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

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Summary. — We report on the search for charged long-lived heavy particles, predicted by several theories beyond the Standard Model. Such particles are potentially detectable at the LHC, given either their anomalous $\mathrm{d}E/\mathrm{d}x$ loss measurable in the ATLAS Inner Detector, or their slow motion ($\beta < 1$) which can be detected by the Calorimeter, or even their muon-likeness identified by the Muon Spectrometer. In particular, the Inner-Detector–based search, measuring the track parameters in the vicinity of the interaction point, is sensitive to possible metastable particles, or to changes in the charge due to interactions with the detector material, which may make the particles invisible to farther subdetectors. Results of this search with the Inner-Detector–based approach on part of the data sample collected by ATLAS during 2011 are shown.

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1. – Introduction

Heavy long-lived particles (LLPs) are predicted by several extensions of the Standard Model (SM). In particular, supersymmetry (SUSY) models foresee [1] meta-stable squarks ($\tilde{q}$) and gluinos ($\tilde{g}$); they are colored and can hadronize either with a light SM quark system, or with gluons, forming heavy bound states called R-hadrons. Such R-hadrons may be either singly or doubly charged, or neutral, or may even change their electric charge by nuclear scattering processes with the detector material. R-hadrons may also decay with a finite lifetime, but for this search we focus on long-lived particles.

The experimental signature for these objects consists on them being massive, and moving at low velocities compared to the speed of light, and thus behaving differently than other observable particles. In particular, either anomalous energy deposition or time of flight are sensitive to particle velocity and can be effectively measured by various sub-detectors of ATLAS, which is described in detail elsewhere [2].

We report on the results obtained by ATLAS in the search for heavy LLPs, using its different sub-detectors. The most recent result shown has been obtained with the

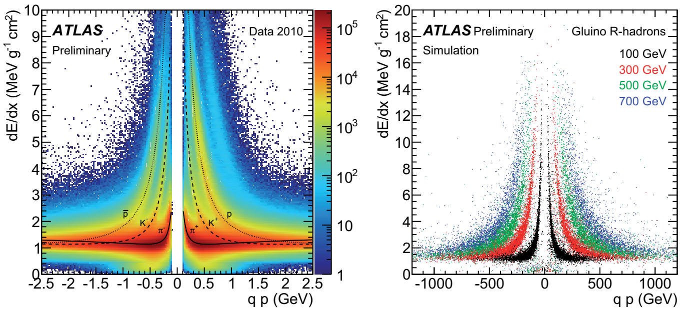

Fig. 1. – Left: Distribution of dE/dx *versus* signed momentum for minimum bias collisions. In this data sample, from 2010 collisions, tracks are reconstructed down to 100 MeV in p_T. The distribution of the most probable value for the fitted probability density functions of pions (solid), kaons (dashed) and protons (dotted) are superimposed. Right: Simulated distribution of specific energy loss *versus* momentum for singly charged hypothetical R-hadrons of various masses.

information provided by the Inner Detector (ID) [3], and using part of the data collected during 2011. Previous results on data collected during 2010 and searching for LLPs with the Calorimeter [4] or the Muon Spectrometer [5] are also summarized.

2. – ID-based search

2·1. *Strategy and dataset*. – In this search we do not explicitly require any confirmation of the signal out of the ID (Pixel + Semiconducter Tracker). Therefore, such a search is open to different models, *i.e.* meta-stable R-hadrons, while remaining sensitive to stable R-hadrons as well.

The analysis described here relies mainly on the detection of the anomalous specific energy loss (dE/dx) of R-hadrons. It is based on LHC pp collision data at $\sqrt{s} = 7\,\text{TeV}$, recorded in the period between March and August 2011. This corresponds to an integrated luminosity of $2.06\,\text{fb}^{-1}$ after data quality cuts. Monte Carlo simulated $\tilde{g}$ R-hadron samples have been generated in a range of masses from 200 to 1000 GeV, in 100 GeV intervals. The analysis is insensitive to lower masses due to trigger constraints and large backgrounds. In all Monte Carlo samples, the primary collision event is overlaid with minimum bias simulated events to mimic the pile-up conditions in data.

2·2. *Mass measurement with the Pixel detector*. – Masses of slow charged particles can be measured using uniquely the ID information, *i.e.* by fitting each dE/dx and momentum measurement to an empirical Bethe-Bloch function, and deducing their mass value. This particle identification method, explained in [6], uses a five-parameter function to describe how the most probable value of dE/dx ($\mathcal{M}_{\mathrm{d}E\mathrm{d}x}$) depends on β:

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

Figure 1 (left) shows how this function overlaps data for low-momentum tracks. Figure 1 (right) shows the simulated Pixel dE/dx spectra for singly charged hypothetical

R-hadrons of masses 100, 300, 500 and 700 GeV. As expected, these distributions extend into the high-$\mathrm{d}E/\mathrm{d}x$ region even for high-momentum tracks. A minimum ionizing particle (MIP) is expected to have an average $\mathrm{d}E/\mathrm{d}x$ of about $1.2\,\mathrm{MeVg^{-1}\,cm^2}$, with a spread of about $0.2\,\mathrm{MeVg^{-1}\,cm^2}$ and a slight dependence on pseudo-rapidity (η), increasing by about 10% from central to high-η regions. For all tracks having a reconstructed momentum p and a measured $\mathrm{d}E/\mathrm{d}x$ above the value for MIPs, a mass estimate is obtained by inverting the fitted function (eq. (1)), *i.e.* by numerically solving the equation $\mathcal{M}_{\mathrm{d}E\mathrm{d}x}(p/m) = \mathrm{d}E/\mathrm{d}x$ for the unknown mass m.

The procedure is continuously monitored through precise ($< 1\%$) measurements of the mass of known particles (kaons and protons) and allows hypothetical heavy slow particles to be identified through their abnormal $\mathrm{d}E/\mathrm{d}x$ in a range $0.3 < \beta < 0.8$.

2˙3. *Event selection.* – The measurement of high ionization close to the interaction point is not available at the trigger level, therefore other signatures must be used. In particular, the strong nature of gluino production mechanisms and the associated QCD radiation are exploited. A large missing energy component from initial state radiation (ISR) jets enables the use of the lowest unprescaled missing transverse energy (E_T^{miss}) trigger available in the data taking period ($E_T^{miss} > 70\,\mathrm{GeV}$). The overall acceptance in the mass range of interest is around 20%, with a slight mass dependence.

In order to suppress background, several selection criteria are applied. Among all the events, we keep only those with a E_T^{miss} calculated offline which exceeds 85 GeV, and with an identified primary vertex with at least five associated tracks. Then, we require the presence in the event of at least one track of good quality and high transverse momentum ($p_T > 50\,\mathrm{GeV}$), and with longitudinal and transverse impact parameter below 1.5 mm. These high-p_T tracks are then required to be isolated, *i.e.* with no other track of $p_T > 5\,\mathrm{GeV}$ within a radius of 0.25. The tracks must also have momentum higher than 100 GeV. Finally, high ionization is required, by means of an η-dependent selection criterion: $\mathrm{d}E/\mathrm{d}x > 1.8 - 0.045|\eta| + 0.115|\eta|^2 - 0.033|\eta|^3\,\mathrm{MeVg^{-1}\,cm^2}$, which takes into account a remnant of dependence on the pseudo-rapidity, ensuring a constant signal-to-noise ratio, at all η values.

2˙4. *Background estimation.* – The background is estimated by a data-driven approach. Properly selected data samples are used to parameterize the key variables. A first sample, which consists of tracks surviving the main selection, but with a low-ionization requirement ($\mathrm{d}E/\mathrm{d}x < 1.8\,\mathrm{MeVg^{-1}\,cm^2}$), is used to describe the momentum and η shapes, along with their inter-dependences; tracks with momentum lower than 100 GeV are used instead to parameterize the $\mathrm{d}E/\mathrm{d}x$ distribution, in bins of η. High-statistics random samples are then generated starting from these distributions. A background mass spectrum is obtained from the ionization and momentum generated, following the procedure described in sect. **2**˙2, and is normalized to data by matching the sideband regions at low masses ($m < 140\,\mathrm{GeV}$). The resulting background mass spectrum is shown in fig. 2 (left), with the mass distributions for data and some simulated $\tilde{g}$ R-hadrons events.

2˙5. *Systematic uncertainties.* – A number of sources of systematic uncertainties has been evaluated. Systematic uncertainties affecting the signal efficiency are due to theoretical uncertainties in the accuracy of the model, and to several quantified discrepancies between simulation and data in the trigger efficiency, E_T^{miss} scale, pile-up conditions, ionization and momentum parameterizations, and to specific inefficiency of various subdetectors during data-taking (19–14%, varying with increasing mass). Uncertainties affecting the background estimation are related to the choice of the intervals for the

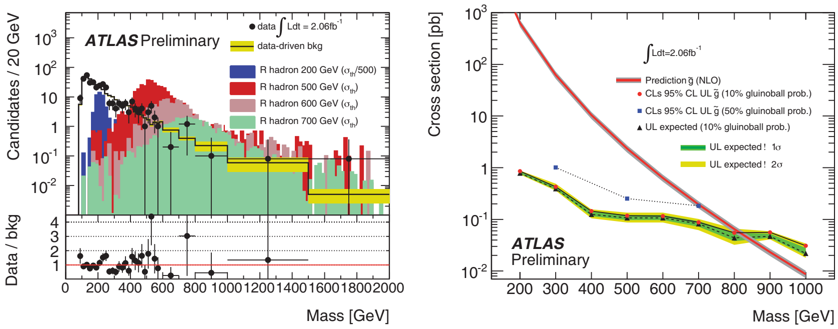

Fig. 2. – Left: Mass distribution for data, background, and four simulated gluino R-hadron signal samples, scaled to the expected cross sections. Right: Upper limits on gluino production cross-section.

generation, the alternative choice of acceptable functional forms to describe the distributions, as well as to the effect of changing pile-up conditions (1–10%, varying with mass). Finally, an uncertainty on the luminosity (3.7%), and on the theoretical cross-sections calculated with Prospino [7] (15%) are taken into account.

2·6. *Results.* – No significant deviations from the SM are observed. For each mass hypothesis, an upper limit (UL) on the gluino production cross-section is calculated with the CLs method [8] at 95% of confidence level (CL). A mass exclusion for gluino R-hadrons with mass below 810 GeV is obtained by comparing the observed ULs with the expected cross-sections and by assuming gluino-gluon bound states at a rate of 10%. Limits for all tested masses are shown in fig. 2 (right).

3. – Previous ATLAS results

In previous searches, ATLAS reported results based on data collected during 2010, and corresponding to an integrated luminosity of $\sim 34\,\text{pb}^{-1}$. One of this searches [4] relied on a combination of sub-detectors, Pixel-based specific energy loss $\mathrm{d}E/\mathrm{d}x$ and Calorimeter-based time of flight, excluding masses for gluino (stop, sbottom) R-hadrons below 586 (309, 294) GeV at 95% CL. Another analysis [5] relied on time-of-flight measured by the Muon Spectrometer, excluding masses for gluino R-hadrons below 544 GeV at 95% CL.

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