PROCEEDINGS OF SCIENCE

Search for metastable heavy charged particles with large ionization energy loss in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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Many extensions of the Standard Model predict the existence of massive charged long-lived particles, such as *R*-hadrons. These particles, if produced at the Large Hadron Collider (LHC), should be moving non-relativistically and therefore be identifiable through the measurement of an anomalously large specific energy loss in the ATLAS Pixel Detector. Measuring heavy long-lived particles through their track parameters in the vicinity of the interaction vertex allows the investigation of the case where these are metastable with lifetimes in the nanosecond range. A search for such particles, produced in proton-proton collisions at $\sqrt{s} = 13$ TeV at the LHC with the ATLAS detector, corresponding to an integrated luminosity of 3.2 fb^{-1}, is presented in these proceedings. No significant deviation from Standard Model background expectations is observed, and lifetime-dependent upper limits on *R*-hadron production cross sections and masses are set. Gluino *R*-hadrons with lifetimes above 0.4 ns and decaying to $q\bar{q}$ plus a 100 GeV neutralino are excluded at the 95% confidence level, with lower mass limit ranging between 740 and 1590 GeV. In the case of stable *R*-hadrons the lower mass limit at the 95% confidence level is 1570 GeV.

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1. Introduction

Heavy long-lived particles (LLPs) are predicted by several extensions of the Standard Model. Some Supersymmetry models [1] predict the existence of meta-stable sleptons, in particular in Gauge-Mediated SUSY Breaking (GMSB) with the τ slepton ($\tilde{\tau}$) as a 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 Standard Model quark system or a gluon, forming an 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.

These proceedings present a search for massive charged long-lived particles produced in proton-proton collisions at $\sqrt{s} = 13$ TeV at the LHC using the ATLAS experiment [2]. The data set used corresponds to an integrated luminosity of 3.2 fb^{-1}. The search strategy focuses on decays occurring within the active detector volume, which covers lifetimes from around 1 ns to several tens of ns. Such R-hadrons with lifetimes consistent with decaying inside the ATLAS detector are referred to as metastable. On the other hand, R-hadrons whose lifetime disfavors decay within the ATLAS detector are considered as stable. The approach described in these proceedings allows direct observation of charged R-hadrons which are either stable or metastable and traverse at least seven silicon layers of the ATLAS inner tracking system.

2. Mass measurement

The Pixel subsystem of the ATLAS detector provides measurements of ionization energy loss ($\mathrm{d}E/\mathrm{d}x$) for charged particles and can be used to distinguish highly ionizing particles from Standard Model particles. In 2014 the ATLAS Pixel detector was upgraded with the insertion of an additional layer, the Insertable B-Layer (IBL), which was installed inside the Pixel Detector, mounted on a new beam pipe of smaller diameter. Including the IBL charge information reduces the tails of the $\mathrm{d}E/\mathrm{d}x$ distribution, and increases the fraction of tracks for which the ionization measurement is well defined from 77% to 91%.

The masses of slow charged particles can be measured by relying on ID information only. In particular, the $\mathrm{d}E/\mathrm{d}x$ 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 0.3 and 1.5. This range overlaps the expected average $\beta\gamma$ of LLPs produced at the LHC, which decreases with the particle mass from $\langle\beta\gamma\rangle \approx 2.0$ at 100 GeV to $\langle\beta\gamma\rangle \approx 0.5$ at 1600 GeV. This particle identification method is based on a five-parameter function which describes the behavior of the most probable value of $\mathrm{d}E/\mathrm{d}x$ with $\beta\gamma$:

$$(\mathrm{d}E/\mathrm{d}x)_{\mathrm{MPV}}(\beta\gamma) = \frac{p_1}{\beta^{p_3}}\ln(1+[p_2\beta\gamma]^{p_5}) - p_4 \tag{2.1}$$

A mass estimate is obtained by numerically solving the equation, after having calibrated it with low-momentum pions, kaons and protons. This function for known Standard Model minimum ionizing particles (MIPs), superimposed on data for low momentum tracks, is shown in Figure 1 (left). LLPs are expected to release more energy than MIPs, even for high momentum tracks, as can be seen in Figure 1 (right), for singly charged R-hadrons of masses 800, 1600, 2400 GeV.

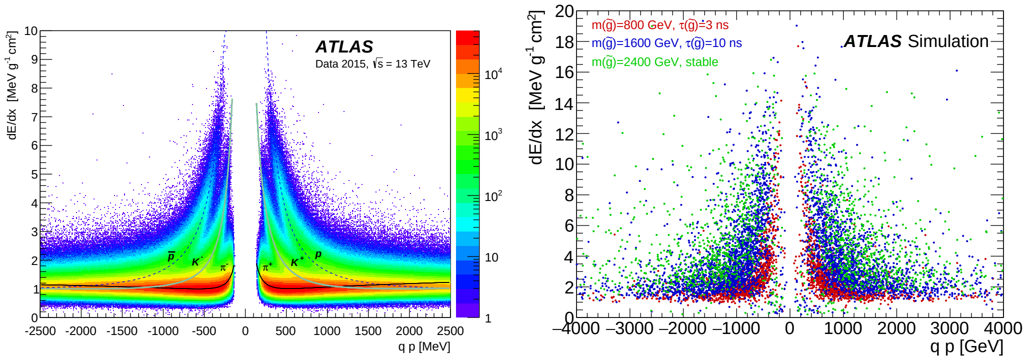

Figure 1: (left) Distribution of d$E/$dx versus signed momentum for minimum bias 2015 collisions, with tracks reconstructed down to p_T of 100 MeV. The distributions of the most probable value for the fitted probability density functions of pions (solid), kaons (dashed) and protons (dotted) are superimposed [2]. (right) Simulated distributions of d$E/$dx versus signed momentum for R-hadrons of various masses.

3. Event selection

The data sample used in this analysis have been recorded by ATLAS in 2015, corresponding to an integrated luminosity of 3.2 fb^{-1}. The selection of the candidate events are based on a missing transverse energy (E_T^{miss}) trigger, with a 70 GeV threshold. In addition, among the full cut-flow [2], events are selected with E_T^{miss} confirmed offline as greater than 130 GeV, and with a track of $p_T > 50$ GeV and $p > 150$ GeV, isolated from jets and other tracks, not compatible with the electron, jet and muon (only for the metastable case) hypothesis, and with d$E/$d$x > (1.8 + f(\eta))$ MeVg^{-1}cm^{2}, where $f(\eta)$ accounts for a residual dependence of the ionization on the pseudorapidity. The overall signal selection efficiency depends on the mass and lifetime of the signal, ranging from about 19% for a 1600 GeV R-hadron with a lifetime of 10 ns to less than 1% for R-hadrons with a lifetime of 0.4 ns.

4. Background estimate and systematic uncertainties

The expected shape and normalization of the mass distribution of background events from Standard Model processes is derived from data. The distributions of key variables are extracted in two control regions in data and these templates are used to generate the expected background distribution in the signal region. The choice of control samples takes into account the measured correlations between the key variables p, d$E/$dx and η, and the control region selections minimize the possible signal contamination. In the first control region all the selections for the signal are applied, except for the requirement on high ionization, which is inverted. The tracks in this control region are kinematically similar to those in the signal region. The expected p and $\eta(p)$ distributions of tracks from background processes are extracted from this region. The second control region is defined by inverting the E_T^{miss} requirement, while keeping all other selections unchanged. Tracks from this region are used to derive dE/dx templates in bins of η. The signal contamination is less than 1% in both control regions for all R-hadron masses and lifetimes considered in this search.

Several systematic uncertainties affect this search. They can be grouped into uncertainties on the theoretical cross-sections, on the background estimation, on the luminosity, and on the signal efficiency. The latter are mainly due to systematic discrepancies between data and simulation in trigger efficiency, momentum resolution, β and dE/dx calibrations, and E_T^{miss} scale.

5. Results and conclusions

In data, 16 events are observed for the stable R-hadron selection and 11 are observed for the metastable selection. Table 1 summarizes the background estimates with total statistical and systematic uncertainty as well as the observed events for the metastable and stable R-hadron selection.

Selection region	**Background exp.**	**Data**
Metastable R-hadron	11.1 ± 1.7 (stat.) ± 0.7 (syst.)	11
Stable R-hadron	17.2 ± 2.6 (stat.) ± 1.2 (syst.)	16

Table 1: Estimated number of background events and the number of observed events in data in the final selection regions. The background predictions show both the statistical and systematic uncertainties.

The mass distribution for data and background for metastable particle searches is shown in Figure 2. The yellow band around the background estimation includes both the statistical and systematic uncertainties. Two examples for signals as expected for gluino R-hadrons in the explored mass range are superimposed.

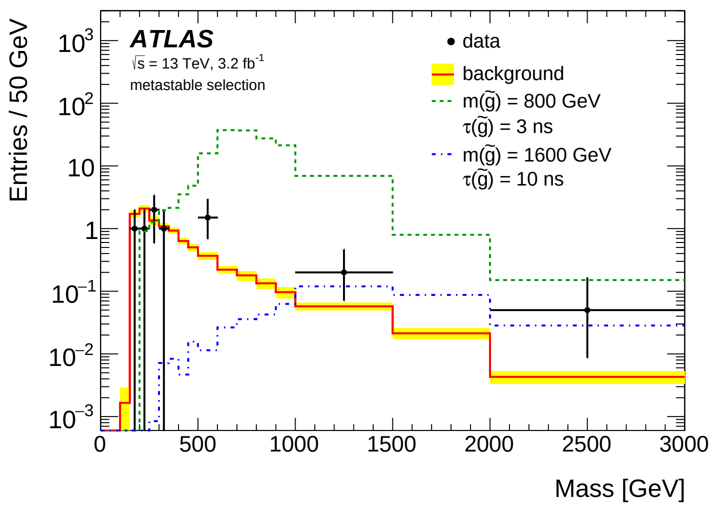

Figure 2: Mass distribution for data and background for metastable particle searches. The yellow band around the background estimation includes both the statistical and systematic uncertainties. Also shown are two examples for signals as expected for gluino R-hadrons in the explored mass range [2].

No evidence of a signal above the background is observed. Expected and observed upper limits on R-hadron production cross sections are evaluated at 95% confidence level (CL) for a discrete set of R-hadron mass values. The strongest mass limits are obtained for lifetimes of 10 ns or more and the excluded regions on the lifetime-mass plane for R-hadrons decaying to $q\bar{q}$ plus a light neutralino of mass $m(\tilde{\chi}_0) = 100$ GeV are shown in Figure 3.

Gluino R-hadrons with lifetimes above 0.4 ns and decaying to $q\bar{q}$ plus a 100 GeV neutralino are excluded at the 95% confidence level with lower mass limit range between 740 GeV and 1590 GeV. In the case of stable R-hadrons the lower mass limit at the 95% confidence level is 1570 GeV. The observed lower limit on R-hadron masses increases by up to approximately 400 GeV relative to the equivalent analysis at $\sqrt{s} = 8$ TeV [3].

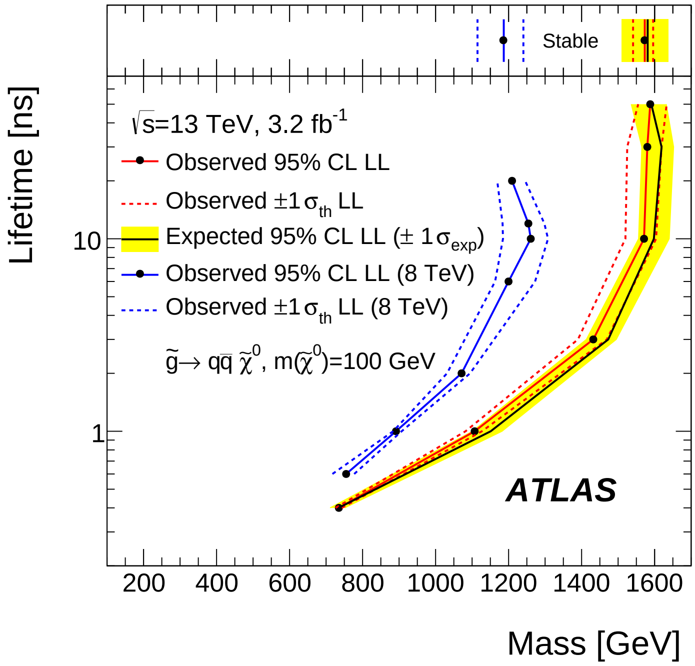

Figure 3: Excluded range of lifetimes as a function of gluino R-hadron mass. The expected lower limit (LL), with its experimental $\pm 1\sigma$ band, is given with respect to the nominal theoretical cross-section [2]. The observed 95% LL obtained at $\sqrt{s} = 8$ TeV [3] is also shown for comparison.

References

[1] M. Fairbairn *et al.*, *Stable massive particles at colliders*, Phys.Rept. 438 (2007) 1-63.

[2] ATLAS Collaboration, *Search for metastable heavy charged particles with large ionization energy loss in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS experiment*, Phys.Rev. D93 (2016) no.11, 112015

[3] ATLAS Collaboration, *Search for metastable heavy charged particles with large ionisation energy loss in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS experiment*, Eur.Phys.J. C75 (2015) no.9, 407