# $R$-HADRONS AT ATLAS — DISCOVERY PROSPECTS AND PROPERTIES*

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$R$-hadrons are massive, meta-stable particles predicted in several Supersymmetry scenarios. Studies exploring the discovery potential of $R$-hadrons at the ATLAS detector have mainly focused on gluino $R$-hadrons. These studies have shown that gluino $R$-hadrons should be discovered in early running of the LHC, that they are easily isolated by simple cuts and that their mass can be measured to an accuracy of a few percent.

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## 1. Introduction

Stable Massive Particles (SMPs) [1] appear in many theories beyond the Standard Model [2]. They are predicted in supersymmetry (SUSY) [3] models, such as Split-SUSY [4] and Gauge Mediated Supersymmetry Breaking [5]. They are also predicted in other exotic scenarios, *e.g.* Universal Extra Dimensions [6] and lepto-quark theories [7]. Because of this both discovery and non discovery is important in excluding different exotic models.

SMPs containing a heavy colored particle are called $R$-hadrons. ATLAS [8] 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 Supersymmetry uncalled for. Given this condition, supersymmetry can be broken at a very high energy scale, leading to heavy scalars, light fermions and a light finely tuned Higgs particle [4]. Within this phenomenological picture squarks will be much heavier than gluinos, the

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gluino decay will then be suppressed, causing gluinos to be the meta-stable. If the lifetime of the gluinos are long enough they will hadronise giving final states of $R$-mesons ($\tilde{g}q\bar{q}$), $R$-baryons ($\tilde{g}qqq$) and so-called $R$-gluinoballs ($\tilde{g}g$).

The details of $R$-hadron interactions in matter are highly uncertain. However, some features are well understood. The gluino can be regarded as a heavy non-interacting spectator, surrounded by a cloud of interacting quarks [9]. $R$-hadrons change their properties through interaction with the detector, most $R$-mesons will turn into $R$-baryons [12] and they can also change the sign of their electric charges.

At the Large Hadron Collider (LHC) the gluino $R$-hadrons are pair produced approximately back-to-back in the transverse plane. PYTHIA [10], with default settings, predicts that 55% of the $R$-hadrons are produced neutral and escape detection in the Inner Detector. Charged $R$-hadrons can leave tracks in both the Inner Detector and the Muon Spectrometer, given that the lifetime is long enough. Furthermore, charge flipping complicates this picture; $R$-mesons or $R$-baryons produced neutral can become charged and *vice versa*. However, charge flipping is a powerful tool in isolating a pure sample of $R$-hadrons.

$R$-hadrons are heavy and in many cases move with a speed less than the speed of light; their arrival in the Muon Spectrometer will therefore be delayed compared to ordinary muons. $R$-hadrons with a value of $\beta$ larger than 0.7 are always identified with the same bunch crossing as the rest of the event and satisfy the requirements of the trigger [11].

## 2. ATLAS studies on *R*-hadrons

Within the last couple of years (2004–2006) there have been several studies of $R$-hadrons at ATLAS. They have all been studies of gluino $R$-hadrons within the Split-SUSY scenario, using the implementation of Kraan's interaction model in GEANT3 [12, 13]. Recently the model was implemented in GEANT4 [14] as well [15].

### *2.1. Search using global variables*

The discovery of $R$-hadrons at ATLAS is possible using global variables only [12]. This work used a parametrized detector simulation program (ATLFAST [16]). The focus was to investigate a strategy for discovering $R$-hadrons at ATLAS using solely global event variables. These were:

- missing transverse energy due to neutral $R$-hadrons, $E_{\mathrm{T}}^{\mathrm{miss}}$,
- the total energy of the event, $E_{\mathrm{tot}}$,
- transverse momentum of the muon track, $p_{\mathrm{T}}$.

Fig. 1 shows $E_{\mathrm{T}}^{\mathrm{miss}}$, $E_{\mathrm{tot}}$ and $p_{\mathrm{T}}$ distributions for background (upper plots) and 300 and 900 GeV/$c^2$ mass $R$-hadrons (lower plots). From these plots we see that cutting on the above-mentioned quantities can provide a high discrimination between signal and background. In fact by using global variables only, it was shown that $R$-hadrons up to masses of 1400 GeV/$c^2$ could be discovered for an integrated luminosity of 30 fb$^{-1}$. Including time-of-flight information, using the method described in Section 2.3, increased this limit up to 1800 GeV/$c^2$. For masses below 1000 GeV/$c^2$ a signal significance above 5 could be reached after a few days.

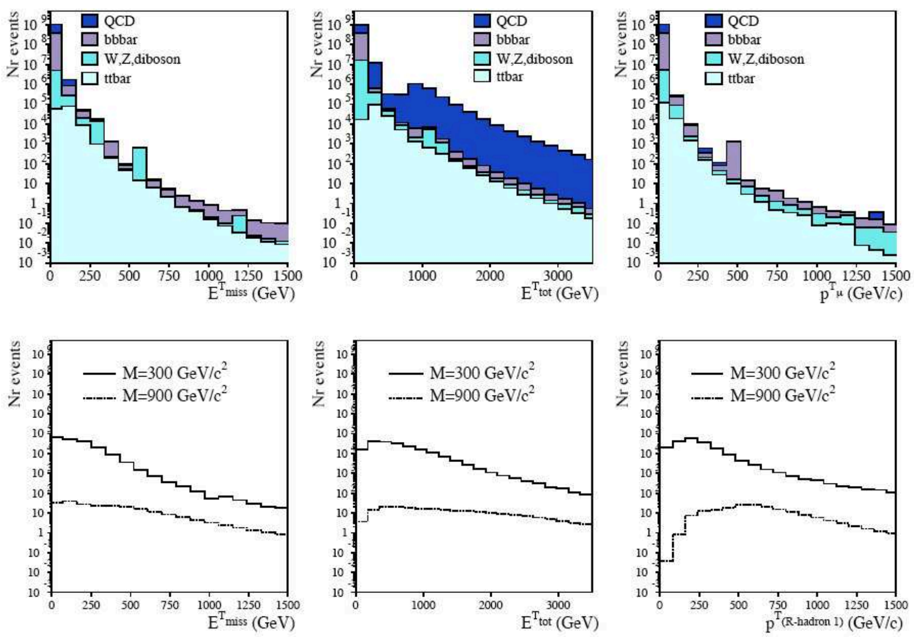


Fig. 1. The missing transverse energy and the total visible energy, after high level trigger requirements for background (top) and signal ($R$-hadron with masses of 300 and 900 GeV/$c^2$). The number of events corresponds to an integrated luminosity of 1 fb$^{-1}$ [11].

This strategy is relatively model independent, and shows good prospects for discovering any Stable Massive Particle, regardless of scenario. However it is not suitable for measuring the $R$-hadron quantum numbers and cannot distinguish between a gluino $R$-hadron and another SMP.

### *2.2. Search using charge flippers*

A full GEANT3 detector simulation of $R$-hadron interactions was used for the first time [9]. The purpose of this work was to show how the charge flipping property could be used to isolate a pure sample of $R$-hadrons. Three different selection criteria were used:

1. Opposite charge tracks in Inner Detector (ID) and Muon Spectrometer (MS).
2. Two same sign, high $p_{\mathrm{T}}$-tracks in the Muon Spectrometer.
3. Two same sign, high $p_{\mathrm{T}}$-tracks in MS and explicitly no tracks in ID.

For masses 300 and 500 GeV/$c^2$ tracks were required to have $p_{\mathrm{T}} > 150$ GeV/$c$, while for 1000 GeV/$c^2$ masses the requirement on track momenta was increased to $p_{\mathrm{T}} > 350$ GeV/$c$. Additional requirements were put on the track reconstruction, the quality of track matching *etc.* Both signal and QCD, $b\bar{b}$, $t\bar{t}$ and $W$, $Z$ diboson background were exposed to the same cuts.

Fig. 2 shows the distribution of signed transverse momentum ($q \times |p_{\mathrm{T}}|$) in the muon system($p_{T_\mu}$) divided by the absolute value of transverse momentum in ID ($p_{\mathrm{T_{ID}}}$) for background and signal. Particles in both samples were produced with negative charge. The background (primarily muons from $W, Z$ and top production) distribution in the leftmost plot shows that the SM particles are still negative when detected in the muon system, while approximately 50% of the $R$-hadrons have changed electric charge as shown in the rightmost plot.

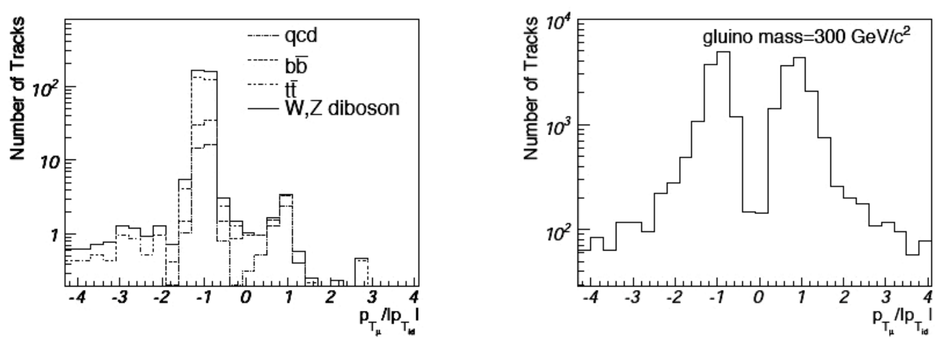


Fig. 2. Signed $p_{\mathrm{T}}$ in the Muon Spectrometer over the absolute value of $p_{\mathrm{T}}$ in the inner detector for background (left) and signal (right) for particles produced with negative charge.

The results from applying these cuts on signal and background events are shown in Table I. The leftmost column give the result for selection criterion 1, which explicitly selects particles that have changed charge while traversing the detector. As expected a very good background rejection is shown, since charge flipping does not commonly occur among ordinary muons.

TABLE I

Selection 1: Results from selecting opposite charge tracks in Inner Detector and Muon Spectrometer. Selection 2: Results from selecting two high $p_{\mathrm{T}}$-tracks in the Muon Spectrometer. Selection 3: Results from selecting two same sign, high $p_{\mathrm{T}}$ tracks in MS and explicitly no tracks in ID. No background events satisfied the selection. Entries with no number signifies less than one event at 95% confidence level.

| Source | | Number of tracks passed Scaled to $2\mathrm{fb}^{-1}$ | | |
|---|---|---|---|---|
| | | **Selection 1** | **Selection 2** | **Selection 3** |
| Signal | 300 | 21 598 | 16328 | 5199 |
| Gluino mass | 500 | 1742 | 1488 | 455 |
| (GeV/$c^2$) | 1000 | 16 | 13 | 6 |
| Background | QCD | 11 | 0.9 | — |
| $p_{\mathrm{T}} > 150$ GeV/$c$ | $b\bar{b}$ | 4.0 | 1.8 | — |
| | $t\bar{t}$ | 0.9 | 1.8 | — |
| | $W$, $Z$, diboson | 1.1 | 6.8 | — |
| | total | 17 | 11.3 | — |
| Background | QCD | 0.6 | — | — |
| $p_{\mathrm{T}} > 350$ GeV/$c$ | $b\bar{b}$ | 0.7 | — | — |
| | $t\bar{t}$ | — | — | — |
| | $W$, $Z$, diboson | 0.33 | 0.8 | — |
| | total | 1.6 | 0.8 | — |

The central column shows the result of picking two same sign high $p_{\mathrm{T}}$ tracks in MS. Two same sign muons with large transverse momentum is also a rare signature, and again very few background events satisfy the selection.

The effect of requiring two same sign, high $p_{\mathrm{T}}$ tracks in MS and explicitly no track in the Inner Detector is shown in the rightmost column. $R$-hadrons that are produced electrically neutral and later convert into charged particles in the calorimeter will be selected. No background events satisfy this selection, leaving a pure sample of $R$-hadrons.

From Table I we see that selection criteria 1–3 all give very good background rejection. Also note that criterion 1 and 3 can also identify the particles as gluino $R$-hadrons, since no other $R$-hadron or SMP can flip electric charge.

### 2.3. *Mass determination of R-hadrons*

The most recent ATLAS-study [18] illustrates the possibility of measuring the mass of gluino $R$-hadrons using the time-of-flight method [19]. Information on the track fitting parameters is available in the full GEANT3 detector simulation. Here the Moore [20] track-fitting reconstruction algorithm is tuned for relativistic particles with $\beta = 1$. For heavier particles, like $R$-hadrons, this will lead to an over-estimation of the drift time[1]and will give a bad $\chi^2$ for the track fit. If, however, different values of $\beta$ are assumed during track-reconstruction, the $\chi^2$-distribution will have a minimum where the true value of $\beta$ is, as shown in the left plot of Fig. 3. In this way a measurement of $\beta$ can be obtained. The measured $\beta$ can then be used in the relativistic momentum relation to extract the mass. The plot on the right in Fig. 3 shows the reconstructed mass for 300 GeV $R$-hadrons, in this plot the mean value is $306.3 \pm 0.1$ GeV/$c^2$.

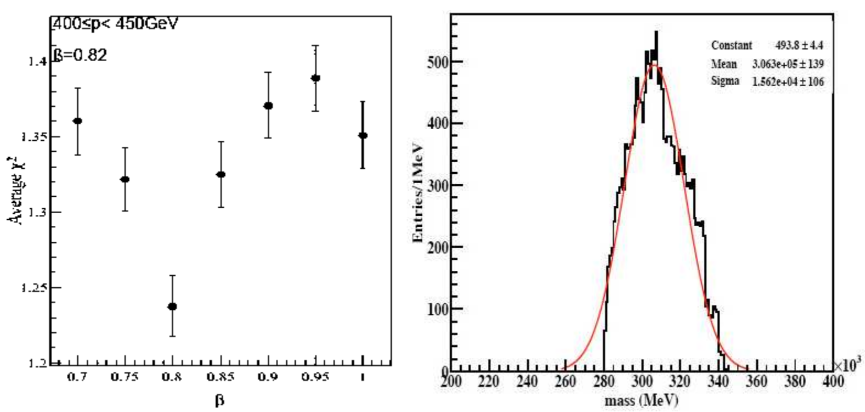


Fig. 3. Left: Average $\chi^2$ as a function of $\beta$. The distribution has a minimum around 0.8 which matches the true value of $\beta = 0.82$ Right: Reconstructed mass of 300 GeV/$c^2$ $R$-hadrons.

## 3. Conclusion

Since SMPs are predicted in many scenarios beyond the Standard Model, they will have to be searched for at ATLAS. Their discovery or non-discovery will be an important tool in excluding many exotic models. One such scenario is Split-SUSY where gluinos hadronise to form meta-stable massive $R$-hadrons. Studies in ATLAS have shown that early discovery of $R$-hadrons up to 1400 GeV/$c^2$ masses is possible, and that the charge-flipping property of gluino $R$-hadrons can be used to isolate a pure signal sample. This allows for determination of the gluino $R$-hadron mass up to a few percent.

[1] Drift-time = Total time $-L/c\beta$, where $L$ is the distance traveled, $c$ the speed of light and $\beta = v/c$ .

## REFERENCES


[1] M. Fairbairn *et al.*, hep-ph/0611040.

[2] M. Fairbairn, A. Kraan, D. Milstead, P. Skands, T. Sjöstrand, "Stable Massive Particles at Colliders", 2006, submitted to *Phys. Rep.*

[3] S.P. Martin, hep-ph/9709356.

[4] N. Arkani-Hamed, S. Dimopoulos, *J. High Energy Phys.* **0506**, 073 (2004) [hep-th/0405159].

[5] S. Raby, *Phys. Rev.* **D56**, 2852 (1997).

[6] C. Friberg, E. Norrbin, T. Sjšstrand, *Phys. Lett.* **B403**, 329 (1997).

[7] T. Appelquist, H. Cheng, B.A. Dobrescu, *Phys. Rev.* **D64**, 035002 (2001).

[8] The ATLAS Collaboration, ATLAS: Detector and Physics Performance Technical Design Report, CERN-LHCC-99-14.

[9] S. Hellman, D. Milstead, M. Ramstedt, ATL-COM-PHYS-2005-065.

[10] T. Sjöstrand *et al.*, hep-ph/0308153.

[11] A.C. Kraan, Interactions and Detection of *R*-hadrons, Ph.D. Thesis, the Niels Bohr Institute, Copenhagen University, 2005.

[12] A.C. Kraan, *Eur. Phys. J.* **C37**, 91 (2004).

[13] CERN Program Library Long Writeup W5013.

[14] S. Agostinelli *et al*, *Nucl. Instrum. Methods Phys. Res.* **A506**, 250 (2003).

[15] R. Mackeprang, A. Rizzi, hep-ph/0612161.

[16] E. Richter-Was, D. Froidevaux, L. Poggili, ATLFAST fast simulation package for ATLAS, ATL-PHYS-98-131.

[17] A.C. Kraan, J.B. Hansen, P. Nevski, SN-ATLAS-2005-053.

[18] S. Hellman, M. Johansen, D. Milstead, ATL-PHYS-PUB-2006-015.

[19] G. Polesello, A. Rimoldi, ATL-MUON-99-006.

[20] <https://uimon.cern.ch/twiki/bin/view/Atlas/MooreMuidInfo>