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Searches for heavy long-lived sleptons and R-hadrons with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ TeV ☆

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ABSTRACT

A search for long-lived particles is performed using a data sample of 4.7 fb^{-1} from proton–proton collisions at a centre-of-mass energy $\sqrt{s} = 7$ TeV collected by the ATLAS detector at the LHC. No excess is observed above the estimated background and lower limits, at 95% confidence level, are set on the mass of the long-lived particles in different scenarios, based on their possible interactions in the inner detector, the calorimeters and the muon spectrometer. Long-lived staus in gauge-mediated SUSY-breaking models are excluded up to a mass of 300 GeV for $\tan\beta = 5$–20. Directly produced long-lived sleptons are excluded up to a mass of 278 GeV. R-hadrons, composites of gluino (stop, sbottom) and light quarks, are excluded up to a mass of 985 GeV (683 GeV, 612 GeV) when using a generic interaction model. Additionally two sets of limits on R-hadrons are obtained that are less sensitive to the interaction model for R-hadrons. One set of limits is obtained using only the inner detector and calorimeter observables, and a second set of limits is obtained based on the inner detector alone.

1. Introduction

Heavy long-lived particles (LLP) are predicted in a range of theories which extend the Standard Model (SM). Supersymmetry (SUSY) [1–9] models allow long-lived charged sleptons ($\tilde{\ell}$), squarks ($\tilde{q}$) and gluinos ($\tilde{g}$). Heavy LLPs produced at the Large Hadron Collider (LHC) could travel with speed measurably lower than the speed of light. These particles can be identified and their mass, m, determined from their speed, β, and momentum, p, using the relation $m = p/\gamma\beta$, with γ being the relativistic Lorentz factor. Four different searches are presented in this Letter, using time-of-flight to measure β and specific ionisation energy loss, $\mathrm{d}E/\mathrm{d}x$, to measure $\beta\gamma$. The searches are optimised for the different experimental signatures of sleptons and composite colourless states of a squark or gluino together with SM quarks and gluons, called R-hadrons.

Long-lived charged sleptons would interact like muons, releasing energy by ionisation as they pass through the ATLAS detector. A search for long-lived sleptons identified in both the inner detector (ID) and in the muon spectrometer (MS) is therefore performed ("slepton search"). The results are interpreted in the framework of gauge-mediated SUSY breaking (GMSB) [10–16] with the light stau ($\tilde{\tau}$) as the LLP. In these models a substantial fraction of the events would contain two LLP candidates, and this feature is also utilised in discriminating signal from background. Direct pair production of sleptons is also used to interpret the data independently of the mass spectrum of the other SUSY particles.

Coloured LLPs ($\tilde{q}$ and $\tilde{g}$) would hadronise forming R-hadrons, bound states composed of the LLP and light SM quarks or gluons. They may emerge as charged or neutral states from the pp collision and be converted to a state with a different charge by interactions with the detector material, and thus arrive as neutral, charged or doubly charged particles in the muon spectrometer.

In ATLAS, LLPs can be identified via the timing information in the muon spectrometer or calorimeters and via the measurement of the energy loss in the silicon pixel detector. All of these techniques are combined in this analysis to achieve optimal sensitivity for the "full-detector R-hadron search". In addition, searches based on only the calorimeter and the inner detector information ("MS-agnostic R-hadron search"), and based solely on the inner detector ("ID-only R-hadron search") are performed. The latter two cases are motivated by the limited understanding of R-hadron interactions in matter, in particular the possibility that R-hadrons are electrically neutral in the MS. Furthermore, these searches are sensitive to scenarios in which the R-hadrons decay before reaching the MS. In all searches the signal particles are assumed to be stable within the ATLAS detector, at least to the point it hits the last relevant component of the subdetector used for detecting it.

Previous collider searches for LLPs have been performed at LEP [17–20], HERA [21], the Tevatron [22–28], and the LHC [29–35].

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2. Data and simulated samples

The work presented in this Letter is based on 4.7 fb^{-1} of pp collision data collected at a centre-of-mass energy $\sqrt{s} = 7$ TeV in 2011. The events are selected online by muon triggers for the slepton search and by missing transverse momentum and muon triggers for the R-hadron searches. Data and Monte Carlo $Z \rightarrow \mu\mu$ samples are used for timing resolution studies. Monte Carlo signal samples are used to study the expected signal behaviour and to set limits.

The GMSB samples are generated with the following model parameters: number of super-multiplets in the messenger sector, $N_5 = 3$, messenger mass scale, $m_{\text{messenger}} = 250$ TeV, sign of the Higgsino mass parameter, $\text{sign}(\mu) = 1$, and C_{grav}, the scale factor for the gravitino mass which determines the $\tilde{\tau}$ lifetime was set to 5000 to ensure that the $\tilde{\tau}$ does not decay in the detector. The ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta$, is varied between 5 and 40 and the SUSY-breaking mass scale Λ is varied from 50 to 150 TeV, corresponding to light $\tilde{\tau}$ masses varying from 122.2 to 465 GeV. The mass spectra of the GMSB models are obtained from the SPICE program [36] and the events are generated using HERWIG [37].

The R-hadron samples are generated with gluino (squark) masses from 300–1500 GeV (200–1000 GeV). The pair production of gluinos and squarks is simulated in PYTHIA [38], incorporating specialised hadronisation routines [39–41] to produce final states containing R-hadrons. A 10% gluino-ball fraction is assumed in the gluino sample production. The simulation of R-hadron interactions with matter is handled by dedicated GEANT4 [42,43] routines based on a generic model [44]. All Monte Carlo events pass the full ATLAS detector simulation [42,45] and are reconstructed with the same programs as the data. All signal Monte Carlo samples are normalised to the integrated luminosity of the data.

3. The ATLAS detector

The ATLAS detector [46] is a multipurpose particle physics detector with a forward–backward symmetric cylindrical geometry and near 4π coverage in solid angle.[1] The ID consists of a silicon pixel detector, a silicon micro-strip detector, and a transition radiation tracker. The ID is surrounded by a thin superconducting solenoid providing a 2 T magnetic field, and by high-granularity liquid-argon sampling electromagnetic calorimeters (LAr). An iron/scintillator-tile calorimeter provides coverage for hadrons in the central rapidity range. The end-cap and forward regions are instrumented with liquid-argon calorimeters for both electromagnetic and hadronic measurements. The MS surrounds the calorimeters and consists of three large superconducting air-core toroids each with eight coils, a system of precision tracking chambers, and detectors for triggering.

The ATLAS trigger system is designed to select the events of most interest with a data-taking rate of about 400 Hz from a beam bunch crossing rate as high as 40 MHz. The first-level trigger (level-1) selection is carried out by custom hardware and identifies detector regions and the bunch crossing for which a trigger element is found. The high-level trigger is performed by dedicated software, seeded by data acquired from the bunch crossing and regions found at level-1. The components of particular importance to this analysis are described in more detail below.

3.1. The pixel detector

As the innermost detector system in ATLAS, the silicon pixel detector provides at least three precision measurements for each track in the region $|\eta| < 2.5$ at radial distances from the LHC beam line $r < 15$ cm. The sensors in the pixel barrel (covering the central $|\eta|$-region) are placed on three concentric cylinders around the beam-line, whereas sensors in the end-cap (covering the high-$|\eta|$ region) are located on three disks perpendicular to the beam axis on each side of the barrel. In the barrel (end-cap) the intrinsic accuracy is 10 μm in the $r\phi$-plane and 115 μm in the $z(r)$-direction. The data are only read out if the signal is larger than a set threshold. The time for which the signal exceeds that threshold, ToT, is recorded. The larger the initial signal is the longer this time.

3.1.1. Pixel detector specific ionisation ($\mathrm{d}E/\mathrm{d}x$) measurement

The relation between the ToT and the charge deposition in each pixel is measured in dedicated calibration scans and shows a good linearity. Therefore, the ToT measurement is well correlated with the energy loss of a charged particle in the pixel detector. The maximum ToT value corresponds to 8.5 times the average charge released by a minimum ionising particle (MIP) for a track perpendicular to the silicon detectors and leaving all its ionisation charge on a single pixel. If this value is exceeded, the ToT (and therefore the charge) is not correctly measured. In LHC collisions the charge generated by one track crossing the pixel detector is rarely contained in just one pixel. Neighbouring pixels are joined together to form clusters and the charge of a cluster is calculated by summing up the charges of all pixels after calibration correction. The specific energy loss $\mathrm{d}E/\mathrm{d}x$ is defined as the average of all individual cluster charge measurements for the clusters associated with the track. To reduce the Landau tails, the average is evaluated after having removed the cluster with the highest charge (the two clusters with the highest charge are removed for tracks having five or more clusters).

3.1.2. Mass measurement with the pixel detector

The masses of slow charged particles can be measured using solely the ID information by fitting each $\mathrm{d}E/\mathrm{d}x$ and momentum measurement to an empirical Bethe–Bloch function and deducing their $\beta\gamma$ value. The measurable $\beta\gamma$ range lies between 0.2 and 1.5, the lower bound being defined by the overflow in the ToT spectrum, and the upper bound by the overlapping distributions in the relativistic rise branch of the curve. This particle identification method [47] uses a five-parameter function to describe how the most probable value of the specific energy loss ($\mathcal{M}_{\frac{\mathrm{d}E}{\mathrm{d}x}}$) depends on $\beta\gamma$:

$$\mathcal{M}_{\frac{\mathrm{d}E}{\mathrm{d}x}}(\beta\gamma) = \frac{p_1}{\beta^{p_3}} \ln\bigl(1 + (p_2\beta\gamma)^{p_5}\bigr) - p_4. \tag{1}$$

Fig. 1(left) shows how this function describes data for low momentum tracks. Fig. 1(right) shows the simulated pixel $\mathrm{d}E/\mathrm{d}x$ spectra for singly-charged hypothetical R-hadrons of masses 100, 300, 500 and 700 GeV. As expected, these distributions extend into the high pixel $\mathrm{d}E/\mathrm{d}x$ region even for high momentum tracks. The most probable value of $\mathrm{d}E/\mathrm{d}x$ for MIPs is about 1.2 $\text{MeV}\,\text{g}^{-1}\,\text{cm}^2$ with a spread of about 0.2 $\text{MeV}\,\text{g}^{-1}\,\text{cm}^2$ and a slight η dependence, increasing by about 10% from low-η to high-η regions.

For all tracks having a reconstructed momentum p and a measured specific energy loss $\mathrm{d}E/\mathrm{d}x$ above the value for MIPs, a mass estimate $m_{\beta\gamma} = p/\beta\gamma$ is obtained by inverting Eq. (1). The procedure is continuously monitored through precise ($< 1\%$)

[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector and the z-axis coinciding with the axis of the beam pipe. The x-axis points from the interaction point to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.