Searches for Dark Matter at the LHC in forward proton mode

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We analyze in detail the LHC prospects at the center-of-mass energy of 14 TeV for charged electroweakino searches, decaying to leptons, in compressed supersymmetry scenarios, via exclusive photon-initiated pair production. This provides a potentially increased sensitivity in comparison to inclusive channels, where the background is often overwhelming. We pay particular attention to the challenges that such searches would face in the hostile high pile–up environment of the LHC, giving close consideration to the backgrounds that will be present. The signal we focus on is the exclusive production of same-flavour muon and electron pairs, with missing energy in the final state, and with two outgoing intact protons registered by the dedicated forward proton detectors installed in association with ATLAS and CMS. We present results for slepton masses of 120–300 GeV and slepton-neutralino mass splitting of 10-20 GeV, and find that the relevant backgrounds can be controlled to the level of the expected signal yields. The most significant such backgrounds are due to semi-exclusive lepton pair production at lower masses, with a proton produced in the initial proton dissociation system registering in the forward detectors, and from the coincidence of forward protons produced in pile-up events with an inclusive central event that mimics the signal. We also outline a range of potential methods to further suppress these backgrounds as well as to enlarge the signal yields.

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1. Introduction

This text describes only the main points of the analysis which has been published in Ref. [1] (for details and references, see this paper).

One of the main goals of the physics program at the LHC and future colliders is the search for beyond the Standard Model (BSM) physics. A possibility that has received significant recent attention in the context of the LHC and future collider searches is the electroweak pair production of R-parity conserving states in compressed mass scenarios of supersymmetry (SUSY). That is, where the mass difference between the heavier state (e.g. the chargino, $\widetilde{\chi}^{\pm}$, or slepton, $\tilde{l}(g)$) and the Lightest SUSY Particle (LSP) $\widetilde{\chi}_1^0$ is small, see references in Ref. [1]. Searches in the compressed mass region via standard inclusive channels are experimentally very challenging, in particular because the SM WW background produces a very similar final state and the visible decay products have low momenta and therefore often do not pass detector acceptance thresholds. In order to trigger on such events, generally the presence of an additional jet or photon due to initial state radiation is required, providing the final-state particles with a boost in the transverse plane, and thus generating a large missing transverse momentum.

The potential to search for these comparatively light charged SUSY particles via photon–initiated production in hadron collisions has been widely discussed over the past few decades [2, 3, 4, 5, 6]. One clear benefit is its model independence, in sharp contrast to many other reactions. That is, the production cross sections are directly predicted in terms of the electric charges of the relevant states. Now, the development of the forward proton detectors (FPD) at the LHC allows us to perform a wide program of such searches [7, 8]. In particular, dedicated AFP [9, 10] and PPS [11] FPDs have recently been installed in association with both ATLAS and CMS, respectively. The purpose of these near-beam detectors is to measure intact protons arising at small angles, giving access to a wide range of Central Exclusive Production (CEP) processes

$$pp \rightarrow p + X + p \,, \tag{1.1}$$

where the plus sign indicates the presence of the Large Rapidity Gaps (LRG) between the produced state and outgoing protons. The experimental signature for the CEP of electroweakinos is then the presence of two very forward protons that are detected in the FPD and two leptons from the slepton $\tilde{l}(g) \rightarrow l + \widetilde{\chi}^0$ decay whose production vertex is indistinguishable from the primary vertex measured in the central detector. The well–defined initial state and presence of the tagged outgoing protons provides a unique handle, completely absent in the inclusive case, that is able to greatly increase the discovery potential.

In Ref. [1] we studied in detail the LHC prospects for searching for such exclusive slepton pair production in compressed mass scenarios at the center-of-mass energy of $\sqrt{s} = 14$ TeV. We performed for the first time a systematic analysis of the various challenges and sources of backgrounds that such studies must deal with, a serious consideration of which is essential to assess the potential of these exclusive channels. In particular, as well as the irreducible exclusive WW background, we also consider the reducible backgrounds from semi–exclusive lepton pair production, where a proton produced in the initial proton dissociation registers in the FPDs, and the pile–up background where two soft inelastic events coincide with an inelastic lepton pair production event.

Di–lepton	$5 < p_{T,l_1,l_2} < 40$ GeV	$|\eta_{l_1,l_2}| < 2.5 \ (4.0)$
	$\mathrm{Aco} \equiv 1 - |\Delta\phi_{l_1 l_2}|/\pi > 0.13 \ (0.095)$	$2 < m_{l_1 l_2} < 40$ GeV
	$\Delta R(l_1, l_2) > 0.3$	$|\eta_{l_1} - \eta_{l_2}| < 2.3$
	$\bar{\eta} \equiv |\eta_{l_1} + \eta_{l_2}|/2 < 1.0$	$||\vec{p_{Tl_1}}| - |\vec{p_{Tl_2}}|| > 1.5$ GeV
	$W_{\mathrm{miss}} > 200$ GeV	
FPD	$0.02 < \xi_{1,2} < 0.15$	$p_{T,\mathrm{proton}} < 0.35$ GeV
No–charge	No hadronic activity	z-veto

Table 1: Cuts used in this analysis.

2. Signal cross section and selection cuts

We consider the direct pair production of smuons and selectrons $\tilde{l}_{L,R}$ ($l = e, \mu$) only, where the subscripts L, R denote the left- and right-handed partner of the electron or muon. The four sleptons are assumed to be mass degenerate and to decay with a 100% branching ratio into the corresponding SM partner lepton and $\widetilde{\chi}_1^0$ neutralino. We take four slepton mass points, 120, 200, 250 and 300 GeV, with in each case a mass splitting of $\Delta M = M_{\tilde{l}} - M_{\widetilde{\chi}_1^0} = 10$ GeV and 20 GeV. For all exclusive processes below, we use the SUPERCHIC 2.07 Monte Carlo (MC) generator [12]. All applied cuts in this analysis are summarized in table 1 and can be divided into three classes, namely: cuts on the detected protons in the FPDs ('FPD cuts'); requiring no other additional charged particles in the central detector ('no-charged cuts'); and the selection applied to the lepton pair ('di–leptons cuts').

3. Backgrounds

The predicted signal production cross sections are small, being ~ 0.1 fb or less after accounting for all relevant cuts and efficiencies, depending on the slepton mass in the experimentally allowed region. Therefore it is essential to collect these events at nominal LHC luminosities and for any backgrounds to be under very good control. We have considered: the irreducible photon–initiated WW background; the reducible background from the semi–exclusive photon–initiated production of lepton pairs and QCD–initiated production of gluon and c–quark jets (via leptonic decays of hadrons produced in hadronization) at low mass, where a proton produced in the initial proton dissociation registers in the forward proton detectors; the reducible pile–up background where (dominantly) two independent single–diffractive events coincide with an inelastic lepton pair production event. For the proton dissociation and pile–up backgrounds we have performed dedicated MC simulations, including most of relevant detector effects and efficiencies, in order to evaluate their impact as accurately as possible. To evaluate the effect of pile–up backgrounds we generate the dominant source of inclusive lepton production, due to non–diffractive (ND) jet production, with both PYTHIA 8.2 [13] and HERWIG 7.1 [14, 15].

We have found that requiring that the lepton pair lie in the signal $m_{ll} < 40$ GeV region, combined with further judicially chosen cuts on the lepton momenta leads to significant reductions in the background. The pile–up backgrounds are strongly reduced by the use of time-of-flight (ToF) subdetectors in the FPDs (cuts to suppress pile–up backgrounds in general are elaborated in Ref [16, 17]), as well as the aforementioned lepton cuts and a further cut on the proton transverse momentum. These also help to reduce the semi–exclusive backgrounds considerably.

4. Results

Event yields /	$\langle\mu\rangle_{PU}$		
$\mathscr{L} = 300 \text{ fb}^{-1}$	0	10	50
Excl. sleptons	0.6—2.9	0.5—2.4	0.3—1.4
Excl. l^+l^-	1.4	1.2	0.7
Excl. K^+K^-	~ 0	~ 0	~ 0
Excl. W^+W^-	0.7	0.6	0.3
Excl. $c\bar{c}$	~ 0	~ 0	~ 0
Excl. gg	~ 0	~ 0	~ 0
Incl. ND jets	$\sim 0/\sim 0$	0.1/0.1	1.8/2.4

Table 2: The event yields corresponding to an integrated luminosity of 300 fb^{-1} as a function of pile–up amount for the slepton signal and all considered backgrounds. All numbers correspond to the di–lepton mass range $2 < m_{ll} < 40$ GeV and lepton $p_T > 5$ GeV and a tracker coverage of $|\eta| < 2.5$. The ranges in the signal event yields illustrate the spread obtained from the entire studied slepton mass range: the lower value comes from the $M_{\tilde{l}} = 300$ GeV, the higher from the $M_{\tilde{l}} = 120$ GeV scenario.

We collect our results for the expected signal and background event yields in tables 2 and 3. Here, the former case corresponds to $|\eta| < 2.5$ (i.e. the current tracker coverage) while the latter corresponds to $|\eta| < 4.0$ (i.e. the tracker coverage for the Run III upgrade of ATLAS [18] and CMS [19]). To give a global picture, these results correspond to the full di–lepton mass range of $2 < m_{ll} < 40$ GeV, although information about individual lepton p_T ranges for processes where it is relevant can be found in tables 3, 4 and 5 of Ref [1]. In summary, we observe that in total 2–3 signal events for 300 fb^{-1} can be expected, with a $S/B \sim 1$. We note that PYTHIA 8.2 and HERWIG 7.1 give similar predictions for the contamination from the inclusive ND jets. There are however various ways to improve the S/B ratio. From the point of view of the phenomenological analysis presented here, the situation may be improved by cutting on the variable proposed in [6], namely the maximum kinematically allowed values of $m_{\tilde{\chi}}$ and $m_{\tilde{l}}$ assuming the signal decay chain. Following the approach of [6], we have checked that after applying the FPD acceptance and lepton

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Excl. l^+l^-	1.1	0.9	0.5
Excl. K^+K^-	~ 0	~ 0	~ 0
Excl. W^+W^-	0.6	0.5	0.3
Excl. $c\bar{c}$	~ 0	~ 0	~ 0
Excl. gg	~ 0	~ 0	~ 0
Incl. ND jets	$\sim 0/\sim 0$	0.03/0.05	0.6/0.7

Table 3: The same as in table 2 but for the enlarged tracker coverage $|\eta| < 4.0$.

p_T and η cuts, and requiring the maximum neutralino mass to be larger than 100 GeV (to be consistent with the $W_{\text{miss}} > 200$ GeV cut in table 1), the signal yields are increased by 50-80% depending on the mass configuration, while the WW background remains the same. We may also expect some reduction in the low mass dilepton SD and DD backgrounds, but in the absence of a full MC implementation this cannot currently be calculated.

Experimentally, the signal yield can be doubled by taking all di–lepton masses into account. This would, however, not only increase the background but also the average di–lepton mass itself and hence limit the possibility of estimating the unknown mass of the DM particle by measuring the central system mass via the FPDs. Another way to increase the signal yield would be to increase the lepton reconstruction efficiencies. The background contamination, in turn, could be lowered by rejecting events with a displaced vertex which can be done by restricting track longitudinal, z_0, and transverse, d_0, impact parameters to some small values, or by a cut on the so called pseudo-proper lifetime. Furthermore, as discussed above, both ATLAS and CMS are upgrading their trackers to cover the additional region $2.4 < |\eta| < 4$. Both are also considering adding timing detectors in these forward areas with resolution of about 30 ps [20, 21]. By getting this timing information we acquire another ToF rejection factor in addition to that shown in table 6 of Ref. [1].

5. Conclusions

We have discussed the prospects for searching for slepton pair production via leptonic decays in compressed mass scenarios at the LHC, via photon–initiated production. In this case the experimental signal is simple, comprising only four charged particles in the final state, namely two forward outgoing protons and two leptons in the central detector.

After accounting for all relevant effects, we find that the backgrounds from pile–up and semi–exclusive photon–initiated lepton pair production are expected to be of the same order as the signal, with the irreducible *WW* background being somewhat lower. We have also discussed a variety of ways in which this situation could be improved upon, with the potential for increased tracker acceptance combined with timing detectors at the HL–LHC being particularly promising. While a detailed study of the possibilities at the HL–LHC is beyond the scope of the current work, this provides a strong motivation for further work on this area, and for collecting data with tagged protons there. Certainly the main backgrounds are in principle reducible and therefore with further investigation we may be able to reduce these further.

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