# SEARCH FOR EWKINO PRODUCTION AND LONG-LIVED PARTICLES AT THE LHC

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The Large Hadron Collider has extended the reach of particle-physics experiments with a potential for discovery of new physics at the TeV scale and many searches have been carried out by both ATLAS and CMS. Searches for long-lived particles and electroweak ino production using 2012 LHC data have been carried by both ATLAS and CMS. The methodology of the searches (reconstruction techniques, background suppression, etc.) and the sensitivity of these searches are reviewed. Many models of physics beyond the Standard Model predict new particles with long lifetimes. Examples include Supersymmetry with R-parity violation, suppressed decays of the next-to-lightest Supersymmetric particle, or models with hidden sectors. The decay vertices of particles with lifetimes of order 10 ps to 10 ns can be efficiently identified by the ATLAS and CMS detectors. In addition, in quark and gluons collisions it is easy to produce coloured objects like gluinos and squarks, which decay typically to jets and MET, while the cross sections for Electroweak productions are smaller and the mass reach substantially reduced. These "ewkinos" decays typically produce many leptons and MET. The searches of these decays are generally based directly or indirectly on MET analyses.

## 1 Introduction

The standard model (SM) of particle physics has proven extremely successful, but despite its many successes still remains incomplete. SUSY [1] model represents a possible extension of the SM and solves many problems as the fine-tuning or the unification of the couplings.

However, the SUSY particle production cross section is tiny, compared to the total SM background production rate. Thus the challenge of searches for SUSY extensions is to distinguish the rare SUSY events on top of a huge background. This can be achieved in multileptonic signatures, namely final states with at least three leptons including electrons, muons and taus. Those signatures are often referred as the "Golden Channel" since its is a clean signature, clean in the sense that SM processes with three prompt leptons are rare, whereas it can be enhanced in many SUSY models. This note presents few searches with ATLAS and CMS detectors for the direct production of charginos and neutralinos decaying to a final state with three and four leptons (electrons or muons) and missing transverse momentum, the latter originating from the two undetected LSPs and the neutrinos.

In addition,the searches of long-lived particles are also presented.

### *1.1 Ewkino Production*

Many SUSY searches are motivated by the direct electroweak production of charginos, neutralinos, and sleptons. The corresponding final states do not necessarily contain much hadronic activity and thus may have eluded detection in other searches. This signature characterizes

SUSY models that describe the pair production of charginos $\tilde{\chi}^{\pm}$and neutralinos $\tilde{\chi}^{0}$, mixtures of the SUSY partners of the gauge and Higgs bosons, and of sleptons $\tilde{\ell}$, the SUSY partners of leptons. Depending on the mass spectrum, the charginos and neutralinos can have significant decay branching fractions to leptons or on-shell vector bosons, yielding multilepton final states. Similarly, slepton pair production gives rise to final states with leptons. In all these cases, two stable, lightest-SUSY-particle (LSP) dark matter candidates are produced, which escape without detection, leading to significant missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$ (if R-parity [2] is conserved). Neutrinos present in the final state yield additional $E_{\mathrm{T}}^{\mathrm{miss}}$.

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 Higgs and electroweak gauge bosons. These are the Higgsinos, and the winos, zino, and bino, collectively known as gauginos. Naturalness requires the lightest chargino and neutralino j (and third-generation squarks) to have masses in the hundreds of GeV range. In scenarios where squark and gluino masses are larger than a few TeV, the direct production of gauginos may be the dominant SUSY process at the LHC.

### *1.2 Long-lived Particle production*

New heavy particles with long lifetimes are predicted in many models of physics beyond the SM, such as hidden valley scenarios [3] or supersymmetry (SUSY) with gauge-mediated symmetry breaking (GMSB [4]) or anomaly-mediated symmetry breaking (AMSB [5]). These particles may be neutral and decay into SM and/or weakly interacting particles that escape detection.

Four possible examples are presented in this work: long-lived charginos in AMSB model with disappearing tracks (RPV models [6]), R-hadrons (eg. Split SUSY [7]), LSP gravitino in GMSB interactions, and Higgs decay to hidden sector neutral particles: leptonjets and displaced vertex.

## 2 Multi Leptons final state

In SUSY models isolated leptons are produced dominantly in the leptonic decay of the next to lightest neutralino ($\tilde{\chi}_2^0 \rightarrow \ell^+\ell^-\tilde{\chi}_1^0$) and the lightest chargino ($\tilde{\chi}_1^{\pm} \rightarrow \ell\nu\tilde{\chi}_1^0$ ). The simultaneous production of neutralinos and charginos with the subsequent decay to leptons leads to multileptonic signatures, whereas in the Standard Model prompt leptons results from boson decays ($W^{\pm}$, Z/$\gamma^*$) including top quark decays $t \rightarrow Wb$. The dominant irreducible background with three/four prompt leptons is formed by the di-boson production ($W^{\pm}$Z, ZZ). An additional dangerous background consists of dileptonic SM processes like Drell-Yan or $tt$ with the subsequent decay to leptons accompanied by so called fake leptons mimicking a multileptonic signature. Fake leptons are mainly leptons from heavy flavor decays in jets and false identification as prompt leptons.

### *2.1 Three Leptons Final State Analysis*

This analysis required selected events with exactly three signal leptons in the final state. The analysis strateges applied in the two experiments use different signal regions but defined by the same variables.

In ATLAS [8] three signal regions are then defined: two Z-depleted regions (SR1a and SR1b), with no SFOS (same-flavour-opposite-sign) pairs having invariant mass within 10 GeV of the nominal Z-boson mass; and a Z-enriched one (SR2), where at least one SFOS pair has an invariant mass within 10 GeV of the Z-boson mass. Events in SR1a and SR1b are further required to contain no b-tagged jets to suppress contributions from b-jet-rich background processes, where a lepton could originate from the decay of a heavy-flavor quark. The background predictions have been tested in various validation regions.

In CMS [9] the events are classified into exclusive search regions depending on their values of M($\ell^+\ell^-$), $E_{\mathrm{T}}^{\mathrm{miss}}$ and $M_T$. Events are required to have $E_{\mathrm{T}}^{\mathrm{miss}} > 50$ GeV and the SFOS dilepton mass has to be close to the Z mass. The different regions are defined using the following classification: the $M(\ell^+\ell^-)$ regions for SFOS dilepton pairs are [$M(\ell^+\ell^-) < 75$ GeV], [75 GeV $< M(\ell^+\ell^-) < 105$ GeV], and [105 GeV $< M(\ell^+\ell^-)$]. Further event classification is in $E_{\mathrm{T}}^{\mathrm{miss}}$ bins of [50,100], [100,150], [150,200], and [$> 200$] GeV. Finally, the $M_T$ regions are [<120], [120-160], and [>160] GeV.

### *2.2 Four Leptons Final State Analysis*

In CMS [9], the four leptons search represents an extension of the three leptons case where we have the production of ZZ events associated with neutralinos. For the ZZ signature, a specific gauge-mediated supersymmetry breaking (GMSB) Z-enriched higgsino model that enhances the ZZ + $E_{\mathrm{T}}^{\mathrm{miss}}$ final state has been considered. In addition, the sleptons are considererd too massive to participate, so that the branching fractions to vector bosons are 100%. The object selection criteria are the same as for the three leptons final state, requiring exactly four leptons.

In ATLAS [10], the four leptons final state are interpreted in term of R-Parity violation interactions. The LSPs ($\tilde{\chi}^0$) decay via RPV interactions leading to final states with 4 leptons and non-zero MET due to the presence of neutrinos.

In the ATLAS cut flow, the selected events must contain four or more signal leptons. The invariant mass of any same-flavour opposite-sign (SFOS) lepton pair, m(SFOS), must be above 12 GeV, otherwise the lepton pair is discarded to suppress background from low-mass resonances. Z-boson candidates are vetoed by removing events with pairs, triplets or quadruplets of leptons with an invariant mass inside the [81.2, 101.2] GeV interval. Lepton pairs and triplets considered for this Z-veto must contain a SFOS pair, while lepton quadruplets must consist of two SFOS pairs. Two signal regions are then defined with signal region with $E_{\mathrm{T}}^{\mathrm{miss}}$ >50 GeV (SR1), and one with effective mass $m_{eff}$ >300 GeV (SR2). SR1 is sensitive to scenarios where RPV LSP decays produce neutrinos in the final state, while SR2 targets models with large particle multiplicities, for example from sparticle cascade decays, and where $E_{\mathrm{T}}^{\mathrm{miss}}$ may be small.

## 3 Summary and Results on multi-leptons final state analyses

The results on the multi-leptons final state studies can be divided in three or four leptons searches. In the three leptons final state, no significant excess of events is found in any of the three ATLAS signal regions. Upper limits on the visible cross-section, defined as the production cross-section times acceptance times efficiency, of 1.3 fb are placed at 95% CL.

In the CMS four leptons analysis no excess above the Standard Model expectation is observed in six signal regions that are either enriched or depleted in Z-boson decays. Chargino and heavy neutralino masses are excluded up to 600 GeV if these particles decay through sleptons and up to 315 GeV if they decay via gauge bosons to a massless lightest neutralino. In ATLAS for the four leptons, the limits are placed on various R-parity violating simplified models, where the lightest supersymmetric particle ($\tilde{\chi}_1^0$) decays promptly to first and second-generation leptons. Charged-Winos are excluded up to a mass of 710 GeV, left-handed sleptons up to 450 GeV, sneutrinos up to 410 GeV and gluinos up to 1300 GeV.

## 4 Long-lived Particle Scenarios

### *4.1 Long-lived charginos in AMSB model*

The results presented, only for the ATLAS detector on 2011 data [11], are interpreted in the context of an R-parity violating supersymmetric scenario. The signature under consideration corresponds to the decay of the lightest supersymmetric particle, resulting in a muon and

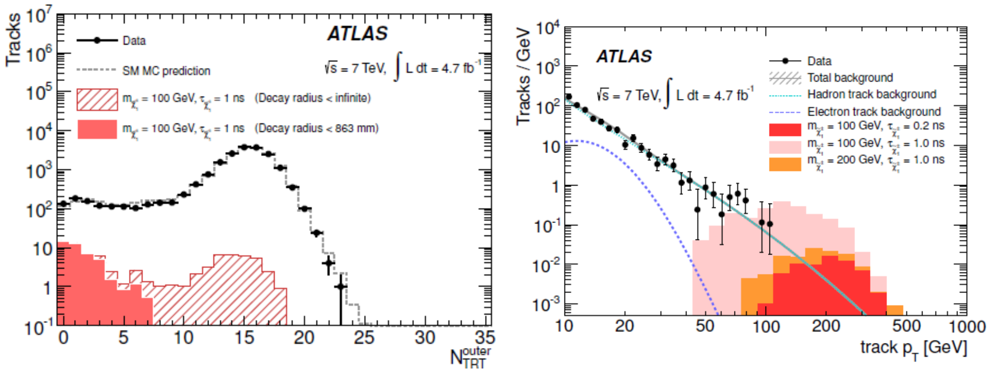


Figure 1: (Left Plot) The $N_{TRT}^{outer}$ distribution for data and signal events (m($\tilde{\chi}_1^{\pm}$)= 100 GeV, $\tau(\tilde{\chi}_1^{\pm})$= 1 ns) with the high-pT isolated track selection. The expectation from SM MC events, normalized to the number of observed events, is also shown. (Right Plot) The $p_{\rm T}$ distribution of candidate tracks. The solid circles show data and lines show background shapes obtained using the background-only fit. The contributions of two background components and the signal expectations are also shown (both plots from ATLAS paper [11]).

many high-pT charged tracks originating from a single displaced vertex (DV). Such scenario is anomaly-mediated supersymmetry with R-parity violation (RPV). The present (largely indirect) constraints on RPV couplings would allow the decay of the lightest supersymmetric particle as it traverses a particle detector at the LHC.

The selection cut flow is based on the number of hits in the Transition Radiation Tracker (TRT) and the $p_{\rm T}$ of the tracks. Figure 1 (left) shows the average number of hits per track, (right) shows the $p_{\rm T}$ spectrum for MC signal, backgrounds and 2011 data.

### *4.2 Long-lived gluinos in R-hadrons*

In this section the analysis strategy and the results for the R-hadrons searches is reported, the selection cut flow and the limits are referred to the CMS experiment [13].

Many extensions of the SM include heavy, long-lived, charged particles that have speed, v, less than the speed of light, c, and/or charge, Q, not equal to 1e. With lifetimes greater than a few nanoseconds, these particles can travel distances larger than the typical collider detector and appear stable (in analogy to the pion or kaon). These particles can be generically referred to as heavy stable charged particles (HSCPs) and can be singly, fractionally or multiply charged. If HSCPs additionally interact through the strong force and form bound states with SM quarks (or gluons) are called R-hadrons. R-hadrons can be charged or neutral. Strong interactions between the SM quarks and detector material increase energy loss and can lead to charge exchange, e.g. converting charged R-hadrons into neutral ones (and vice-versa). The analysis strategy is driven by the their higher rate of energy loss via ionization (dE/dx) and/or through their longer time-of-flight (TOF) to the outer detectors.

The analyses of HSCP candidates fall into multiple topologies and strategies: requiring tracks be reconstructed in both the inner silicon detectors and the muon system, referred to as the tracker+TOF analysis; only requiring tracks be reconstructed in the inner silicon detectors, the tracker-only analysis; only requiring tracks be reconstructed in the muon system, the muon-only analysis.

### *4.3 LSP gravitino in GMSB model*

Assuming R-parity is conserved, SUSY particles are produced in pairs and decay into SM particles (as well as other SUSY particles). In the chosen scenario, the neutralino $\tilde{\chi}^0$is the next-to-lightest supersymmetric particle and decays almost exclusively into a photon ($\gamma$) and a weakly interacting gravitino ($\tilde{G}$, the superpartner of the graviton). The $\tilde{G}$ is the lightest supersymmetric particle (LSP), and gives rise to a momentum imbalance in the transverse plane by leaving the detector without depositing energy. The dominant production mode of the $\tilde{\chi}^0$is through a pair of gluinos via the strong interaction decaying via cascades. The $\tilde{\chi}^0$is expected to be produced in association with high transverse momentum ($p_{\mathrm{T}}$) jets.

The analysis strategy exploites the capabilities of the ATLAS [14] and CMS [15] electromagnetic calorimeters to make precise measurements of the flight direction of photons, as well as the calorimeters excellent time resolution. The long-lived NLSP scenario introduces the possibility of a decay photon being produced after a finite delay and with a flight direction that does not point back to the primary vertex (PV) of the event.

### *4.4 Hidden sector neutral particles*

A specific model of a neutral long-lived, spinless, exotic particle X which has a nonzero branching fraction to dileptons is used in both the experiments. This scenario predicts up to two displaced dilepton vertices in the tracking volume per event. These neutral particles with large decay lengths and collimated final states represent, from an experimental point of view, a challenge both for the trigger and for the reconstruction capabilities of the detector. Collimated particles in the final state can be hard to disentangle due to the finite granularity of the detectors; moreover, in the absence of inner tracking detector information and a primary vertex constraint, it is difficult to reconstruct charged-particle tracks from decay vertices far from the interaction point (IP).

In the ATLAS study [16], the model consists of a Higgs boson decaying to a new hidden sector of particles which finally produce two sets of collimated muon pairs. Possible topological signatures of such extensions of the SM are lepton jets.These arise if light unstable particles with masses in the MeV to GeV range (for example dark photons, $\gamma_d$) reside in the hidden sector and decay predominantly to SM particles.

In the CMS analysis [17], the long-lived particle is a boson X, pair-produced in the decay of a (non-SM) Higgs boson, i.e. $H^0 \to 2X, X \to \ell^+\ell^-$, where the Higgs boson is produced through gluon-gluon fusion.

## 5 Summary and Results on long-lived particles analyses

The ATLAS analysis on long-lived particles in AMSB model explores chargino decays that result in tracks with few associated hits in the outer region of the tracking system. The transverse-momentum spectrum of candidate tracks is found to be consistent with the expectation from the Standard Model background processes (fewer than 0.06 background events are expected in the data sample of 4.4 fb$^{-1}$) and constraints on chargino properties are obtained. For $\Delta$M(chargino-neutralino) $\approx$ 160 (170) GeV the chargino mass is excluded up to 103 (85) GeV. Many different searches R-hadrons has been presented with CMS data at 7 and 8 TeV. Generally no significant excess is observed. Mass limits for gluinos, stops, staus, fractionally charged particles, and multiply charged particles are reported in Figure 2 (right).

In the non-pointing photons analysis ATLAS has shown a good agreement with SM events. The 95% CL exclusion limits for both the experiments are reported in Figure 2 (right), where from the upper limits a mass below 220 GeV and below $c\tau < 6000$ mm can be excluded for the $\tilde{\chi}^0$.

Concerning the Hidden model, in 1.9 fb$^{-1}$ of ATLAS sample no events consistent with this Higgs boson decay mode are observed. The observed data are consistent with the Standard Model background expectations. In CMS, limits are set on the $\sigma \times BR$ to $H \to \gamma_d\gamma_d + X$ as a function of the long-lived particle mean lifetime for m(H) = 100 GeV and 140 GeV. Assuming the SM production rate for a 140 GeV Higgs boson, its branching ratio to two hidden sector photons is found to be below 10%, at 95% CL, for hidden photon $c\tau$ in the range 7 mm $< c\tau <$ 82 mm.

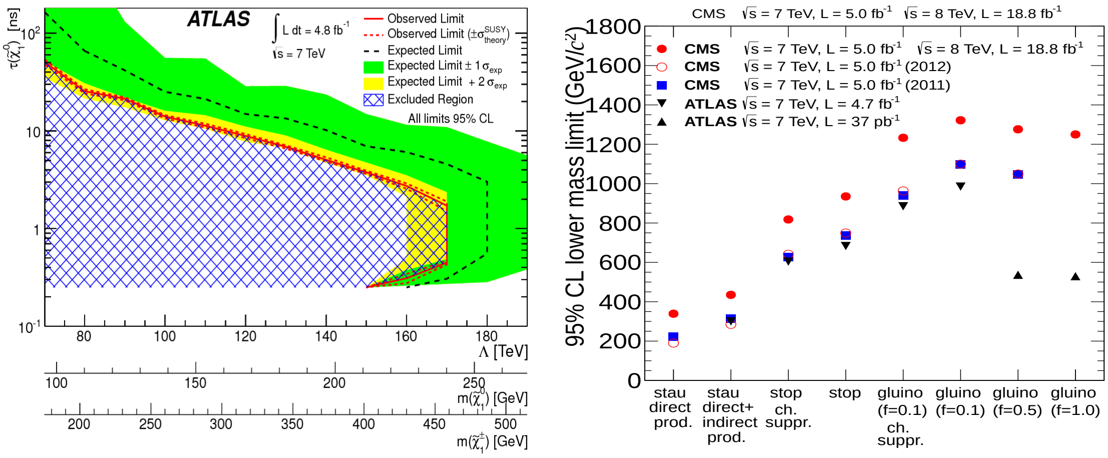


Figure 2: (Left Plot) ATLAS results [14]: the expected and observed limits in the plane of NLSP lifetime versus Lambda (and also versus the $\tilde{\chi}^0$or $\tilde{\chi}^{\pm}$masses). (Right Plot) Obtained mass lower limits at 95% C.L. on various R-hadrons models (on x-axis) compared with previously published results (CMS paper [13]).

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