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Search for metastable heavy charged particles with large ionisation energy loss in *pp* collisions at $\sqrt{s} = 13\,\text{TeV}$ using the ATLAS experiment

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Summary. — Many extensions of the Standard Model predict the existence of charged and heavy long-lived particles, such as R-hadrons. These particles, if produced at the Large Hadron Collider (LHC), should be non-relativistic and are therefore identifiable through the measurement of an anomalously large energy loss in the ATLAS Pixel Detector. The search for heavy long-lived particles using track information in the vicinity of the interaction vertex is sensitive for values of their lifetime in the nanosecond range. The research of metastable and stable R-hadrons with the ATLAS detector using 2015 LHC data is here reported.

1. – Introduction

This analysis [1] searches for massive, long-lived particles (LLPs) such as some R-hadron candidates. These particles are predicted in many extensions of the Standard Model (SM) and they appear, for example, in both R-parity-conserving and -violating supersymmetry (SUSY) and in universal extra dimensions theories. R-hadrons can be stable, or metastable, in the second category we include all those decaying in the detector volume. In this second case the lifetime-range coverage goes from a fraction of a nanosecond to several tens of nanoseconds. If produced at the LHC, such heavy particles are expected to be slow ($\beta \ll 1$) and, if charged, to have a specific ionization higher than any SM particles of unit charge at large momenta. In particular the ATLAS Pixel Detector provides a measurement of the charge deposited by charged particles crossing it and the specific rate of energy loss ($\mathrm{d}E/\mathrm{d}x$) may be used to identify massive, highly ionizing particles. As no trigger is available based on large momentum or highly ionizing tracks, events are selected requiring missing transverse energy (MET), calculated from energy deposits in the calorimeter. For events with R-hadrons which decay before or inside the calorimeter, undetected neutralinos of the R-hadron decays contribute to the measured transverse energy imbalance. As stable R-hadrons are foreseen to deposit little energy in the calorimeters, if they are stable the events are selected by the missing transverse energy trigger only in case the QCD initial-state radiation (ISR) unbalances the momentum of the R-hadron pair.

2. – ATLAS detector

The ATLAS detector [2] consists of a tracker surrounded by a solenoid magnet, followed by calorimeters for measuring the energy of particles that interact electromagnetically or hadronically. A muon spectrometer immersed in a toroidal magnetic field surrounds the calorimeters, and provides tracking for muons. The detector is hermetic and can therefore measure the missing transverse momentum associated with each event. The tracker is made of three detector systems, but the innermost Pixel Detector is crucial for this measurement. The current Pixel Detector provides at least four precision measurements for each track in the region $|\eta| \leq 2.5$ at radial distances of 3.4 to 13 cm from the LHC beam line. 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 Run 1 Pixel Detector, mounted on a new beam pipe of smaller diameter.

3. – Pixel dE/dx

The Pixel $\mathrm{d}E/\mathrm{d}x$ is the key signal discriminant in this analysis [3], it is used to detect massive, highly ionizing particles and to reconstruct their mass based on a parameterization of the most probable value of the specific rate of energy loss. The Pixel $\mathrm{d}E/\mathrm{d}x$ is defined as an average of the individual cluster $\mathrm{d}E/\mathrm{d}x$ measurements (charge collected in the cluster, corrected for the track length), for all good clusters [3] associated to the track. To reduce the Landau tails, the average is evaluated after having removed the cluster(s) with the highest charge. The average energy loss of massive, charged particles is expected to follow the Bethe-Bloch distribution, which can be expressed as a function of the $\beta\gamma$ of the LLPs: the mass estimate M is therefore obtained by numerically solving the Bethe-Bloch for the unknown M.

4. – Event selection and background estimation

The data sample used for this analysis was collected while tracking detectors, calorimeters, muon chambers, and magnets were operating normally and corresponds to an integrated luminosity of $3.2\,\mathrm{fb}^{-1}$ in 2015. Candidate events have been selected online using the missing transverse energy, computed from energy deposits in the calorimeter, with a threshold of 70 GeV. Additionally the event is then requested to have an offline MET > 130 GeV. A primary vertex reconstructed from at least two well-reconstructed charged-particle tracks, each with $p_\mathrm{T} > 400$ MeV, is required in order to remove non-collision background events. The selected events have to contain at least one candidate R-hadron track: it has $p_\mathrm{T} > 50$ GeV and contains at least seven clusters from silicon detector layers in order to make a good measurement of the track's momentum, it also must have a cluster in the innermost Pixel layer if expected, and must be associated with the primary vertex. Moreover the candidate track must have at least two clusters in the Pixel Detector used to measure $\mathrm{d}E/\mathrm{d}x$, in order to ensure a good ionization measurement. To reject background events with overlapping tracks that could produce clusters with significant measured ionization, the candidate track must not contain any cluster that is compatible with contributions from two or more tracks. R-hadrons with a

Table I. – *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.*

Selection region	Background exp.	Data
Metastable R-hadron	$11.1 \pm 1.7 \pm 0.7$	11
Stable R-hadron	$17.2 \pm 2.6 \pm 1.2$	16

lifetime shorter than 50 ns typically do not reach the muon spectrometer, and therefore a muon veto is applied in the metastable R-hadron search. Furthermore to reject hadronic background an isolation requirement on the $\sum p_{\mathrm{T}}$ of nearby tracks of 20 GeV (5 GeV) is applied for candidate metastable (stable) R-hadron tracks. The background strategy estimation is data-driven. The method consists of using control samples in data to parameterize the key variables distributions and their interdependence and then to generate a high-statistics pseudo-data random background sample based on these distributions.

5. – Conclusions and results

The search retains 16 (11) events for the stable (metastable) R-hadron selection. Table I summarizes the background estimates with total statistical and systematic uncertainty as well as the observed events for the metastable and stable R-hadron selection.

No evidence of a signal above the background is observed. 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 [4].

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