

Search for charged long-lived heavy particles with the ATLAS experiment at the LHC

Elisa GUIDO*

On behalf of the ATLAS Collaboration

INFN Genova

E-mail: elisa.guido@ge.infn.it

We report on a search for charged long-lived heavy particles, as predicted by several theories beyond the Standard Model. Such particles can be detected by the ATLAS experiment at the LHC through anomalous specific ionization measured in the Pixel detector, through their slow motion ($\beta < 1$) measured in the Calorimeters, and also through their possible muon-likeness in the Muon Spectrometer. Results of this search on the full data sample collected by ATLAS during 2011, corresponding to an integrated luminosity of $\sim 4.7 \text{ fb}^{-1}$, are shown, combining the information obtained from various sub-detectors.

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*Speaker.

1. Introduction

Heavy long-lived particles (LLPs) are predicted by several extensions of the Standard Model (SM). Some Supersymmetry (SUSY) models [1] predict the existence of meta-stable sleptons, in particular in Gauge-Mediated SUSY Breaking (GMSB) with the τ slepton ($\tilde{\tau}$) as the LLP, and of colored meta-stable squarks (\tilde{q}) and gluinos (\tilde{g}) in split SUSY. Squarks and gluinos can hadronize with either a light SM quark system or a gluon, forming a R -hadron. R -hadrons may be singly charged, doubly charged or neutral, they can either change their electric charge by nuclear scattering processes with the detector material, or decay in the detector given their finite lifetime.

Heavy LLPs should be produced at the LHC as massive particles. They are expected to move slowly ($\beta < 1$), thereby having a measurable time-of-flight, and to release an anomalous amount of energy while passing through the detector. They may also interact like heavy muons.

According to these signatures, several possible searches for LLPs [2] are performed at ATLAS [3], and described in this paper: an Inner Detector (ID)-only search, potentially sensitive to meta-stable R -hadrons not reaching farther sub-detectors, or to stable R -hadrons becoming neutral; an ID+Calorimeters (μ -agnostic) search, where the R -hadron is not required to reach the Muon Spectrometer (MS); a full-detector search, mainly intended for stable R -hadrons; and an ID+MS search, focusing on the search for sleptons.

2. Data and Monte Carlo simulated samples

The search presented here is based on $\sim 4.7 \text{ fb}^{-1}$ of pp -collision data collected in 2011. Monte Carlo (MC) simulated signal samples, re-weighted for the distribution of pile-up events to match the running conditions of the 2011 data, are used for efficiency studies and for setting limits.

The GMSB samples are generated with: the number of super-multiplets in the messenger sector equal to 3, the messenger mass scale of 250 TeV, the sign of the Higgsino mass parameter equal to 1, and the scale factor for the gravitino mass set at 5000. The ratio of the two Higgs doublets vacuum expectation values ($\tan\beta$) varies between 5 and 40, the SUSY particle mass scale (Λ) ranges from 50 to 150 TeV and the corresponding $\tilde{\tau}$ masses from 122.2 to 465 GeV. The mass spectra are obtained from the SPICE program [4] and the events are generated using HERWIG [5].

The R -hadron samples are generated with \tilde{g} (\tilde{q}) masses from 300 to 1500 GeV (200 to 1000 GeV). The pair production of gluinos and squarks is simulated by PYTHIA [6]. Gluinos are assumed to hadronize with a gluon in 10% of the events. The simulation of R -hadron interactions in matter is handled by GEANT4 [7] and based on a generic model [8].

3. Mass and β measurements

The masses of slow charged particles can be measured by relying on ID information only. In particular, the Pixel specific energy loss (dE/dx) and the momentum measurements can be fitted to an empirical Bethe-Bloch function, thus deducing the relativistic boost factor of the particle. The measurable $\beta\gamma$ ranges between 0.2 and 1.5. This particle identification method [9] is based on a five-parameter function which describes the behavior of the most probable value of dE/dx with $\beta\gamma$:

$$\mathcal{M}_{\frac{dE}{dx}}(\beta\gamma) = \frac{p_1}{\beta^{p_3}} \ln(1 + (p_2\beta\gamma)^{p_5}) - p_4. \quad (3.1)$$

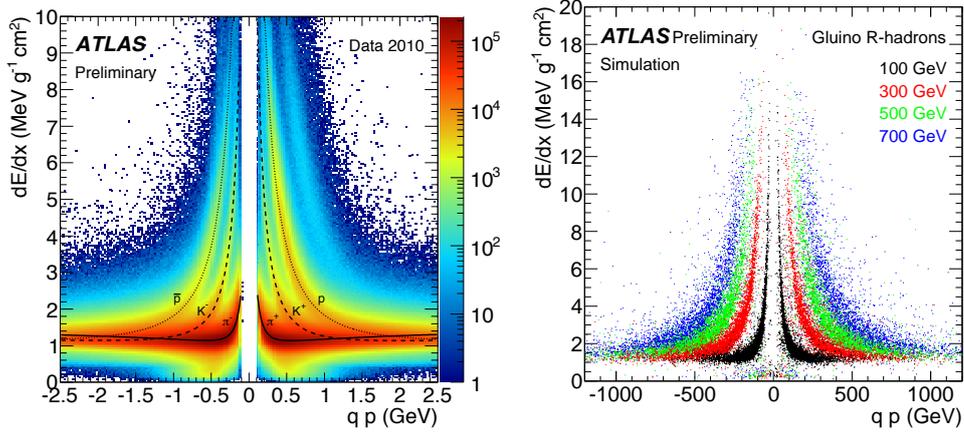


Figure 1: (left) Distribution of dE/dx versus signed momentum for minimum bias 2010 collisions, with tracks reconstructed down to a p_T of 100 MeV. The distributions of the most probable value for the fitted probability density functions of pions (solid), kaons (dashed) and protons (dotted) are superimposed [2]. (right) Simulated distributions of dE/dx versus signed momentum for R -hadrons of various masses [2].

38 This function for known SM minimum ionizing particles (MIPs), superimposed on data for low
 39 momentum tracks, is shown in Fig. 1 (left). LLPs are expected to release more energy than MIPs,
 40 even for high momentum tracks, as can be seen in Fig. 1 (right), for singly charged R -hadrons of
 41 masses 100, 300, 500 and 700 GeV.

42 Both Tile and Liquid Argon Calorimeters can provide a good timing resolution, thus being
 43 able to distinguish between highly relativistic particles and slow LLPs. The MS can perform a
 44 β measurement mainly thanks to the monitored drift-tube and resistive plate chambers; for slow
 45 LLPs a combined track re-fit including ID and MS information is used. For each track, the β
 46 measurements from different detectors, if internally consistent, are also combined in a weighted
 47 average, the weights being obtained from the calculated error of each measurement, corrected for
 48 differences between data and MC for muons from $Z \rightarrow \mu\mu$ decays. The typical resolutions for
 49 Calorimeter-based and combined β measurements are shown in Fig. 2.

50 4. Event selection and background estimation

51 The event selection is optimized separately for the different searches.

52 The slepton search requires a single muon trigger, which has a typical efficiency of $\sim 85\%$. A
 53 loose selection is applied while looking for two LLP candidates, and identifies tracks with $p_T > 50$
 54 GeV, with a veto for the invariant mass region between ± 10 GeV with respect to the nominal Z
 55 mass value, and a combined $\beta < 0.95$; a tighter selection is instead applied when requiring only one
 56 LLP candidate, and it consists in asking for a track with $p_T > 70$ GeV, a β measurement compatible
 57 at a 2σ level among at least two different sub-detectors, and a cut on $m_\beta = p/\beta\gamma$, depending on
 58 slepton mass. The selection efficiency on the signal is typically of $\sim 20\%$.

59 The R -hadron searches are based on a missing transverse energy (E_T^{miss}) trigger, with a 60-70
 60 GeV threshold and a typical efficiency of $\sim 15\%$. For the full-detector and μ -agnostic analyses,
 61 we look for a track of momentum between 140 GeV and 3.5 TeV, and isolated from jets and other

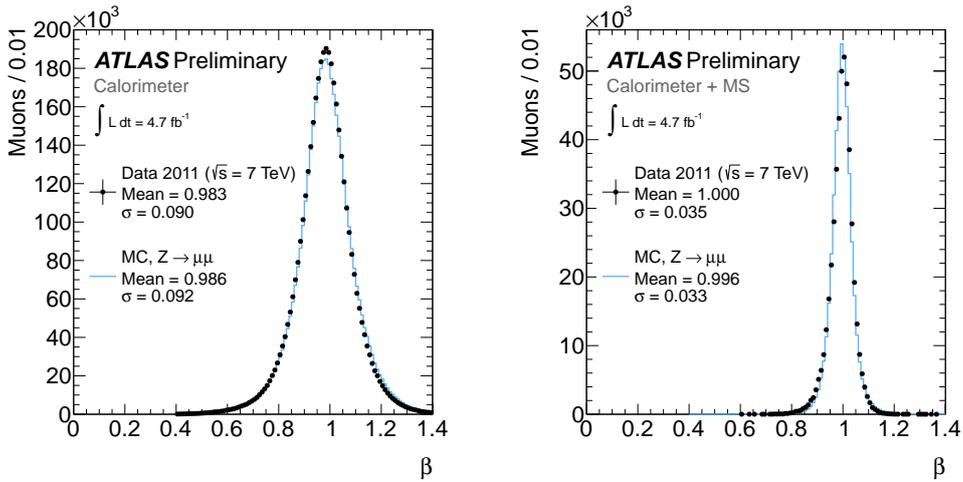


Figure 2: Distribution of β (left) for the calorimeter and (right) for the combined resistive plate chambers, monitored drift-tube chambers and calorimeter measurements, obtained for selected $Z \rightarrow \mu\mu$ decays in data and MC simulation [2].

62 tracks, with a $\beta\gamma < 1.5 - 2.0$ and either a combined or a calorimetric $\beta < 0.8 - 0.9$. A tighter
 63 selection is applied in the case of the ID-only analysis: we search for events with E_T^{miss} confirmed
 64 offline as greater than 85 GeV, and with a track of $p_T > 50$ GeV and $p > 100$ GeV, more severely
 65 isolated, not compatible with the electron hypothesis, and with $dE/dx > (1.8 + f(\eta)) \text{ MeVg}^{-1}\text{cm}^2$,
 66 where $f(\eta)$ accounts for a residual dependence of the ionization on the pseudorapidity. The selec-
 67 tion efficiency on the signal varies with the R -hadron mass, and is typically of $\sim 11\%$ ($\sim 6\%$) for
 68 $m(\tilde{g})=900$ GeV in the full-detector (ID-only) search.

69 After the selection is applied, the background is mainly due to high- p_T muons with mis-
 70 measured β . A data-driven approach is used to build high-statistics random samples of background
 71 events, starting from kinematic distributions obtained from data control samples.

72 5. Systematic uncertainties

73 Several systematic uncertainties affect this search. They can be grouped into uncertainties on
 74 the theoretical cross-sections, on the background estimation, on the luminosity, and on the signal
 75 efficiency. The latter are mainly due to systematic discrepancies between data and simulation in
 76 trigger efficiency, momentum resolution, β and dE/dx calibrations, and E_T^{miss} scale. A summary of
 77 the uncertainties for the different analyses is given in Table 1.

Systematic uncertainty	sleptons	R-hadrons
Theoretical cross-sections	5.0%	15-30%
Signal efficiency	4.4-6.3%	11-13%
Background estimation	11-13%	15-20%
Luminosity	3.9%	3.9%

Table 1: Summary of systematic uncertainties, as in [2].

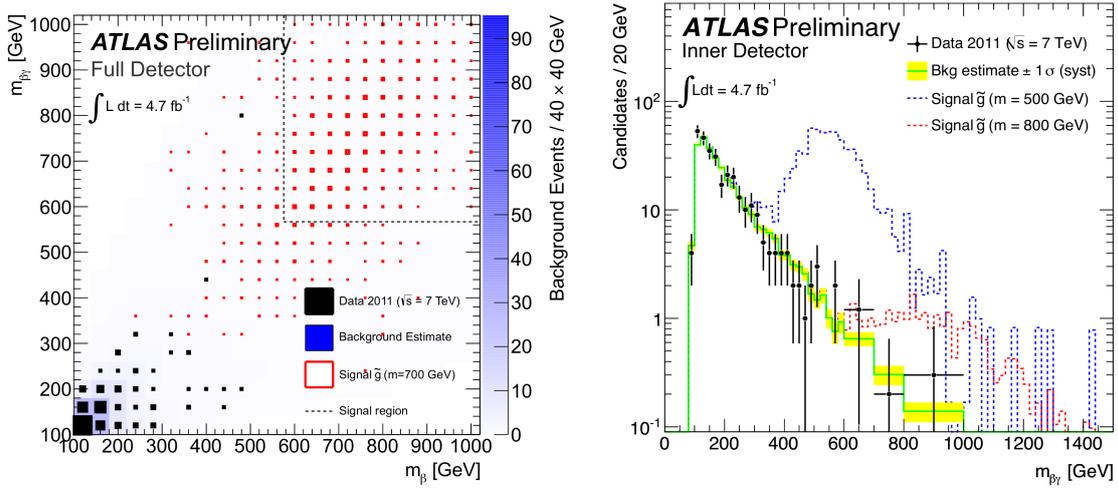


Figure 3: Observed data, background estimate and expected signal (left) in the full detector and (right) in the ID-only R -hadron search [2].

6. Results

Examples of the mass distributions for the expected signal and for the estimated background, while considering also systematic uncertainties, compared to the observed distributions on data, are shown in Fig. 3. Similar behaviors are found in the μ -agnostic and slepton searches [2]. No significant indications of a signal above the background expectations are found, and 95% confidence level (CL) upper limits are set on the cross-section for the production of sleptons and R -hadrons, following the CL_s prescriptions [10]. Lower limits on the masses for the LLPs can be deduced, as summarized in Table 2. In the GMSB scenario, limits are also set as a function of Λ and $\tan\beta$. Two examples of the results are shown in Fig. 4.

	full-detector	μ -agnostic	ID-only
$m(\tilde{g}) > [\text{GeV}]$	985	989	940
$m(\tilde{t}) > [\text{GeV}]$	683	657	604
$m(\tilde{b}) > [\text{GeV}]$	612	618	576
sleptons			
$m(\text{GMSB } \tilde{\tau}) > [\text{GeV}]$	300 - 268 ($5 < \tan\beta < 40$)		
$m(\text{directly produced sleptons}) > [\text{GeV}]$	278 ($5 < \tan\beta < 40$)		

Table 2: Summary of resulting 95% CL limits on the masses of LLPs, as in [2].

7. Conclusions

A search for LLPs using data from pp -collisions collected by the ATLAS detector in 2011 has been presented. It represents an interesting complement to searches where SUSY particles decay promptly. Several signatures have been considered, and different detection techniques have

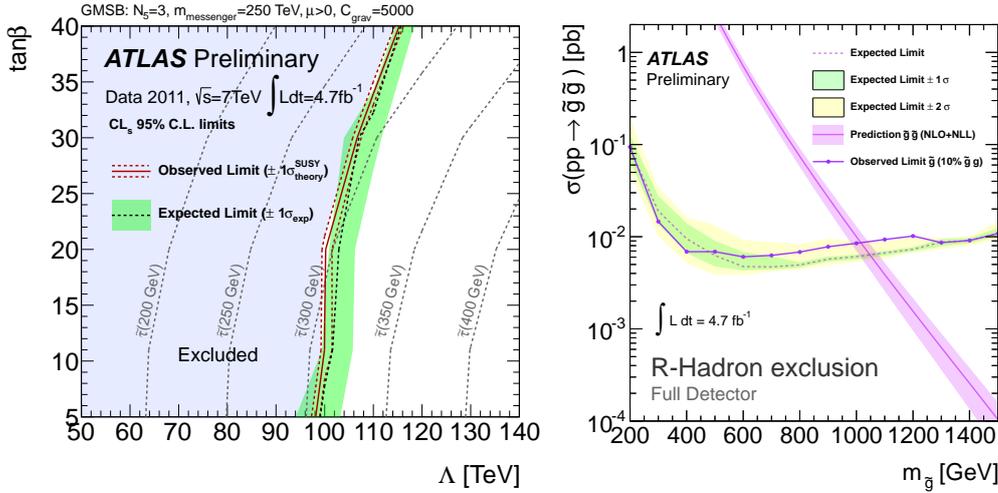


Figure 4: (left) Limits on Λ and $\tan\beta$ in GMSB models. The expected limit is drawn as a dashed black line with green 1σ band while the observed limit is a solid red line with the 1σ theoretical uncertainty bounded by red dashed lines. (right) The cross-section exclusion limits for gluino R -hadrons using the full detector reconstruction are shown as the expected limit (dashed line) with ± 1 (green) and $\pm 2\sigma$ (yellow) uncertainty bands. The observed upper limit is represented by the solid line with markers. The purple solid line is the theoretical prediction for the production cross-section calculated at NLO+NLL [2].

91 been set up in order to perform this analysis. No significant deviations from the SM background
 92 expectations are found. The 95% CL limits obtained on the cross-section for the production of
 93 LLPs, and therefore on the LLPs masses, extend ATLAS previous limits [11, 12], thanks both to
 94 the increased luminosity and to a more refined analysis approach.

95 References

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