cancel{E}_T$, deriving from one or more neutrinos. Values larger than the mass ratio will be considered for the definition of the R_{ISR} requirements together with $R_{\text{ISR}} < 1$.

Figure 4. Distribution of the M_T^V as a function of R_{ISR} for the diboson background (a) and the signal samples $M_{\tilde{\chi}_1^\pm} = M_{\tilde{\chi}_2^0} = 200 \text{ GeV}$, $M_{\tilde{\chi}_1^0} = 185 \text{ GeV}$ (b) and $M_{\tilde{\chi}_1^\pm} = M_{\tilde{\chi}_2^0} = 150 \text{ GeV}$, $M_{\tilde{\chi}_1^0} = 125 \text{ GeV}$ (c). One demands preselection criteria, $N_{b\text{-jet}}^{\text{ISR}} = 0$, $p_{\text{ISR},T}^{\text{CM}} > 50 \text{ GeV}$ and $M_T^V < 100 \text{ GeV}$.

Figure 3b shows the distribution of $p_{\text{ISR},T}^{\text{CM}}$. The mass scales for the signal and background samples are similar, and the variable has limited impact. In the absence of other requirements, the slope of the signal distributions is paradoxically more severe than the background one, since events with non-radiative jets forced into the ISR-system. A minimal requirement on $p_{\text{ISR},T}^{\text{CM}}$ is essential to exploit the RJR technique with multi-lepton final states. The requirement applied to this variable, the only large-scale observable in this study together with $\cancel{E}_T$, will be moderately tighter for the largest mass splittings probed since the criterion on R_{ISR} is relaxed.

It is interesting to note that the number of events passing the preselection criteria is smaller for the signal sample with $M_{\tilde{\chi}_1^\pm} = M_{\tilde{\chi}_2^0} = 200 \text{ GeV}$ and $\Delta M = 15 \text{ GeV}$ compared to the sample with $M_{\tilde{\chi}_1^\pm} = M_{\tilde{\chi}_2^0} = 300 \text{ GeV}$ and $\Delta M = 50 \text{ GeV}$. There has been a conservative minimal choice of transverse momentum for electrons and muons of 10 GeV and, consequently, when the mass splitting approaches a much more compressed regime, the kinematics are such that one of the three leptons is less likely to satisfy this transverse momentum constraint. In order to probe the extreme compressed regime ($\Delta M < 15 \text{ GeV}$), a parametrization of the efficiency in the reconstruction of soft electrons and muons ($p_T \lesssim 10 \text{ GeV}$) must be implemented. This is considered beyond the scope of this paper, due to the difficulty of getting these details correct outside of an experimental collaboration.

Figure 4 shows the two-dimensional distributions of M_T^V as a function of R_{ISR} for the dominant Standard Model background and two representative signal samples for events passing the preselection criteria, and after applying a veto for jets tagged as being initiated by a b -quark ($N_{b\text{-jet}}^{\text{ISR}} = 0$). The final state signal events populate low values of M_T^V with a complementarity with high values of R_{ISR} . Vice versa, for the diboson background, simultaneous low values of M_T^V and R_{ISR} close to one are disfavored, as shown in figure 4a.

Using the two RJR observables in concert provides an increasingly powerful discrimination the smaller the absolute and relative mass splitting of the signal sample. In the low M_T^V regime ($M_T^V < 100 \text{ GeV}$), and for values of the ratio close to unity ($R_{\text{ISR}} > 0.6$), additional handles to decrease the SM background yield are provided by the compressed-transverse RJR angles and $M_{\ell^+\ell^-}$. Figure 5 shows the distribution of $\Delta\phi_{\text{ISR},I}$ (a), $\Delta\phi_{\text{CM},I}$

Figure 5. Distributions of $\Delta\phi_{\text{ISR},I}$ (a), $\Delta\phi_{\text{CM},I}$ (b) and $M_{\ell+\ell-}$ (c) for the events satisfying the preselection criteria, $N_{b\text{-jet}}^{\text{ISR}} = 0$, $p_{\text{ISR},T}^{\text{CM}} > 50$ GeV, $M_T^V < 100$ GeV and $R_{\text{ISR}} > 0.6$.

(b) and $M_{\ell+\ell-}$ for final state events with only two of the three leptons with same flavor (c). For the signal events, the transverse mass of the two leptons has a clean end-point at the expected ΔM .

Selection criteria applied on the compressed RJR observables, as shown in table 1, can be used to define signal regions for probing chargino-neutralino associated pair production in final states with three leptons and missing transverse momentum. One or more additional jets are assumed to be radiated from the initial state, and a minimal requirement on $p_{\text{ISR},T}^{\text{CM}}$ (and $\cancel{E}_T$) allows us to focus on the final states of interest and probe the compressed spectra. The signal regions target five particular mass splittings. A special treatment is assumed for the selection criteria applied to R_{ISR} , since this observable is related to the mass ratio, $M_{\tilde{\chi}}/M_{\tilde{\nu}}$, rather than the absolute value of the mass splitting.

For the largest mass differences ($\Delta M = 50, 75$ GeV), tighter selection criteria are used for the only large-scale variables ($p_{\text{ISR},T}^{\text{CM}}$ and $\cancel{E}_T$), the jet multiplicity and $\Delta\phi_{\text{CM},I}$, since the R_{ISR} requirement is relaxed. An upper bound is imposed for M_T^V , progressively more stringent to the decrease of ΔM ; while for $M_{\ell+\ell-}$, the maximum required coincides with the mass splitting itself. In final states with three electrons or three muons, only the M_T^V requirement is applied; while for events with two same and one different flavor leptons, the selection on $M_{\ell+\ell-}$ is imposed together with $M_T^V < 100$ GeV. The selection criteria applied to the observable R_{ISR} are progressively more stringent the closer the mass ratio to unity, and the values are separated by 0.05, which provides a moderate optimization. Figure 6 shows the distributions of $\Delta\phi_{\text{CM},I}$ and M_T^V applying respectively the N-1 requirements in column 2 and 3 of table 1; namely all the selection criteria except for the one imposed on the observable plotted.

The signal regions expressed by the selection criteria of the RJR observables defined in table 1 are applied to calculate projected sensitivities for compressed spectra signal samples. Figures 7 shows the value of Z_{Bi} , calculated assuming the metric [35], at $\sqrt{s} = 14$ TeV for an integrated luminosity of 300 fb^{-1} . A systematic uncertainty of 20% is assumed constant in the SUSY phase space, with the dominant contribution to the background arising from associated WZ production.

The signal yields in the extreme compressed scenarios can benefit from an improvement in the efficiencies of the detector in the reconstruction of low-momentum leptons, which

	Mass Splitting [GeV]				
Variable	$\Delta M = 15$	$\Delta M = 25$	$\Delta M = 35$	$\Delta M = 50$	$\Delta M = 75$
Object multiplicity selection criteria	3 Leptons (e and μ) with $p_T^{\text{lep}} > 10$ GeV, At least one jet, $p_T^{\text{jet}} > 20$ GeV, $N_{b\text{-jet}}^{\text{ISR}} = 0$				
$p_{\text{ISR},T}^{\text{CM}} (\cancel{E}_T) > [\text{GeV}]$	50			70	120
$N_{\text{jet}}^{\text{ISR}} <$	3	4		3	
$M_T^V <, \text{ for 3 SFL } [\text{GeV}]$	40	50	65	75	90
$M_{\ell^+\ell^-} <, \text{ for 2 SFL } [\text{GeV}]$ ($M_T^V < 100$ GeV)	15	25	35	50	75
$\Delta\phi_{\text{CM},I} <$	1			0.7	0.5
$\Delta\phi_{\text{ISR},I} >$	3				
$R_{\text{ISR}} >$	0.85, 0.9	0.8, 0.85 0.9	0.8, 0.85	0.7, 0.8 0.85	0.65, 0.7 0.75

Table 1. A loosely optimized set of selection criteria for signal regions in the analysis of chargino neutralino production in trilepton final states.

Figure 6. The distributions of the observables $\Delta\phi_{\text{CM},I}$ and M_T^V for signal and Standard Model background events passing the N-1 selection criteria in one of the signal regions of table 1 with $R_{\text{ISR}} > 0.85$.

Figure 7. Projected exclusion and discovery reach for chargino-neutralino associated production in the compressed region ($15 \text{ GeV} \leq \Delta M \leq 75 \text{ GeV}$) at $\sqrt{s} = 14 \text{ TeV}$ for an integrated luminosity of 300 fb^{-1} .

is outside the scope of this work. On the other hand, the significances decrease for mass differences close to the W pole mass, due to the difficulty to discriminate background events derived from topologies with absolute and relative mass scales very close to the signal ones.

The value $\Delta M = 15 \text{ GeV}$ must not be considered as a threshold: the minimum mass difference achievable with any technique is strongly related to the efficiencies for the detector to reconstruct low-momentum leptons. For extremely compressed scenarios, a similar analysis could be used to probe the same final state topologies with only two low-momentum leptons reconstructed. Although the background would differ in that case, one could require two same-sign leptons to suppress the SM yield.

The highest impact of the compressed RJR observables is for the samples of mass splittings in the range $20\text{--}40 \text{ GeV}$, a challenging phase space for SUSY searches [36]. For an integrated luminosity of 300 fb^{-1} , degenerate charginos and neutralinos would be discovered with masses $M_{\tilde{\chi}_1^\pm} = M_{\tilde{\chi}_2^0} > 150 \text{ GeV}$, for a large portion of the samples investigated, and excluded up to 300 GeV for the best scenarios.

Overall, one can improve the performance of the RJR technique by adopting a strategy based not only on transverse observables, exploiting a three-dimensional reconstruction, as in the following study.

3.2 Chargino pair production in final states with two leptons and missing transverse momentum

We now move on to consider a different and still more complicated compressed electroweakino investigation. The signal samples are simulated proton-proton collisions at $\sqrt{s} = 14 \text{ TeV}$ producing a pair of lightest charginos with opposite electric charge and with

Figure 8. The decay tree for the analysis of compressed chargino pair production in events with ISR. The substructure of the S system is specified: each chargino decays to a visible (lepton) and an invisible (neutrino + LSP) object.

$\tilde{\chi}_1^\pm \rightarrow W^{*\pm}(\rightarrow \ell^\pm \nu) \tilde{\chi}_1^0$. The focus is on final states with two leptons as illustrated in the simplified topology in figure 2c. The samples are generated within the mass ranges $100 \text{ GeV} \leq M_{\tilde{\chi}_1^\pm} \leq 300 \text{ GeV}$, with the five mass splittings $\Delta M = M_{\tilde{P}} - M_{\tilde{\chi}} = 15, 25, 35, 50$ and 75 GeV .

The lepton multiplicity of the final state determines the main contributions of the Standard Model processes. In the absence of hadronic jets, the dileptonic channel of a pair of W bosons, constitutes the dominant process, producing a final state with two opposite sign leptons and missing transverse momentum. Searches for chargino pair production in a final state with two leptons are challenging for open mass spectra due to the W^+W^- irreducible background, while other contributions are often negligible. In the compressed regime, the difficulty is exacerbated by the low momenta of invisible and visible objects and by the subsequent kinematics. Moreover, requiring a transverse momentum for the ISR-system introduces an additional complication for the analysis in the compressed regime: Standard Model backgrounds other than WW will contribute quite significantly.

In order to improve the signal-to-background discrimination, the simplified version of the compressed RJR tree in figure 1 is enriched specifying the substructure of the S-system. This is feasible for the dilepton final state, since the provenance of the reconstructed visible sparticle decay products is unambiguous. These decay products can then be assigned to the appropriate position in the tree.

The RJR decay tree is shown in figure 8. Electrons and muons are associated with the ℓ^+ and ℓ^- systems, depending on the electric charge, while the jets are assigned to the ISR-system. The S-system frame is the approximation for the center-of-mass of the two charginos, and each one decays to a lepton and an invisible system. Each invisible system collects the $\tilde{\chi}_1^0 + \nu$ contribution of the hemisphere a or b .

In this approach, a three-dimensional view of the event is considered, and jigsaw rules are applied for reconstructing the topology and the relevant frames of reference. In the overall center-of-mass frame, the ISR and S systems are back-to-back. A Lorentz invariant jigsaw rule is assumed for the estimate of the mass of the invisible objects, while the rapidity

is assigned as to the chargino center-of-mass (equal to the rapidity of the visible objects in the S-system). Finally, a contra-boost invariant jigsaw rule partitions the remaining unknown degrees of freedom associated with I_a and I_b . More information can be found elsewhere [37, 38].

The useful transverse variables of the simplified tree can be computed along with additional experimental observables. Having in mind the simplified tree in figure 1, one can reconstruct the I-system, corresponding to the sum of the two invisible systems, $I = I_a + I_b$, and V, as the sum of the two lepton systems, $V = \ell^+ + \ell^-$, and hence compute the transverse observables: R_{ISR} , $p_{\text{ISR},T}^{\text{CM}}$ and $\Delta\phi_{\text{ISR},I}$.

Three-dimensional scale-sensitive variables and additional angular observables include:

- M^V is the mass associated with the V-system: invariant mass of $(\ell^+ + \ell^-)$.
- $M^{\tilde{\chi}^\pm}$ is the mass associated with the chargino system.
- $\Delta\phi_{\ell^+,I}$ ($\Delta\phi_{\ell^-,I}$) is the polar angle between the positive (negative) charge lepton and $\vec{E}_T$, computed in the Lab frame.
- $\Delta\phi_{\text{CM},I}$ is the opening angle between the CM-system and the I-system.
- $\cos\theta \equiv \hat{\beta}_S^{\text{CM}} \cdot p_{I,T}^S$ is the dot product between the direction of the boost from CM to the reconstructed S-frame and the transverse momentum of the I-system in the S-frame.

Finally, jet multiplicities are considered. For the signal samples, the mass-observable associated with the chargino system, $M^{\tilde{\chi}^+} = M^{\tilde{\chi}^-}$, do not reproduce the actual chargino mass since the true LSPs are massive. The $I_{a,b}$ systems, assumed massless by RJR, are simplifications of the lightest neutralino plus neutrino contribution in each hemisphere.

The dominant SM backgrounds are categorized into four groups: 1) Vector boson + jets, mainly populated by $Z \rightarrow \ell^+\ell^- + \text{jets}$; 2) Production of at least one top quark ($t+X$), with single-top and dileptonic $t\bar{t}$ both contributing; 3) Irreducible diboson processes mostly arising from W^+W^- with two leptons and missing transverse momentum; and 4) Contributions such as vector boson fusion, tri-boson, and gluon fusion plus jets with $H \rightarrow W^+W^-$, are categorized as “others”.

Two leptons (electrons and muons), with $p_T > 10 \text{ GeV}$, are required in the final state and at least one jet, with $p_T > 20 \text{ GeV}$, which is assigned to the ISR-system. Figure 9 shows the distribution of the invariant mass of the two leptons for same and different flavor, assuming a minimal value for the missing transverse momentum $\cancel{E}_T > 20 \text{ GeV}$. Standard Model background samples are stacked together, while the overlaid dashed curves refer to chargino pair production samples with different masses and mass splittings. Notice the peak around 90 GeV for same flavor leptons, due to the Standard Model backgrounds containing Z bosons produced in association with jets (in blue), with a moderate contribution from WZ (in green), and vector boson fusion and tri-boson (in red). In the compressed regime, the final state events for all the signal distributions tend to populate lower values of M^V , and the requirement $M^V < 70 \text{ GeV}$, or tighter, will be used to specify the signal regions.

Figure 9. Distribution of the dilepton invariant mass for same (a) or different (b) flavor.

Notice the additional peak for low values of M^V , arising from Z + jets and vector boson fusion contributions, resulting in a comparable number of events for the cases with two leptons with same or different flavor. The dominant process that contributes in this region is $Z \rightarrow \tau^+\tau^- \rightarrow \ell^+\ell^-\nu\nu\nu\nu$, and sub-dominant contributions arise from Drell-Yan processes with missing transverse momentum ($Z^*(\gamma^*) \rightarrow \tau^+\tau^-$), or W boson production decaying leptonically, with an additional lepton faked by a jet or a photon. For the dileptonic decay of the Z boson via taus, the value for M^V is reconstructed to be below the Z mass, representing a challenge to the analysis in search of compressed charginos.

Herein, we consider the preselection criteria as follows: final states with two leptons and at least one light jet. A veto is applied for the jets tagged as b , τ and fat: $N_{b\text{-jet}}^{\text{ISR}} = 0$, $N_{\tau\text{-jet}}^{\text{ISR}} = 0$ and $N_{\text{fat}}^{\text{ISR}} = 0$.¹ A minimal value for the missing transverse momentum ($\cancel{E}_T > 50$ GeV) in concert with $p_{\text{ISR},T}^{\text{CM}} > 50$ GeV is imposed. In addition, preselection includes the criterion $M^V < 70$ GeV. This last requirement excludes a large portion of the Standard Model background events, in particular $t\bar{t}$ and multi-bosons processes, independently of the flavor of the two leptons reconstructed. Standard Model processes involving a meson decaying in two same flavor leptons are expected with a small value of the invariant mass ($\lesssim 10$ GeV); notably, signal sample events tend to assume larger values.

In the following, the impact of the main RJR observables in reducing the specific Standard Model contributions is presented. Selection criteria will be imposed progressively on the observables sensitive to probe compressed chargino pair mass spectra, with distributions shown in appendix A.

Numerous Standard Model processes result in a low value of M^V , in particular, the boson plus jets contribution. The focus is on the process $Z \rightarrow \tau^+\tau^- \rightarrow \ell^+\ell^-\nu\nu\nu\nu$ plus jets. For such events, the role of the chargino system in figure 8 is assumed by the tau's leptonic decay, while the I systems reconstruct the information of the two neutrinos in each hemisphere. The kinematics of these background events is such that $M^{\tilde{\chi}^\pm}$ is a reconstruction of the mass of the lepton and two neutrinos resulting from the τ decays.

¹In this work a fat jet is defined with $M > 60$ GeV and is a candidate for boosted SM Higgs, vector bosons and top-quark decaying hadronically.

The first two plots in figure 12 show the two-dimensional distributions between $M^{\tilde{\chi}^\pm}$ and the ratio R_{ISR} for the boson plus jets backgrounds and the signal sample $M_{\tilde{\chi}_1^\pm} = 200$ GeV and $M_{\tilde{\chi}_1^0} = 150$ GeV, figure 12c shows the distribution of $M^{\tilde{\chi}^\pm}$ for the five signal samples and for the on-shell/off-shell boson plus jets backgrounds. The lower bound $M^{\tilde{\chi}^\pm} > 24$ GeV is required to suppress the V+jets background.

With this requirement the SM background is dominated by top processes, specifically a pair of (on- or off-shell) top quarks in the dileptonic channel. Figure 13 shows the distribution of the light jet multiplicity as a function of the ratio.

In order to attenuate the $t\bar{t}$ contribution, we demand only one jet in the final state. Despite the requirement of $N_{\text{jet}}^{\text{ISR}} = 1$, and vetoing on jets coming from the fragmentation of bottoms, the $t\bar{t}$ background is still not suppressed. Although the requirement $N_{\text{fat}}^{\text{ISR}} = 0$ attenuates the contribution with the two jets reconstructed in similar directions, one of the two jets could be outside the geometrical acceptance, mismeasured, or of too low momentum to be reconstructed. Also if these events are relatively rare, their contribution is not negligible due to their high cross section, $\sigma_{pp \rightarrow t\bar{t}} \sim \mathcal{O}(10^3 \text{ pb})$, at 14 TeV LHC collisions.

Figure 14a shows the distribution of $\Delta\phi_{\ell^+, \text{I}}$ for the signal samples and the $t + X$ backgrounds, categorized in four sub-processes and stacked together. The events from the top pair contributions tend to populate value close to π , while signal-like events populate low values. Figures 14b and 14c show the two-dimensional distribution $\Delta\phi_{\ell^+, \text{I}}$ vs. $\Delta\phi_{\ell^-, \text{I}}$ for the $t\bar{t}$ background and the signal sample $M_{\tilde{\chi}_1^\pm} = 200$ GeV and $M_{\tilde{\chi}_1^0} = 150$ GeV, assuming the same selection criteria, and requiring $R_{\text{ISR}} > 0.6$. The requirements select background events with kinematics similar to the signal events, and in particular, a simultaneously large value of $\Delta\phi_{\ell^\pm, \text{I}}$ is disfavored.

Such events contain predominantly two top quarks produced with low transverse momenta resulting in final states with two reconstructed leptons and one jet not properly tagged. In the transverse plane, one of the two leptons is expected to fly close to the reconstructed jet (associated with the ISR-system), while the other is expected to be closer to the invisible system. Consequently, background events tend to assume larger values of $\Delta\phi_{\ell^+, \text{I}} + \Delta\phi_{\ell^-, \text{I}}$ than signal events. A similar two-dimensional distribution as in figure 14c is demonstrated by all signal samples studied. A unique light jet associated with the ISR-system together with $\Delta\phi_{\ell^+, \text{I}} + \Delta\phi_{\ell^-, \text{I}} < 2$ dramatically reduce the $t+X$ background.

Applying these selection criteria, the dominant Standard Model contribution is the irreducible diboson background: W^+W^- . The goal is to distinguish between signal and background events with similar event topologies and kinematics, in particular when selection criteria close to the final configuration are imposed. The key difference to exploit is that of the I-system ($I_a + I_b$) for the W^+W^- background composed of two neutrinos. For signal events, on the contrary, a minimum of four weakly interacting particles comprises the invisible system.

Figure 15 shows the angular observables sensitive to the composition of the I-system and used to separate events resulting from compressed chargino samples with respect to WW events. Figure 15a shows the distribution of $\Delta\phi_{\text{ISR}, \text{I}}$. Signal events tend to populate values closer to π , as the mass difference $\Delta M = M_{\tilde{P}} - M_{\tilde{\chi}}$ is reduced. Figure 15b shows the

Variable	Mass Splitting [GeV]				
	$\Delta M = 15$	$\Delta M = 25$	$\Delta M = 35$	$\Delta M = 50$	$\Delta M = 75$
Object multiplicity selection criteria	2 OS Leptons (e and μ) with $p_T^{\text{lep}} > 10$ GeV, $N_{\text{jet}}^{\text{ISR}} = 1$, $N_{b\text{-jet}}^{\text{ISR}} = 0$, $N_{\tau\text{-jet}}^{\text{ISR}} = 0$ and $N_{\text{fat}}^{\text{ISR}} = 0$				
$p_{\text{ISR},T}^{\text{CM}} (\cancel{E}_T) > [\text{GeV}]$	50				
$M^V < [\text{GeV}]$	50			60	70
$\Delta\phi_{\ell^+,I} + \Delta\phi_{\ell^-,I} <$	2				
$M_{\tilde{\chi}_1^\pm} > [\text{GeV}]$	24				
$\Delta\phi_{\text{CM},I} <$	0.5	0.5	0.45		
$\Delta\phi_{\text{ISR},I} >$	3.12	3.10	3.06	3.05	3.04
$\cos\theta >$	0.9	0.85	0.8	0.75	0.7
$R_{\text{ISR}} >$	0.85, 0.9	0.85, 0.9	0.8, 0.85 0.9	0.8, 0.85	0.75, 0.8 0.85

Table 2. Selection criteria for signal regions in the analysis of chargino pair production in final states with two leptons and missing transverse energy.

distribution of the angle between the CM-system and I-system, where in this case signal events are towards zero, almost independently of ΔM or $M_{\tilde{P}}/M_{\tilde{\chi}}$. The distribution of $\cos\theta \equiv \hat{\beta}_S^{\text{CM}} \cdot p_{I,T}^S$ is shown in figure 15c.

Selection criteria defined with the compressed RJR observables result in signal regions used to investigate chargino pair production in final states with two leptons and missing transverse momentum. The requirements for the observable R_{ISR} are tuned depending on the mass ratio, and are more stringent than the chargino-neutralino associated study, due to the larger multiplicity of weakly interacting particles in the final state.

Figure 10 shows the distributions of R_{ISR} and $M_{\tilde{\chi}_1^\pm}$ for SM background and signal sample events passing the selection criteria in table 2. For the lowest mass splitting the requirement $R_{\text{ISR}} > 0.85$ is applied only for the sample $M_{\tilde{\chi}_1^\pm} = 100$ GeV, while for $\Delta M = 25$ GeV, one demands this criterion for three samples ($M_{\tilde{\chi}_1^\pm} \leq 150$ GeV).

The signal regions expressed by the selection criteria of the RJR observables defined in table 2 are applied to calculate projected sensitivities for compressed spectra signal samples. Figure 11 shows the value of Z_{Bi} , the binomial score representing the significance of a given signal, expressed in standard deviations, in the presence of a background hypothesis, at $\sqrt{s} = 14$ TeV for an integrated luminosity of 3000 fb^{-1} . One considers a systematic uncertainty of 20% for the overall Standard Model background: a compromise between a large data sample projection and stringent selection criteria assumed to suppress the individual background yields. Exploiting the RJR technique, one can set limits for the compressed chargino pair production topology at the high luminosity LHC14, with masses ~ 150 GeV being excluded in the best scenarios.

Figure 10. Distributions of R_{ISR} for signal and BG events passing the selection criteria in table 2 column 1 (a) and of $M_{\tilde{\chi}_1^\pm}$, with the requirements in column 2 and $R_{\text{ISR}} > 0.85$ (b).

Figure 11. Projected Z_{Bi} for chargino pair production in the compressed region ($15 \text{ GeV} \leq \Delta M \leq 75 \text{ GeV}$) at $\sqrt{s} = 14 \text{ TeV}$ assuming a systematic uncertainty of 20% for the SM background, and for an integrated luminosity of 3000 fb^{-1} .

4 Conclusions

We have introduced an original approach to searches for compressed electroweakinos based on the imposition of the decay trees as in figures 1 and 8 for the interpretation of reconstructed events, using the Recursive Jigsaw Reconstruction technique.

Putative wino-like $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ could be discovered at the LHC14 with masses $M_{\tilde{\chi}_1^\pm} = M_{\tilde{\chi}_2^0} > 150 \text{ GeV}$, for a large portion of the samples investigated ($15 \text{ GeV} \lesssim \Delta M \lesssim 50 \text{ GeV}$), assuming an integrated luminosity of 300 fb^{-1} , and leveraging only *transverse* observables. The RJR technique is sensitive to the extremely challenging chargino pair topology sce-

narios in the compressed regime. A strategy based on several experimental observables has been used to reduce the W^+W^- and the other main background yields due to the necessity of requiring jets in the final state to be associated with the ISR-system. A potential 95% confidence level exclusion limit can be obtained for an assumed dataset of 3 ab^{-1} , assuming a 20% of systematic uncertainty, for sample spectra with $\Delta M \lesssim 50\text{ GeV}$.

For both the topologies, the signal yields in the extreme compressed scenarios can benefit from an improvement in the efficiencies of the detector in the reconstruction of low transverse momentum leptons ($< 10\text{ GeV}$). On the other hand, for large mass splittings ($\Delta M \gtrsim M_Z$), the bulk analysis should be preferred to a compressed investigation, while for intermediate scenarios ($50\text{ GeV} \lesssim \Delta M \lesssim M_Z$), one can exploit the complementarity of observables based on a reconstruction of the event with or without the ISR-system and include cases with vector bosons decaying hadronically.

The method is expected to have still more impact in the cases of final state topologies with larger lepton multiplicity: pair production of charginos and/or neutralinos with slepton mediated decays. The RJR technique can be extended to these studies and to the pair production of heavy neutralinos in final states with four leptons, exploiting the simplified tree in figure 1, with a modification in the assignment of the objects in the case of sleptons of the third generation.

The results from the simplified models investigated in this work can be partially reinterpreted assuming different compositions for the electroweakinos. The method can be applied for higgsino-dominated charginos and neutralinos, with the latter decaying via an off-shell SM Higgs boson, requiring two b -jets and one lepton in the V-system. When decay modes via off-shell gauge bosons are dominant, the comparison would be straightforward. In particular, for chargino pair production with a mixed higgsino-wino nature, one can simply re-weight the signal yields with the appropriate cross sections: typically, the contributions from off-shell charged Higgs or other sparticles can be neglected since $M_S, M_{H^\pm} \gg M_W$ in most SUSY models.

A Selection criteria for the individual SM backgrounds and $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ samples

Figure 12. Two-dimensional distribution of $M^{\tilde{\chi}^\pm}$ as a function of R_{ISR} for the Standard Model V +jets background (a) and the signal sample $M_{\tilde{\chi}_1^\pm} = 200$ GeV, $M_{\tilde{\chi}_1^0} = 150$ GeV (b), and distribution of $M^{\tilde{\chi}^\pm}$ (c), for the events expected per bin for an integrated luminosity of 3 ab^{-1} at $\sqrt{s} = 14 \text{ TeV}$ satisfying the preselection criteria.

Figure 13. Two-dimensional distribution of N_{jet}^{ISR} as a function of R_{ISR} for the Standard Model $t\bar{t}$ background (a) and the signal samples $M_{\tilde{\chi}_1^\pm} = 100, 200$ GeV and $M_{\tilde{\chi}_1^0} = 75, 150$ GeV ((b) and (c)). We impose preselection criteria and $M^{\tilde{\chi}^\pm} > 24$ GeV.

Figure 14. Distribution of $\Delta\phi_{\ell+,1}$ for Standard Model $t + X$ background and signal events passing preselection criteria and the additional requirements $M^{\tilde{\chi}^\pm} > 24$ GeV and $N_{jet}^{ISR} = 1$ (a). Two-dimensional distribution of the opening angles between the leptons and the I-system for the $t\bar{t}$ background (b) and the signal sample $M_{\tilde{\chi}_1^\pm} = 200$ GeV and $M_{\tilde{\chi}_1^0} = 150$ GeV (c), imposing $R_{ISR} > 0.6$.

Figure 15. Distributions of angular RJR observables for signal samples and diboson Standard Model background, for events passing preselection criteria and the additional requirements $M_{\tilde{\chi}^\pm} > 24$ GeV, $N_{\text{jet}}^{\text{ISR}} = 1$, $R_{\text{ISR}} > 0.6$ and $\Delta\phi_{\ell^+,I} + \Delta\phi_{\ell^-,I} < 2$.

B Cut-flow for the $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ analysis

Selection Criteria	B	S_1	S_2
Preselection	125000	699	170
$N_{b\text{-jet}}^{\text{ISR}} = 0$	113000	698	170
$p_{\text{ISR},T}^{\text{CM}} > 50$ GeV	83900	612	148
$\Delta\phi_{\text{CM},I} < 1$	33800	374	88
$0.85 < R_{\text{ISR}} < 1$, 3SF leptons	1170	66	20
$0.85 < R_{\text{ISR}} < 1$ and $M_T^V < 100$ GeV, 2SF leptons	367	54	16
3SFL: $M_T^V < 65$ GeV, or 2SFL: $M_{\ell^+\ell^-} < 35$ GeV ($M_T^V < 100$ GeV)	257	100	31
$\Delta\phi_{\text{ISR},I} > 3$	43	65	23
$N_{\text{jet}}^{\text{ISR}} < 4$	35	58	20

Table 3. Cut-flow for the total SM background (B) and the two benchmark signal samples $M_{\tilde{\chi}_1^\pm} = M_{\tilde{\chi}_2^0} = 200$ GeV (S_1) and $M_{\tilde{\chi}_1^\pm} = M_{\tilde{\chi}_2^0} = 300$ GeV (S_2), with $\Delta M = 35$ GeV, at the LHC with $\sqrt{s} = 14$ TeV and for $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$. The ordering in figure 16 corresponds to apply the selection criteria in this table. The number of expected signal and background events resulting from each selection requirement is displayed up to three significant figures.

Figure 16. Diagram-flow for the RJR analysis of $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 + \text{jets}$, ($\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0$), ($\tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0$) in trilepton (electrons and muons) final states. The distributions show the number of expected Standard Model background and two benchmark compressed ($\Delta M = 35 \text{ GeV}$) signal sample events passing the selection criteria accumulated, and with the previous selection requirement plotted. Figure 16e (16f) refers to final states with three (two) same flavor leptons.

C Cut-flow for the $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ analysis

Figure 17. Diagram-flow for the RJR analysis of $pp \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- + \text{jets}$, ($\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0$), in final states with two opposite sign leptons (electrons and muons). The distributions show the number of expected Standard Model background and two compressed ($\Delta M = 25 \text{ GeV}$) signal sample events passing the selection criteria accumulated, and with the previous selection requirement plotted.

Selection Criteria	B	S_1	S_2
Preselection and $M^V < 50$ GeV	1.27×10^7	33900	8350
$M_{\tilde{\chi}_1^\pm} > 24$ GeV	2.78×10^6	11900	3920
$\Delta\phi_{\ell^+,I} < 2$	1.52×10^6	9190	2920
$\Delta\phi_{\ell^+,I} + \Delta\phi_{\ell^-,I} < 2$	240000	2270	658
$0.85 < R_{\text{ISR}} < 1$	26700	1490	511
$\cos\theta > 0.85$	6380	577	196
$N_{\text{jet}}^{\text{ISR}} = 1$	1020	154	54
$\Delta\phi_{\text{ISR},I} > 3.1$	610	103	35
$\Delta\phi_{\text{CM},I} < 0.5$	74	65	19

Table 4. Cut-flow for the total SM background (B) and the two signal samples $M_{\tilde{\chi}_1^+} = M_{\tilde{\chi}_1^-} = 125$ GeV (S_1) and $M_{\tilde{\chi}_1^\pm} = 200$ GeV (S_2), with $\Delta M = 25$ GeV, at the LHC with $\sqrt{s} = 14$ TeV and for $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$. Preselection criteria include two opposite sign leptons with $p_T^{\text{lep}} > 10$ GeV, $N_{b\text{-jet}}^{\text{ISR}} = 0$, $N_{\tau\text{-jet}}^{\text{ISR}} = 0$, $N_{\text{fat-jet}}^{\text{ISR}} = 0$, $\cancel{E}_T > 50$ GeV and $p_{\text{ISR},T}^{\text{CM}} > 50$ GeV. The ordering in figure 17 corresponds to apply the selection criteria in this table. The number of expected signal and background events resulting from each selection requirement is displayed up to three significant figures. A more stringent criterion ($0.9 < R_{\text{ISR}} < 1$) is imposed on the sample S_2 for the computation of Z_{Bi} .

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