Searches for long lived supersymmetric particles with the ATLAS detector

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Several supersymmetric extensions of the Standard Model predict the existence of new particles whose lifetime can be comparable or longer than the time of flight through a collider detector. The direct detection of these particles, or of their decays inside the detector, requires dedicated experimental techniques. This talk presents recent ATLAS searches, at the LHC, for supersymmetric particles with long lifetimes, performed with 20 fb^{-1} of $\sqrt{s} = 8$ TeV pp data. The results of searches for decays of gluinos, charginos or neutralinos inside the detector, as well as for the direct detection of long lived gluinos, squarks, charginos and sleptons are presented.

1 Introduction

Supersymmetry (SUSY), is a theoretically well-motivated candidate for physics beyond the Standard Model (SM). Long-lived particle signatures arise in SUSY in different ways. In R-parity violating SUSY, if the parameters λ_{ijk}, λ'_{ijk} or λ''_{ijk} in the super-potential [1,2] are small, the lightest SUSY particle (LSP) can have a long lifetime. In R-parity conserving SUSY, if the difference between the mass of the next-to-lightest SUSY particle (NLSP) and the LSP is small, of the order of 100 MeV as predicted by some models of anomaly-mediated SUSY breaking (AMSB) [3], the NLSP can also be long-lived. In Gauge Mediated SUSY Breaking (GMSB) [4,5,6,7,8,9], the NLSP is the $\tilde{\chi}_1^0$ which decays into either a Z boson or a γ and a graviton which is the LSP. If the neutralino is long-lived, and travels before decaying, the signature is either a displaced vertex (in case of Z decay) or a displaced and delayed γ. Within Split SUSY, gluino decay is suppressed by the high scalar mass. Long-lived gluinos then hadronize into heavy R-hadrons that decay at a detectable distance from their production point [10]. Unless otherwise stated, all results here are based on a data sample of 20.3 fb^{-1} collected at $\sqrt{s} = 8$ TeV of pp collisions at the ATLAS detector [11] at the LHC.

2 Search for massive, long-lived particles using multitrack displaced vertices or displaced lepton pairs

If a particle has a lifetime of order a few ns, it can decay inside the tracking detector, producing a vertex at a distance away from the primary vertex. Some of the processes under study include R-parity violating (RPV) scenarios, long-lived neutralinos in General Gauge Mediation (GGM) and a long-lived R-hadron in Split SUSY [12]. Two signatures are considered: a dilepton signature where the vertex is formed from to oppositely charged leptons and multi-track signature where the displaced vertex (DV) contains at least 5 charged-particle tracks [12].

The standard ATLAS tracking is optimised for tracks coming from the primary interaction point, with a requirement that the tracks transverse impact parameter (d_0) is less than 10 mm. In order to increase efficiency for secondary tracks, the silicon-seeded tracking algorithm was re-run with looser cuts on d_0 using "left-over" hits from the standard tracking. Vertices were discarded if they coincided with regions of dense detector material. This method is able to detect vertices upto 300 mm from the primary interaction point.

The main sources of background for this analysis, for the two signal regions, are low mass DVs that are crossed by an unrelated high-$p_{\rm T}$ track at a large angle (multi-track signal region) and two unrelated leptons crossing close enough for the vertexing method to combine (di-lepton signal region). These backgrounds are estimated using data driven methods of estimation which involve combining a track from one event with a track or vertex from a second event to calculate the probability of background vertex formation.

With no events observed in any signal region, upper-limits are set on the signal yields and production cross-sections as a function of the proper lifetime $c\tau$ and, for Split SUSY, limits are placed on the gluino mass vs. $c\tau$. These are presented in figure 1.

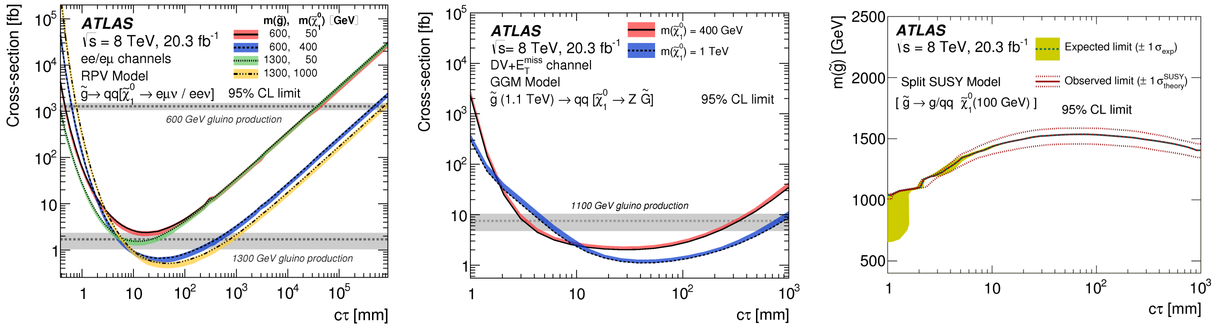

Figure 1 – 95% confidence-level upper limits, obtained from: (left) the dilepton search, on the production cross-section for a pair of gluinos that decay into two quarks and a long-lived $\tilde{\chi}^0_1$ in the RPV scenario with a pure λ_{121} coupling, (middle) the DV+$E_{\rm T}^{\rm miss}$ on the production cross-section for a pair of gluinos of mass 1.1TeV that decay into two quarks and a long-lived $\tilde{\chi}^0_1$ in the GGM scenario. Right plot: the 95% confidence-level excluded regions that lie below the curves shown in the mass-vs-$c\tau$ plane for the split-SUSY scenarios, with the gluino decaying into a gluon or light quarks, plus a 100 GeV $\tilde{\chi}^0_1$. [12]

3 Search for long-lived, weakly-interacting particles that decay to displaced hadronic jets

A search was performed for the decay of neutral, weakly interacting, long-lived particles (LLP) by searching for events with two displaced vertices in either InnerDetector, Muon Spectrometer or both[13]. Displaced jets appear in a variety of models including Stealth SUSY, Scalar boson and Hidden Valley Z. This analysis studies two separate channels, defined by the trigger used.The first channel, used for the Stealth SUSY and Scalar Boson searches, uses a trigger which identifies clusters of muon region-of-interests that are preceded by little or no activity in the tracking or calorimeter detectors. The second channel, which is used for the Z' search, uses a Jet and missing transverse momentum ($E_{\rm T}^{\rm miss}$) trigger. Both channels require good quality vertices, not consistent with material interactions, that are in close proximity to a jet. No significant excess of events above the background expectations is observed and exclusion limits as a function of the proper lifetime of LLP from Higgs boson and scalar boson decays are reported. This paper presents the first upper limits as a function of proper lifetime for Hidden Valley Z' and Stealth SUSY scenarios. The observed 95% CL limits on the branching ration of the Stealth SUSY samples studied is shown in the left plot of figure 2.

4 Search for long-lived heavy charged particles with the ATLAS pixel detector

A search for heavy charged LLP was performed using 18.4 fb^{-1} of data at $\sqrt{s} = 8$ TeV[14]. These particles would have a speed $\beta << 1$ and leave a signature of anomalously large specific energy loss ($\frac{dE}{dx}$) in the pixel detector. Measuring such particles in the vicinity of the interaction vertex allows sensitivity to metastable particles with lifetimes in the nanosecond range. Additionally, as long as the particle travels at least 45 cm (in radius, r) it can be studied, with little dependence on its subsequent interactions or decay mode.

To select candidate events, an 80 GeV threshold E_T^{miss} trigger is used with an offline E_T^{miss} cut of 100 GeV. In order to remove the main source of background, muons from W decays, a transverse mass cut of $m_T > 130$ GeV was employed. Both stable and metastable signal regions were used. For the stable signal region, a veto on the track candidate being matched to a reconstructed muon was applied. Each candidate event is required to have at least one isolated track with transverse momentum $p_T > 80$ GeV and $\frac{dE}{dx} >\sim 1.8$ MeV/g cm^{-2}.

Background is estimated by data driven approach by randomly sampling momentum (p), pseudo-rapidity (η) and $\frac{dE}{dx}$ values from control sample distributions and combining. No significant deviation from background expectations is observed and 95% CL limits are placed on the mass of different types of long lived particles. Stable charginos with mass smaller than 549 GeV are excluded. Also excluded are stable gluino (sbottom, stop) R-hadrons with masses smaller than 1102 (745, 758) GeV respectively. In the metastable case, masses exceeding 1200 GeV are excluded for R-hadrons of 12 ns. This is the first measurement of lifetime dependent mass limit for charged R-hadrons in the 1-10 ns range, with little dependence on their decay mode. Figure 2 shows two example exclusion limits in the LLP lifetime-mass plane for gluino R-hadrons and a chargino decaying to $\chi_1^0 + \pi^\pm$.

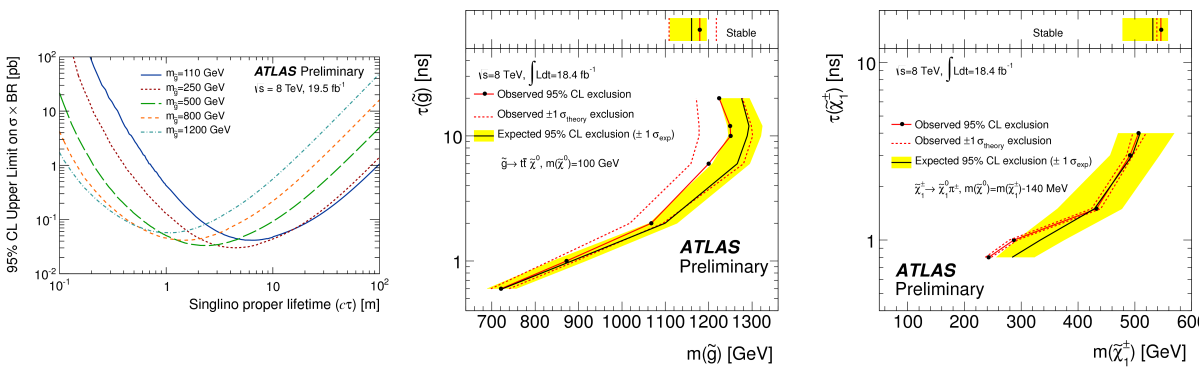

Figure 2 – Left plot: Observed 95% CL limits on $\sigma\times$BR for the Stealth SUSY samples[13], Middle plot: exclusion limits in the τ - m plane for gluino R-hadrons decaying in tt plus a light neutralino of mass $m(\chi_0) = 100$ GeV[14]. Right plot: exclusion limits in the τ - m plane for chargino decaying to $\chi_1^0 + \pi^\pm$ [14].

5 Search for charginos nearly mass-degenerate with the lightest neutralino based on a disappearing-track signature

A search was performed for direct chargino production in AMSB scenarios, via: $pp \to \tilde{\chi}_1^\pm \tilde{\chi}_1^0 +$ jet and $pp \to \tilde{\chi}_1^+ \tilde{\chi}_1^- +$ jet [3]. In AMSB models, the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ are almost mass degenerate with the difference in their mass ($\Delta m_{\tilde{\chi}_1}$) being $\sim$160 MeV. The implication of this is that the $\tilde{\chi}_1^\pm$ has a lifetime $\mathcal{O}(0.1)$ ns and decays into a $\tilde{\chi}_1^0$ and a low momentum ($\sim$100 MeV) $\pi^\pm$. This decay leaves a distinctive signature in the detector of a charged track produced at the primary interaction, from the $\tilde{\chi}_1^\pm$, which disappears before the outer tracking chambers when it decays into the very soft $\pi^\pm$. A search was performed for a high p_T "disappearing track" signature together with large E_T^{miss} and a high p_T jet which is required to trigger the event.

In order to suppress backgrounds from W/Z+jets and top-pair production processes, events with electron or muon candidates are discarded. In order to suppress QCD di-jet events, events are required to have at least one jet with $p_T > 90$ GeV, $E_T^{miss} > 90$ GeV and $\Delta\phi_{min}^{jet-E_T^{miss}} > 1.5$. Candidate "disappearing" tracks are required to be isolated, have $p_T > 15$ GeV, to be of good quality and to have less than 5 hits in the Transition Radiation Tracker. No excess of candidate tracks is observed and upper limits are placed on the $m_{\tilde{\chi}_1^\pm}$ and $\tau_{\tilde{\chi}_1^\pm}$ at 95% CL . For $\Delta m_{\tilde{\chi}_1} = 160$ MeV, a limit of $m_{\tilde{\chi}_1^\pm} > 245^{+24}_{-30}$ GeV is obtained.

6 Limits on metastable gluinos from ATLAS SUSY searches

If the gluino is just a little long-lived, of the order of 1 ns, standard SUSY searches looking for excesses in events with high-p_T jets and large $E_\mathrm{T}^\mathrm{miss}$ should still apply. As the lifetime of the gluino increases, the efficiency of the search will decrease as: lepton vetoes start to fail impact-parameter cuts, jets start to be identified as b-jets, jets start to fail track cleaning cuts based on the track p_T or the fraction of energy, measured in the calorimeter, which is electromagnetic. The results of SUSY searches designed for promptly decaying $\tilde{q}$ and gluinos, produced at 8 TeV pp collisions, are reinterpreted in the context of metastable gluinos [15]. This is the first explicit re-interpretation of prompt SUSY searches for long-lived gluinos. The left and middle plots of figure 3 show the 95% CL exclusion limits for gluino mass as a function of gluino lifetime for $m_{\tilde{\chi}_1^\pm}$=100 GeV and gluino to $q\bar{q}\ \tilde{\chi}_1^\pm/g\tilde{\chi}_1^\pm$ decays and $m_{\tilde{\chi}_1^\pm}$=100 GeV and gluino to $t\bar{t}\ \tilde{\chi}_1^\pm$ decays.

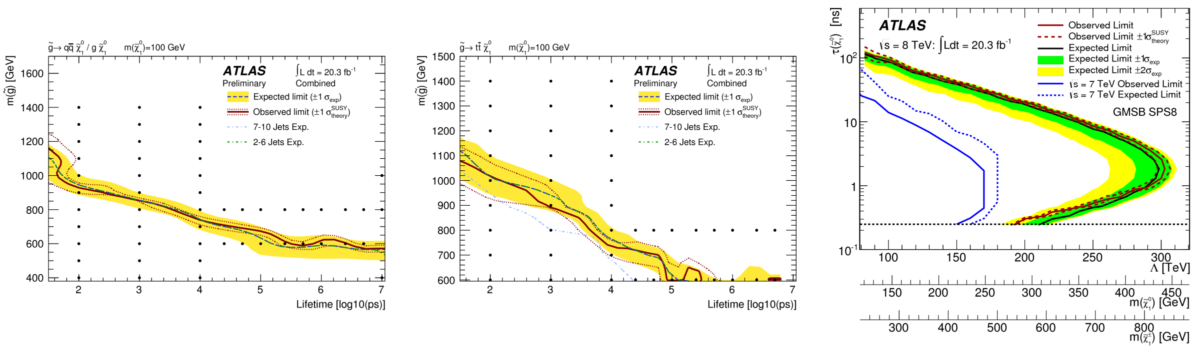

Figure 3 – Left plot: 95% CL excluded gluino mass as a function of gluino lifetime, for $m_{\tilde{\chi}_1^\pm}$=100 GeV and gluino to $q\bar{q}\ \tilde{\chi}_1^\pm/g\tilde{\chi}_1^\pm$ decays[15]. Middle plot: 95% CL excluded gluino mass as a function of gluino lifetime, for $m_{\tilde{\chi}_1^\pm}$=100 GeV and gluino to $t\bar{t}\ \tilde{\chi}_1^\pm$ decays[15]. Right plot: The observed and expected 95% CL limits in the GMSB signal space of $\tilde{\chi}_1^0$ lifetime versus Λ and also versus the $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm$ masses in the SPS8 model[16].

7 Search for nonpointing and delayed photons in the diphoton and missing transverse momentum final state

In GMSB, the NLSP can decay to a γ and a gravitino. If the neutralino is long-lived, the γ may be delayed and non-prompt. This distinct signature arises from finite lifetime (τ) of the NLSP. As GMSB is R-parity conserving, a SUSY-event would contain two SUSY chains with the NLSP ($\tilde{\chi}^0$) decaying to SM particle (γ) and the LSP ($\tilde{G}$). These two γ, would appear as delayed and may not "point-back" to the primary vertex interaction due to the path and β of the $\tilde{\chi}_1^0$.

Events are selected with two photons with $p_\mathrm{T} > 50$ GeV (using loose identification criteria due to the wider possible shower shape of the signal photons) and $E_\mathrm{T}^\mathrm{miss} > 75$ GeV due to the 2 gravitinos [16]. Events with low $E_\mathrm{T}^\mathrm{miss}$ are used as control regions to describe the background data. The distributions of the distance between the z co-ordinate of the primary vertex and the apparent origin of the photon, extrapolated from the calorimeter measurements to the z-axis (Δz_γ), and the relative time of the photon measurement with respect to the primary collision as measured by the liquid argon calorimeter (t_γ) are used to perform a 2D search.

A template fit method is used to fit the 386 events in the signal region with template distributions corresponding to background and signal shape distributions. No evidence of non-pointing and delayed photons is found, and the results 95% CL limits exclude values of τ in the range from 0.25 to 100 ns and values of Λ in the range from 80 to about 300 TeV, as shown in the right plot of figure 3.

8 Searches for heavy long-lived charged particles

There are several candidate particles for LLP which are massive. They include long-lived sleptons in GMSB, directly produced $\tilde{\chi}_1^{\pm}$ (with small $\Delta m_{\tilde{\chi}_1}$) and R-hadrons. The common feature between these candidates is that if they are massive, they will be produced with velocities less than the speed of light, $\beta < 1$. In this scenario, their mass (m) can be determined from their measured speed (β) and momentum (p) by the relation $m = p/\beta\gamma$, where γ in this context is the lorentz factor.

Different strategies were used to measure the particles' speed, and $\frac{dE}{dx}$ which is related to $\beta\gamma$ of the particle. The time-of-flight of the particle is measured from timing information from the muon spectrometer and/or the calorimeters and used to determine β. The silicon pixel detectors are used to measure $\frac{dE}{dx}$. The calorimeters and muon detectors are used to provide a time-of-flight measurement.

No excess is observed in any signal region, and 95% CL limits are placed on the mass of LLP in various SUSY models, examples of which are presented in figure 4 [17]. Long-lived $\tilde{\tau}$ in models with GMSB are excluded up to masses between 440 and 385 GeV for tanβ between 10 and 50, with a 290 GeV limit in the case where only direct $\tilde{\tau}$ production is considered. In the context of simplified LeptoSUSY models, where sleptons are stable and have a mass of 300 GeV, $\tilde{q}$ and gluino masses are excluded up to a mass of 1500 and 1360 GeV, respectively. Directly produced $\tilde{\chi}_1^{\pm}$, in simplified models where they are nearly degenerate to the $\tilde{\chi}_1^0$, are excluded up to a mass of 620 GeV. R-hadrons, composites containing a gluino, $\tilde{b}$ or $\tilde{t}$, are excluded up to a mass of 1270, 845 and 900 GeV, respectively, using the full detector; and up to a mass of 1260, 835 and 870 GeV using an approach disregarding information from the muon spectrometer.

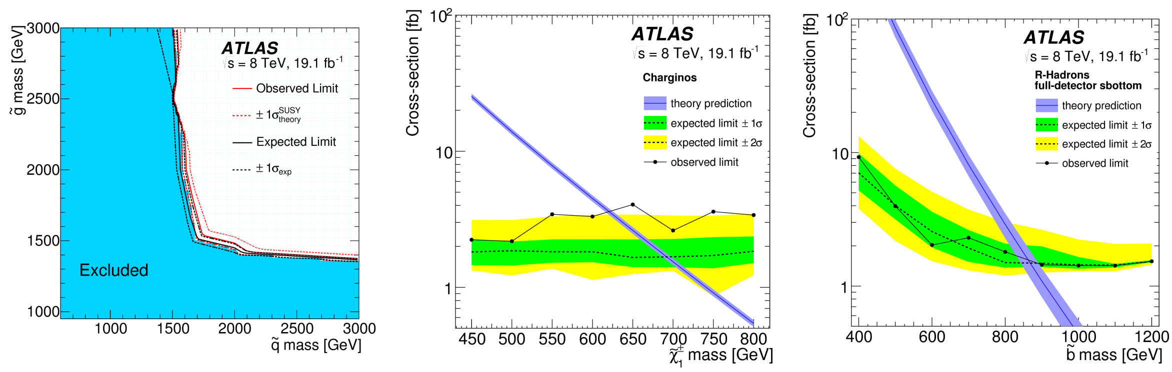

Figure 4 – From left to right: 95% CL excluded regions of squark mass and gluino mass in the LeptoSUSY models; cross-section upper limits for various chargino masses in stable-chargino models; cross-section upper limits as a function of the mass for the sbottom R-Hadron models for the full-detector search. [17]

9 Searches for stopped R-hadrons

A search is performed for $\tilde{g}$, $\tilde{t}$ or $\tilde{b}$ R-hadrons that are produced in a pp collision and have come to rest within the calorimeter, and decay at some later time to hadronic jets and a neutralino, using 5.0 and 22.9 fb^{-1} of pp collisions at 7 and 8 TeV, respectively [18].

Candidate decay events are triggered in selected empty bunch crossings of the LHC to remove pp collision backgrounds. Events are required to have at least one high p_{T} jet, with additional requirements on the jet shape, and no muon candidates. The main background after these selection requirements are events due to beam-halo and cosmic-rays. No excess is observed over the background prediction and limits are set on $\tilde{g}$, $\tilde{t}$, and $\tilde{b}$ masses for different decays, lifetimes, and neutralino masses. With a neutralino of mass 100 GeV, the analysis excludes gluinos with mass below 832 GeV for a gluino lifetime between 10 μs and 1000 s in the generic R-hadron model with equal branching ratios for decays to $q\bar{q} \to \tilde{\chi}^0$ and $g\tilde{\chi}^0$.

10 Summary

With no sign of prompt SUSY decays there has been much speculation that SUSY could be hiding in stable, meta-stable, displaced decays. We are actively addressing this with a number of analyses. Good coverage of different lifetimes is achieved by complementary analyses using different detector systems and novel techniques. Figure 5 shows the constraints on the gluino mass-vs-lifetime plane for a split-SUSY model with the gluino R-hadron decaying into a gluon or light quarks and a neutralino with mass of 100 GeV from different analyses. The reader is invited to read the detailed papers on each of these analyses.

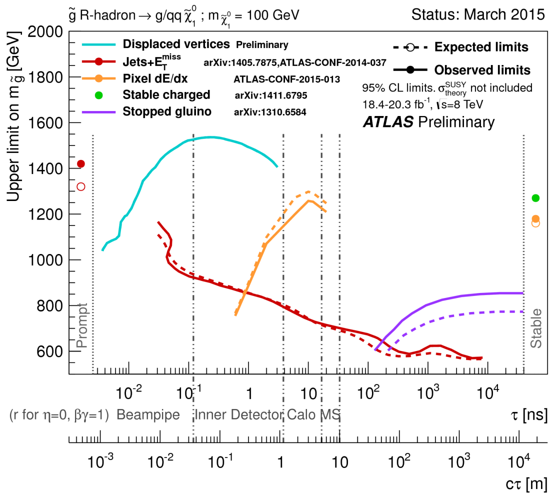

Figure 5 – Constraints on the gluino mass-vs-lifetime plane for a split-SUSY model with the gluino R-hadron decaying into a gluon or light quarks and a neutralino with mass of 100 GeV [19].

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