ATLAS NOTE

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Background studies to searches for long-lived stopped particles decaying out-of-time with LHC collisions

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Abstract

R-hadrons are massive, long-lived particles predicted in several Supersymmetry scenarios. This note describes a first study of backgrounds to a search for gluino R-hadrons which have come to rest within the ATLAS detector volume, particularly the calorimeter, and decay at some later time, dictated by the lifetime of the particle. We isolate events with jets, potentially produced from the 2- or 3- body decays of the gluinos stopped within the calorimeter. Candidate events are triggered in the empty bunch crossings in order to remove collision backgrounds. Simple selection criteria enable the discrimination of signal-like events from backgrounds, the largest of which is from cosmic muons.

1 Introduction

Long-lived massive particles appear in many theories beyond the Standard Model [1]. They are predicted in supersymmetry (SUSY) models, such as split-SUSY [2, 3] and Gauge Mediated Supersymmetry Breaking [4]. They are also predicted in other exotic scenarios, e.g. Universal Extra Dimensions [5] and lepto-quark theories [6]. Due to this variety of theoretical predictions, both discovery and non-discovery is important in excluding different exotic models. Long-lived massive particles containing a heavy colored particle are called R-hadrons. ATLAS [7] studies focus on gluino R-hadrons that occur in split-SUSY. Split-SUSY suggests that the hierarchy problem can be addressed by the same fine-tuning mechanism that solves the cosmological constant problem, making low energy SUSY uncalled for. Given this condition, SUSY can be broken at a very high energy scale, leading to heavy scalars, light fermions and a light finely tuned Higgs particle [2]. Within this phenomenological picture, squarks will be much heavier than gluinos, suppressing the gluino decay and resulting in meta-stable gluinos. If the lifetime of the gluinos are long enough they will hadronize into final states of R-mesons ($\tilde{g}q\bar{q}$), R-baryons ($\tilde{g}qqq$) and so-called R-gluinoballs ($\tilde{g}g$).

R-hadron interactions in matter are highly uncertain. However, some features are well predicted. The gluino can be regarded as a heavy, non-interacting spectator, surrounded by a cloud of interacting quarks. R-hadrons change their properties through strong interactions with the detector, most R-mesons will turn into R-baryons [8] and they can also change their electric charge. At the Large Hadron Collider (LHC) at CERN [9], the gluino R-hadrons (if they are realised in nature) will be produced in pairs and approximately back-to-back in the transverse plane. Some fraction of these R-hadrons can lose all of their momentum, mainly from ionization energy loss, and can come to rest within the detector volume, only to decay at some later time. In order to measure such decays one has to devise a search strategy to reduce the background processes as effectively as possible. For this search we use a trigger operating only in the empty bunches of the LHC bunch structure to remove backgrounds from collision processes, leaving only some machine related backgrounds and natural sources such as cosmic rays. In this note we describe and motivate the selection criteria we apply to isolate a region of phase space in which to perform a study of the backgrounds to such a search.

We determine an event selection that will be reasonably efficient at reconstructing late decaying, stopped gluinos. We ensure that these selection criteria when applied to a sample of cosmic ray data do not retain a large fraction of the background. Finally, we compare the yield from cosmic ray data to that of out-of-time bunches in collision data to see if it looks similar to cosmics. We summarize the note with result of these event yields from both cosmic ray data and the early data collected with 7 TeV proton-proton collisions at the LHC.

A previous search for stopped gluino R-hadrons was performed by the D0 collaboration [10] which excluded a signal for gluinos with masses up to 250 GeV[1)]. This analysis, however, could only use the filled crossings in the TeVatron bunch scheme and demanded that there were no non-diffractive interactions present to suppress collision related backgrounds. Search techniques similar to those described herein have also been considered by the CMS collaboration [11].

2 Experimental setup

The ATLAS detector [7] covers almost the whole solid angle around the collision point with layers of tracking detectors, calorimeters and muon chambers. It has been designed to study a wide range of physics topics at LHC energies [12]. For the measurements presented in this note, the calorimeters and muon system are of particular importance.

[1)] Natural units, with c=1, are used throughout.

High granularity liquid-argon (LAr) electromagnetic sampling calorimeters, with excellent performance in terms of energy and position resolution, cover the pseudo-rapidity range $|\eta| < 3.2$. The hadronic calorimetry in the range $|\eta| < 1.7$ is provided by a scintillator-tile calorimeter, which is separated into a large barrel and two smaller extended barrel cylinders, one situated on either side of the central barrel. In the end-caps ($|\eta| > 1.5$), LAr technology is used for the hadronic calorimeters, matching the outer $|\eta|$ limits of the end-cap electromagnetic calorimeters. The LAr forward calorimeters provide both electromagnetic and hadronic energy measurements, and extend the coverage to $|\eta| = 4.9$.

Jets are constructed using the infrared and collinear-safe anti-k_T jet algorithm [13] with a distance parameter (η-ϕ space)[2)] set to R = 0.4. The inputs to the jet algorithm in both cosmic and collision data samples are energy deposits in the calorimeter clusters. ATLAS jet reconstruction algorithms are described in more detail elsewhere [14].

The ATLAS Muon Spectrometer [4] designed to detect tracks over a large region of pseudo-rapidity $|\eta| < 2.7$, is made of a large toroidal magnet (with an average magnetic field of 0.5 Tesla) and consists of four detectors, each using a different technology. It has one Barrel Region (BR) and two End-cap Regions (ER). Monitored Drift Tube chambers (MDT) in both the BR and ER sections and Cathode Strip Chambers (CSC) are used as precision chambers, whereas Resistive Plate Chambers (RPC) in the BR and Thin Gap Chambers (TGC) in the ER are used as trigger chambers. The chambers are arranged in three layers, so particles traverse up to three stations with a lever arm of several metres.

The MDT chambers are composed of layers of grounded tubes filled with an Argon-CO_2 gas mixture. In the middle of each tube there is a wire to which a high voltage is applied. When a charged particle passes through a tube it ionizes the gas, and the ionized electron drifts toward the wire. The hit position is obtained from the particle drift time, the result being a circle around the wire. A segment is reconstructed as a line tangent to the radii in the different layers.

The ATLAS detector has a three-level trigger system: Level 1 (L1), Level 2 (L2), and the Event Filter (EF). For these measurements, the trigger relies on the Jet triggers from the calorimeter which fire during an empty bunch crossing where there are no protons present. There are a variety of periods during the LHC orbit in which no proton-proton collisions occur in ATLAS. We utilise information from the beam timing pick-ups in order to correctly define the bunch groups. We define an “empty” bunch crossing by requiring neither monitor fire. Our Level 1 trigger requirement is then to demand a jet be recorded during these empty bunch crossings.

3 Data samples used

The studies performed herein present the data collected with a trigger running in the empty bunches of the LHC running at $\sqrt{s}$ = 7 TeV. The expected sources of events in this sample come primarily from cosmic rays, with some negligible residual beam-halo and beam-gas background. In order to test this assumption, we compare the data collected with ATLAS in 2009 from dedicated runs to record cosmic ray events, used to commission the detector, prior to any collisions being performed by the LHC. Specifically, we select runs between May and November in 2009 when the detector configuration and reconstruction algorithms closely match those used in the collision data taking. These data have a sample size of 5.42×10^6 events satisfying a 10 GeV jet requirement at the Level-1 trigger.

We compare these to the data analyzed from the March to June period of the 2010 run. These data represent a sample of $2.7 \pm 0.3\,\mathrm{nb}^{-1}$.

[2)])The ATLAS reference system is a Cartesian right-handed coordinate system, with nominal collision point at the origin. The anti-clockwise beam direction defines the positive z-axis, with the x-axis pointing to the center of the LHC ring. The pseudo-rapidity is defined as η = -ln(tan(θ/2), where the polar angle θ is taken with respect to the positive z direction.

4 Event Selection

The analysis described herein is geared towards the first months data taking with ATLAS operating at the LHC with a 7 TeV centre-of-mass (CM) collision energy.

The data analysed here is triggered during the gaps between crossings in the LHC beam structure. This limits the background sources to those from cosmic rays, and beam related background such as beam-gas interactions and beam-halo. These background sources are studied in data to get a handle on both their shapes and yields. The candidate event selection proceeds by limiting the events considered to be only those where one or more jets are present in the triggered sample, the jets should be central and requirements are imposed on their shape. In order to further reduce backgrounds we impose requirements on the cluster shapes of energy depositions. These criteria are described in section 5. We compare the extracted yield of events with those expected from background sources. Data from dedicated ATLAS runs to collect cosmic rays, performed in 2009 before the LHC began stable collisions, are used as the sample to which the data is compared.

4.1 Background Sources

The most pertinent background source is cosmic events where no muon candidate is recorded, but which deposit considerable energy in the calorimeter volume. An additional background source arises from beam-halo events, where a halo proton interacts with the tertiary collimators producing a forward boosted muon which does not leave a track in the muon system, but deposits some of its energy in the calorimetry of ATLAS. Other backgrounds could come from stray protons in the empty bunches which interact with particles in the interaction region, either the beampipe itself or gas in the interaction region, causing a ”collision-like” event to occur within the empty bunch, these will be referred to as ”beam-gas” events. Actual pp collisions between such particles are extremely unlikely since they are off-beam momentum and diffusely distributed.

These beam-backgrounds cannot be measured without circulating beam, and so we have only been able to get a handle on their rates with first data, and on potential criteria that can eliminate them, should they become a cause for concern. Both types of events have specific topologies which differ from those of a stopped particle decay; beam-halo events should be associated with a track, or segment, in one or other muon endcaps, beam-gas events will be associated with tracks in the tracker pointing to a vertex inside, or on, the beampipe. In principle, beam-halo may be removed by masking time buckets adjacent to filled bunches, either offline or in the trigger, although we assume this will be unnecessary. Furthermore, beam-halo events will have a characteristic ϕ distribution for the calorimeter energy deposits related to the positions of the collimators where particles are arising from, and the muon endcaps where they have first deposited energy. Should the background from this source become difficult to deal with we can always cut away these regions of phase-space, with some loss of efficiency for the signal.

Another source of potential background comes from noise in the calorimeter in the form of bursts of noise, either in isolated cells, or in the whole data acquisition system. Such backgrounds can be particularly troubling due to the potential lack of any correlation with other detector activity. The ways we attempt to suppress these and other processes are discussed in the next section.

5 Event Selection Criteria

The basic selection criteria imposed to isolate signal-like events from background-like events demand at least one high energy jet and no tracks or segments reconstructed in the muon system. Additionally, the reconstructed jet should be central in η. Since most of the gluino bound states are produced centrally in η we restrict ourselves to searching only in the central barrel and extended barrel of the calorimeter and require that the leading jet satisfy $|\eta| < 1.2$. The jet energy in the calorimeters should also be high. In order to reject energy depositions from MIPs we demand the leading jet energy be greater than 50 GeV. We allow for additional jets (up to 3 jets in total) in order to retain sensitivity to the decay mode $\tilde{g} \to q\bar{q}\chi^0$. In order to remove events where we would be sensitive to a single channel "spike" in the calorimeter, due to noise in the electronics or data corruption, we veto events where 90% of the energy deposit of the leading jet (n90) is contained inside three or fewer cells. Furthermore, we also demand that the leading jet contains 50% of its energy (n50) in 5 or fewer calorimeter cells.

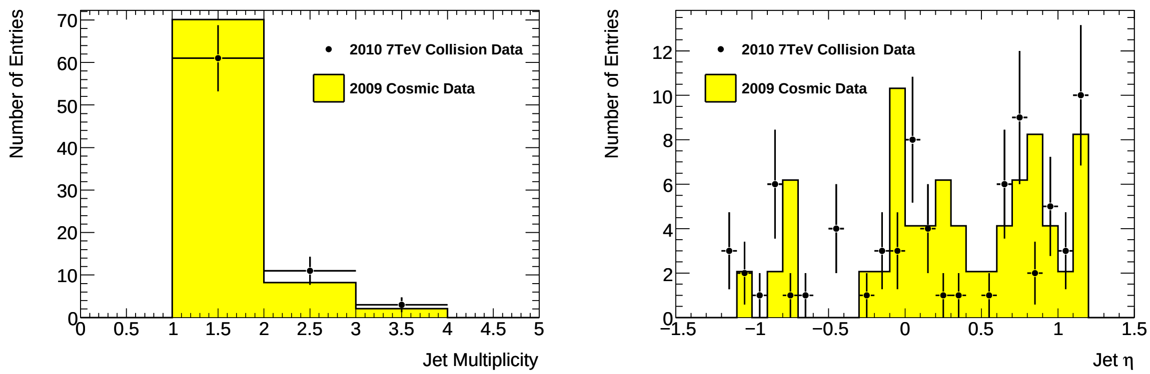
A dedicated algorithm was implemented in order to flag noise bursts. The principle is the following: for each front end board (FEB - 128 channels), the number of channels with a pulse shape inconsistent with ionization signal is extracted; if the FEB contains more than 30 channels that are bad, it is declared as noisy; if the events contains 5 FEBs with 30 or more noisy channels, the event is flagged as suffering from a noise burst, and should be discarded. This requirement is referred to as "LAr Noise" in what will follow.

Noise bursts which affect a large fraction of the subdetector are expected to be flagged at the data quality step of the processing. Only such blocks of data are considered here where the calorimeters' (both hadronic and electromagnetic) data quality flags are marked as good, as well as stable beams are present in the LHC, with the high voltages of the subdetectors successfully ramped.

The events selected in data are collected with a 10 GeV jet trigger which must fire in concert with an empty bunch. Tab. 1 presents the number of events surviving each cut on the 2009 cosmic data collected with ATLAS while also showing the event yield after each selection criteria in the 2010 collision data. Given the different detector conditions, and potentially different levels of detector noise, we do not expect to be able to directly compare the initial yields of the runs recorded in the 2009 cosmic data to those from the 2010 collision data. In order to make a more accurate comparison between these samples they are processed further prior to being compared. In particular, the line corresponding to "Good runs and data quality cuts" in Tab. 1 includes only events passing the data quality criteria, the trigger requirements, LAr noise and after the removal of bad runs from the cosmics. By doing this we attempt to reduce any bias arising from detector conditions, reconstruction versions and data quality requirements used for the samples. Therefore the distributions and tables are only normalized after these effects have been removed and the jet $|\eta|$ requirement is imposed. The level of agreement is compared by scaling the raw yields in Tab. 1 using this normalization. Figs 1(a), 1(b), 2(a), 2(b), 3(a), 3(b) are scaled using this normalization, and the yields correspond to the number of entries after demanding no muon segments are present and that the leading jet energy be greater than 50 GeV. Fig. 1(a) shows the number of jets surviving this selection and demonstrates that the majority of events have only a single jet. The pseudorapidity of the leading jet is plotted for each sample in Fig. 1(b). In order to exploit the shape difference between deposits from cosmics and the expected signal shape, we make further requirements on the shape of the leading jet. In particular, the first moment of the radial jet energy distribution (jet width), plotted in Fig. 2(b), demonstrates good agreement in the shape of the energy deposits within jets in the background-like events. Similarly, the jet electromagnetic fraction, the fraction of energy deposited in the electromagnetic calorimeter, (Jet EMF) shows good agreement between the empty bunch triggered data and the 2009 cosmic sample. We impose that the jet width$>$0.05 and jet EMF$<$0.95.

6 Results

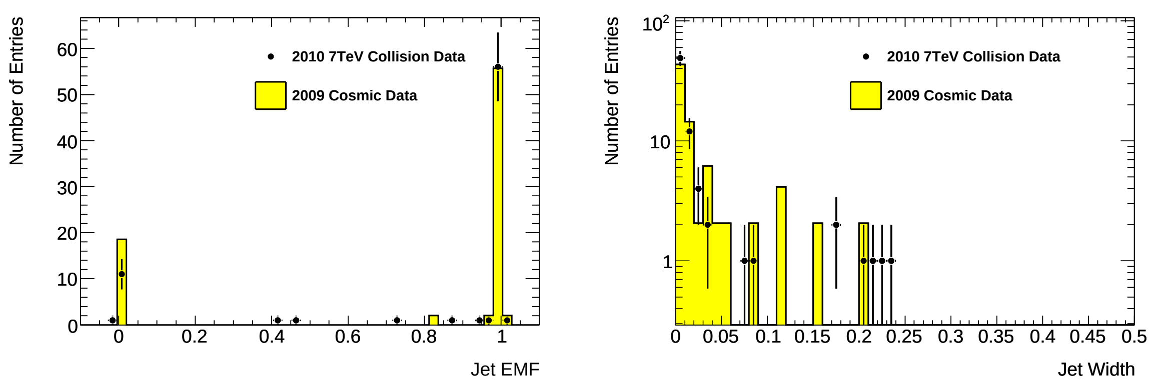
We impose our selection criteria to the samples defined in section 3. As can be seen from Tab. 1 the number of background events in the 2009 Cosmic data sample, surviving our selection criteria is low. These data were taken prior to beam being present in the LHC and so there is no chance of signal events being present in this data sample. The sample represents runs from periods spanning May-November 2009. The total number of events satisfying all selection criteria is two. Four events survive the same



(a) Jet multiplicity

(b) Leading jet η

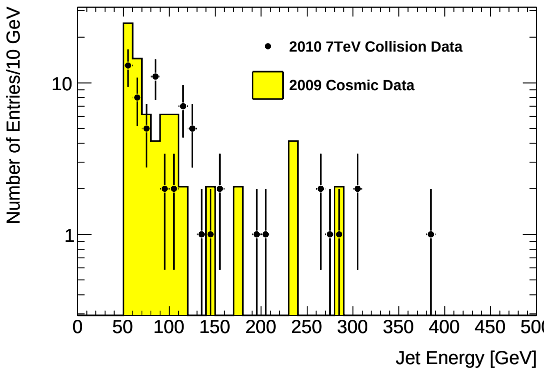
Figure 1: Jet variables plotted for the empty bunch triggers in 7 TeV collision data (black points) compared with 2009 cosmic data (filled histogram). We demand that all cleaning cuts described in the text are applied and that n90>3. We further require that there are zero reconstructed muon segments, that there be a leading jet with energy greater than 50 GeV and situated within $|\eta| < 1.2$. The jet multiplicity (left) and leading jet η (right) are plotted. The normalization of the cosmic data is described in section 5.



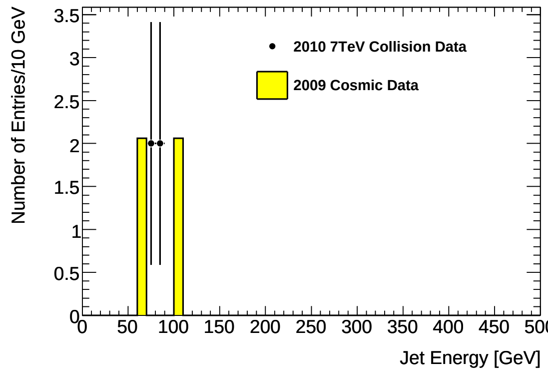
(a) Leading jet electromagnetic fraction

(b) Leading jet width

Figure 2: Jet variables plotted for the empty bunch triggers in 7 TeV collision data (black points) compared with 2009 cosmic data (filled histogram). We demand that all cleaning cuts described in the text are applied and that n90>3. We further require that there are zero reconstructed muon segments, that there be a leading jet with energy greater than 50 GeV and situated within $|\eta| < 1.2$. The leading jet electromagnetic fraction (left) and leading jet width (right) are plotted. The normalization of the cosmic data is described in section 5.



(a) Leading Jet Energy



(b) Leading Jet Energy, after all selection criteria

Figure 3: Jet energy plotted for the empty bunch triggers in 7 TeV collision data (black points), compared with 2009 cosmic data (black histogram). We demand there be no muon segments reconstructed in the muon detectors. There must be a leading jet with energy$>$ 50 GeV and situated within $|\eta| < 1.2$. For the Figure on the right we additionally impose that the leading jet width$>$0.05, n90$>$3, n50$<$6 and jet electromagnetic fraction$<$0.95. The normalization of the cosmic data is described in section 5.

Table 1: Selection criteria overview table for 2009 cosmic data collected between May and November 2009 compared with the 2010 collision data collected between March and June 2010.

	2009 Cosmic Data		2010 Collision Data
Selection Criteria	Yield of cosmics	Cosmics (scaled)	Yield of data
Good runs and data quality cuts	9.43×10^5	–	1.58×10^6
Leading Jet $\|\eta\|$ <1.2	6.26×10^5	1.29×10^6	1.29×10^6
Jet n90>3	3.83×10^5	7.89×10^5	7.90×10^5
number of Jets<4	3.82×10^5	7.87×10^5	7.83×10^5
Muon Segment Veto	530±23.0	1092±47.4	1170
Leading Jet Energy > 50 GeV	39±6.2	80±12.8	75
Leading Jet Width > 0.05	6±2.4	12±4.9	8
Jet n50<6	3±1.7	6±3.5	4
Leading Jet EMF<0.95	2±1.4	4±2.9	4

selection criteria in data and these agree well given the scaling factor between the samples. Given the corresponding time period involved, the operations of the detector during this period, and the number of events considered, these data represent a running period on the order of two months, as opposed to the entire period encompassed by the cosmic runs. Given that, we would be sensitive to some small number of background events per month, on the order of one or two.

Due to the large number of empty bunches available to us to trigger in during the early collision data these can be considered similar to the cosmic runs as far as the expected rate of backgrounds from cosmic muons is concerned. Therefore in the current data set we would expect approximately four background events from cosmic muon sources, a yield consistent with this, within the expected uncertainty is observed given that four events pass the selection criteria in the collision data sample.

7 Discussion

Given that the number of bunches, and the LHC operating parameters, will evolve over coming months, the empty bunch triggered background rate cannot be accurately extrapolated over the entire period during which LHC will run at $\sqrt{s} = 7$ TeV. For the purposes of this particular note we satisfy ourselves that the current yields in the cosmic sample from 2009, after removing noise and applying cleaning requirements to the sample, and the empty bunch triggered data collected during collisions at 7 TeV, are in good agreement. This shows that the empty bunch triggered data are consistent with arising from cosmic muons sources alone.

8 Summary and conclusion

We have presented first results from the ATLAS experiment comparing data collected with a jet trigger operating in the empty bunch crossings of the LHC to a sample of cosmic muon data collected in 2009. These data show good agreement with the hypothesis that the events constituting this sample arise mostly from cosmic muon sources. Furthermore, we have demonstrated that with a simple set of jet requirements and demanding no reconstructed muon segments we can reduce the rate of these backgrounds by six orders of magnitude.

The search strategy will evolve in the coming months as we continue to collect data. In particular beam backgrounds will be estimated from the unpaired bunch crossings (where only beam travelling in one direction is present) and an estimate of the search sensitivity will be performed using signal simulation samples. These will be combined with the work presented herein, along with the study of additional variables which may help us separate signal and background-like events, as we converge on a result of the search for stopped long-lived particles.

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