Cilt 10, Sayı 2, Sayfa 290-294, 2021 Volume 10, Issue 2, Page 290-294, 2021

Araştırma Makalesi https://doi.org/10.46810/tdfd.1019096 Research Article

Türk Doğa ve Fen Dergisi
Turkish Journal of Nature and Science
www.dergipark.gov.tr/tdfd

Probing Compressed Slepton Production at Future Large Hadron Collider

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(Alınış: 04.11.2021, Kabul: 20.11.2021, Online Yayınlanma: 31.12.2021)

Keywords
SUSY,
LHC,
33 TeV

Abstract: Various supersymmetry searches are carried out at the Large Hadron Collider (LHC) at CERN. While some searches have focused on the color sector, others focused on electroweak production of charginos-neutralinos and sleptons. Since no sign of supersymmetry has yet to be found, limits are set on the masses of the supersymmetric particles. In this phenomenological study, we probe direct slepton signal production in compressed mass spectra scenario at the potential future proton-proton collider operating at a center of mass energy of 33 TeV. We show that slepton signal with masses up to 270 GeV can be discovered at the future hadron collider with the data corresponding to 100 fb^{-1} integrated luminosity when $\Delta M = 5$ GeV.

Büyük Hadron Çarpıştırıcısında Slepton Sinyalinin Küçük Kütle Farkı Durumunda İncelenmesi

Anahtar Kelimeler
SÜSİ,
BHÇ,
33 TeV

Öz: CERN'deki Büyük Hadron Çarpıştırıcısı'ndaki (BHÇ) deneylerden toplanan verilerle süpersimetri izi aranmaktadır. Araştırmalardan bazıları renkli süpersimetrik parçacıklara odaklanırken, bazıları ise chargino-nötralino veya sleptonların elektrozayıf üretimine odaklanmışlardır. Şu ana kadar yapılan deneysel araştırmalarda süpersimetrik parçacık izine rastlanılmadığından, bu parçacıkların kütleleri üzerine sınırlamalar getirilmiştir. Bu fenomenolojik çalışmada, 33 TeV'lik Kütle Merkezi (K.M.) enerjisinde proton-proton çarpıştırıcısında slepton sinyali incelenmiş ve 100 fb^{-1} ışıklılığa karşılık gelen verilerle, en hafif süpersimetrik parçacık ile slepton arasındaki kütle farkının çok küçük olduğu durumda ($\Delta M = 5$ GeV), 270 GeV'ye kadar kütleye sahip slepton sinyalinin keşfedilebileceği gösterilmiştir.

1. INTRODUCTION

Standard Model (SM) of particle physics is one of the best theories that humankind has achieved so far. However, it is not considered a complete theory for a few reasons, some of which are that it is unable to answer the Higgs hierarchy problem and the existence of the dark matter whose presence is proved by the works [1–3]. However, the supersymmetric extension of the standard model (SUSY), predicting a superpartner for every corresponding particle in the SM, has the ability to solve the hierarchy problem in Higgs mass, and unify three interactions into a single one in addition to having a dark matter candidate.

Studies for searching supersymmetric particles are being carried out by CMS and ATLAS collaborations at the LHC. Both experiments put limits on the masses of strongly produced colored supersymmetric particles, and their masses are excluded below 2 TeV [4–12]. However, limits on the electroweakly produced charginos-neutralinos and sleptons are less constrained as these particles suffer from smaller production cross section in a hadron collider.

Directly produced sleptons are searched for by CMS and ATLAS experiments at both 8 and 13 TeV [13–17] in the final states with di-leptons and the lightest supersymmetric particle (LSP). Since LSP leaves no trace in the detector, it contributes to missing energy (E_T^{miss}) an important discriminator between SUSY signal and backgrounds in SUSY searches. Slepton signal production was also probed in phenomenology works in final states with E_T^{miss}, di-lepton and an initial state radiation (ISR jet) at 14 TeV collision energy, assuming the mass difference between slepton and LSP are $\Delta M \leq 20$ GeV and $\Delta M \leq 60$ GeV [18,19]. Ref. [18] was able to reach 5σ discovery for left-handed sleptons of ≈ 150 GeV with an integrated luminosity of 100 fb^{-1}. Using the search strategy of Ref. [19], it is shown that 4.7σ with 300 fb^{-1} data could be obtained for $m_{\tilde{\mu}} = 110$ GeV in the case of $\Delta M = 60$ GeV. In another study on slepton production via vector boson fusion topology, $3-6\sigma$ is obtained for slepton mass range 115-135 GeV and mass splittings of 5-15 GeV [20].

We probe slepton pair production from the proton-proton (pp) collisions (depicted in Figure 1) at 33 TeV at a potential future hadron collider called HE-LHC. Results are presented in the context of the R-parity conserving minimal supersymmetric extension of the SM (MSSM) [21,22]. We assume that neutralino ($\tilde{\chi}_1^0$) is LSP and purely Bino. In order to obtain correct relic density [23] LSP is assumed to be almost mass degenerate with slepton.

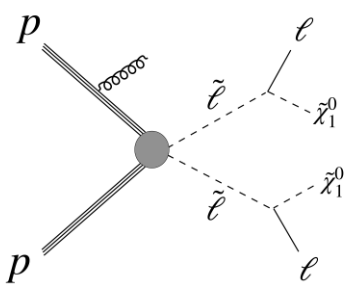

Figure 1. Slepton pair production along with an ISR jet coming from one of the incident partons.

2. ANALYSIS STRATEGY

The signal we probe in this analysis is the production of a pair of left/right-handed selectrons ($\tilde{e}$) or smuon ($\tilde{\mu}$) pair, which are produced from Z^* or γ^* exchange from quark anti-quark/gluon-quark pair, along with a single additional jet emitted from one of the incident partons. Left and right-handed selectrons and smuons are assummed to be mass degenerate. When the slepton pair is produced, both sleptons decays to LSP and the same flavor leptons, which are expected to be soft products in the case where the mass difference between slepton and LSP is small, called compressed mass spectra scenario. In the compressed scenario, we face the difficulty of reconstruction of leptons as they are most likely to be soft, and consequently, they are indistinguishable from the SM process $\bar{q}q \to \gamma^*/Z^* \to \bar{l}l$. In order to overcome the low acceptance due to reconstruction of the soft leptons, we require a highly energetic ISR jet, which will recoil against the sleptons and create a boost in transverse momentum (p_T) of pair produced sleptons as well as in their decay products of same flavor opposite sign (SFOS) leptons and $\tilde{\chi}_1^0$ pair. Hence, our signal is characterized by the existence of one hard jet, significant amount of missing energy, coming from LSPs, and SFOS lepton pair in the final state.

The major Standard Model backgrounds that have a similar topology as our signal are $t\bar{t}$, $VV + jet$ and $Z + jets$. Signals and all the SM backgrounds are generated with MadGraph_aMC@NLO version 2.6.7 [24] then pushed into Pythia 6 [25] for parton showering and hadronization, which is followed by detector simulation with Delphes 3 [26] using default delphes card prepared for HE-LHC [27]. While single vector backgrounds are simulated up to four partons, all other backgrounds and signal samples are generated up to two partons. Due to computational difficulties, some of the samples with higher production cross sections and higher jet multiplicity, such as $\bar{t}t$ and $Z + jets$ are generated ≈ 20 and 30 million respectively. MLM scheme [28] is performed to avoid double counting. Parameter cards used in Madgraph for signal generation are produced with the SUSY spectrum generator called SUSY-HIT [29].

Results presented here are for the signal mass point of $m_{\tilde{l}} = 235$ GeV with $\Delta M = 5$ GeV; however, we scanned heavier slepton masses of $m_{\tilde{l}} = 245, 250, 260$ and 270 GeV for the cases of $\Delta M = 3, 5$ GeV. Event selection criteria that are global to all mass splittings are shown below. Residual cross sections after applying each cut for both SM backgrounds and the signal are shown in Table 1.

1. Veto on tagged hadronically decaying τ
2. We require two SFOS leptons with $p_T > 7$ GeV and $|\eta| < 2.4$
3. Veto events with tagged b-jet with $p_T > 30$ and $|\eta| < 2.4$ GeV to reduce any contribution from $t\bar{t}$ background
4. Require only one hard jet with $p_T > 180$ GeV and reject any events with additional jets having $p_T > 30$ GeV.
5. Require $E_T^{miss} > 180$ GeV. Along with high jet p_T requirement, this requirement will reduce significant amount of the remaining $t\bar{t}$ as well as Z background.
6. Z-veto (i.e., rejects events with $81 \text{ GeV} < M_{ll} < 101$ GeV)
7. $\cos\theta^*_{l_1,l_2} < 0.5$ applied. It is introduced in Ref. [30], applied in Ref. [31], and is effective to distinguish spin-0 parent particles from spin-1, which also yields the same final products as in slepton decay.
8. Upper cut on scalar sum of the p_T of both leptons ($p_{T_{l_1}} + p_{T_{l_2}} < 50$ GeV for $\Delta M = 5$ GeV, $p_{T_{l_1}} + p_{T_{l_2}} < 35$ for $\Delta M = 3$ GeV)
9. As the requirement of a highly energetic jet creates a boost in slepton or, in other words in LSPs, decay products of sleptons, E_T^{miss} and jet will be back-to-back in compressed scenario. Thus, $\Delta\Phi(\text{Jet}, E_T^{miss}) > 0.95$ requirement will be beneficial to reduce backgrounds while keeping a large amount of the signal.
10. Along with E_T^{miss}, both leptons will recoil against ISR jet. Thus, a lower cut of 0.65 on ϕ difference between jet and vector sum of 1st and 2nd leptons'

momentum ($\Delta\Phi(\mathrm{Jet}, l_1 l_2) > 0.65$) will help to eliminate backgrounds as well.

11. Upper cut on mass difference between kinematic variable, stransverse mass m_{T2} [32,33] and trial mass, for given LSP mass. m_{T2} is used to estimate the minimum mass of the mother particle (slepton) from the kinematics of the visible and invisible decay products. In order to calculate the variable, we make use of the bisection code provided by the authors of reference [34]. Masses of each mother and daughter particles are assumed to be equal. The code requires transverse momentum of visible particles, missing transverse momentum, and masses of LSP's as input.

Table 1. Residual cross section (fb) for backgrounds and signal sample after applying each cut given 1-11.

Selections	$t\bar{t}$ + jets	ZZ + jets	WZ + jets	WW + jets	Z + jets	S^{235}_{230}
Initial	3919650.00	40154.80	149999.00	308871.00	137857000.00	129.72
τ Veto	3562280.00	38706.20	143452.00	296032.00	136270000.00	128.74
2OSSF	44919.70	1571.05	2767.32	2527.33	2462960.00	10.58
b-jet Veto	13190.2	1423.38	2670.50	2497.93	2453960.00	10.46
Jet $p_T > 180$ GeV	65.14	8.89	20.69	43.63	3382.10	0.34
MET >180 GeV	21.35	1.75	2.25	14.68	47.50	0.33
$81 < M_{ll} < 101$	18.43	0.07	0.65	13.18	9.50	0.32
$\cos\theta^{*}_{l_1,l_2} < 0.5$	10.40	0.05	0.41	8.93	9.50	0.26
$p_{T_{l_1}} + p_{T_{l_2}} < 50$	0.55	0.01	0.02	0.93	-	0.23
$\Delta\Phi(\mathrm{Jet}, \mathrm{MET})$	-	0.01	0.01	0.81	-	0.22
$\Delta\Phi(\mathrm{Jet}, \mathrm{l1l2})$	-	0.01	0.01	0.53	-	0.19
$m_{T2} - \mu < 5$	-	-	-	0.06	-	0.18

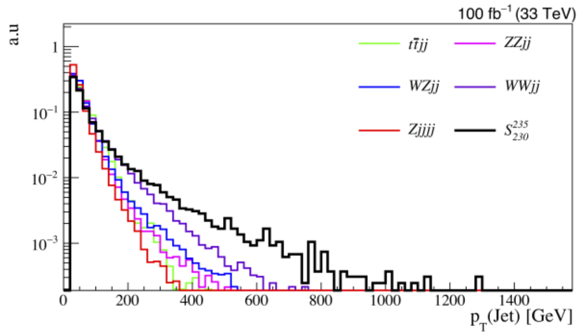

Figure 2. Leading jet p_T distribution, normalized to unity. Events shown in the plot have passed cuts 1-3.

Figure 2 shows leading jet transverse momentum from both SM backgrounds and signal event, a 235 GeV $\tilde{l}$ decaying to a 230 GeV LSP, after applying the first three event selection criteria. To get a transverse boost that will make the signal stand out against backgrounds, we require a lower cut of 180 GeV on jet p_T. For the mass point (235,230) GeV, jet p_T cut removes more than 99.8% of the backgrounds and increases the signal to background ratio by a factor of ≈ 23.

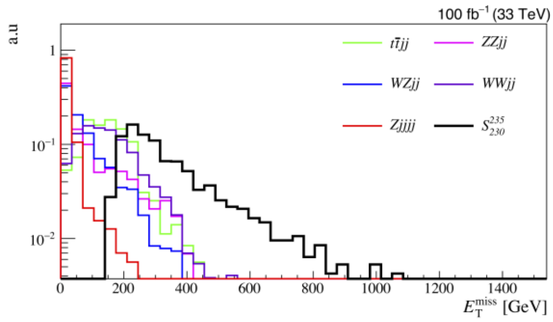

Figure 3. MET distribution, normalized to unity. Events surviving cuts 1-4 are plotted. As seen from the distribution, because of a highly energetic ISR jet requirement, events from signals are mostly populated beyond 180 GeV.

Requiring a highly energetic ISR jet will produce a large, anti-collimated missing transverse momentum as well. Hence, in addition to the 180 GeV cut on jet p_T, we also require a lower cut of 180 GeV on E_T^{miss}. As seen from Figure 3 and expected most of the signal events are located beyond 180 GeV. A cut of 180 GeV on missing energy increases signal significance ($S/\sqrt{B}$) by a factor of 6 and signal to background ratio by a factor of ≈ 39.
The transverse momentum of leptons is a measure of the mass difference between slepton and LSP and thus might be a useful variable to reduce the SM backgrounds. Therefore, we imposed an upper cut for the scalar sum of the leptons' transverse momentum. It is shown in Figure 4, the sum of the leptons' p_T for the signal sample separated from SM backgrounds around 80 GeV. However, with an upper cut of 50 GeV, the highest signal significance is obtained.

As $\approx 90\%$ of signal samples and 5% of SM backgrounds survive, signal significance and data to MC ratio increased by a factor of ≈ 3.9 and ~ 17, respectively.

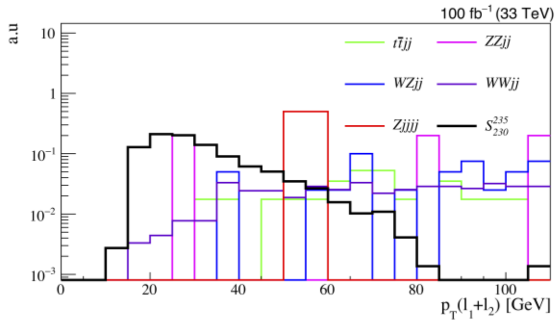

Figure 4. The scalar sum of the transverse momentum of leptons for both signal and background samples. Distribution normalized to unity. Events shown in the plot have passed cuts 1-7. As seen from the distribution, almost no events from signal survive beyond 80 GeV, although backgrounds are the most populated ones. An upper cut of 50 GeV gives the highest significance.

Although upper cut on the scalar sum of leptons' p_T helps reduce SM backgrounds, a direct measure of mass difference variable, $m_{T2} - \mu$ is better at separating the backgrounds from the signal. Figure 5 and Figure 6 show $m_{T2} - \mu$ distributions before and after applying an upper cut of 5 GeV on the $m_{T2} - \mu$ variable. As seen from Figure 5, signal events are located mostly below 5 GeV, whereas SM backgrounds populated beyond 5 GeV. Therefore, applying an upper cut of 5 GeV (for $\Delta M = 3$ GeV cases, backgrounds and signals are mostly separated with an upper cut of 3 GeV) dramatically increases the signal background ratio from 0.35 to ≈ 3.0 and lets the signal significance reach close to 7.4σ.

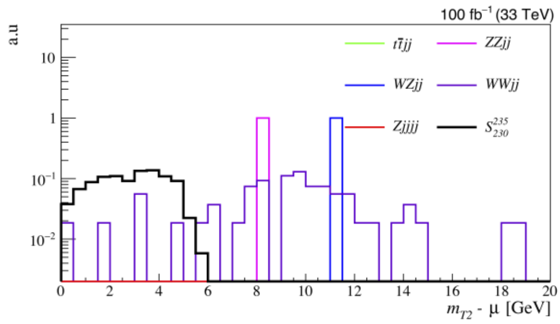

Figure 5. $m_{T2} - \mu$ distribution for backgrounds and signal sample after passing the cuts 1-10. As expected, backgrounds are mostly distributed beyond 5 GeV for the case of $\Delta M = 5$ GeV

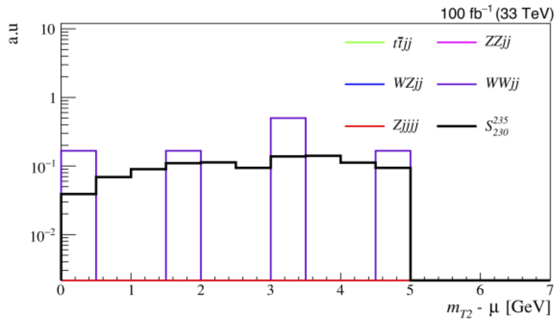

Figure 6. $m_{T2} - \mu$ distribution showing both signal and background events after passing all the cuts 1-11.

3. CONCLUSION

Pair production of slepton signal at potential future pp collider colliding protons heads-on at $\sqrt{s} = 33$ TeV is probed. The signal events include mass degenerate right/left-handed selectrons and smuons. Branching ratio for the process $\tilde{l} \rightarrow l\,\widetilde{\chi_1^0}$ is fixed to 100%. To optimize the kinematic parameters, separating signals from backgrounds, we checked signal significance and signal to background ratio at every single step. With the optimum parameters, we found that, $m_{\tilde{l}} \approx 235$ GeV can be reached at the future collider with close to 7.4σ discovery in the case where mass difference is 5 GeV (see Figure 7). These selection criteria remain effective for larger masses of choice up to 270 GeV for $\Delta M = 5$ GeV.

Although we assumed 100 fb^{-1} integrated luminosity, a better significance could be obtained with higher luminosity.

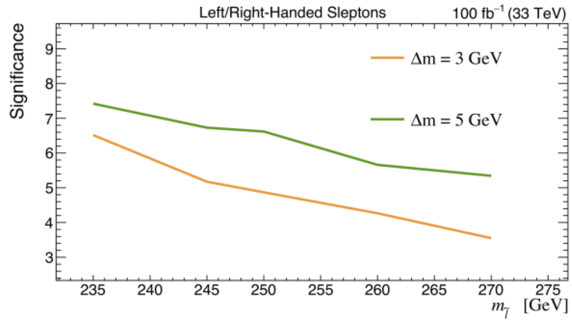

Figure 7. Slepton mass as a function of significance ($S/\sqrt{B}$) for $\Delta M = 3$ and 5 GeV.

Acknowledgement

This study was supported by Mehmet Akif Ersoy University Scientific Research Projects Unit. Project Number:0669-YL-20. Computing resources used in this work were provided by the National Center for High Performance Computing of Turkey (UHeM) under grant number 1008362020.

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