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Search for long-lived, heavy particles in final states with a muon and multi-track displaced vertex in proton-proton collisions at sqrt(s) = 7 TeV with the ATLAS detector

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Abstract. We present the results of a search for particles which decay at a significant distance from their production point, using a final state containing charged hadrons and an associated muon. This analysis uses a data sample of proton-proton collisions at a center-of-mass energy of 7 TeV with an integrated luminosity of 4.4 fb^{-1} collected in 2011 by the ATLAS detector operating at the Large Hadron Collider. No signal events are observed and limits are set on the production cross-section as a function of the neutralino lifetime.

1 Introduction

In R-parity violating (RPV) supersymmetric model, the lightest supersymmetric particle (LSP) is no longer stable. For small RPV couplings, the LSP can decay away from the Interaction Point (IP) such that the decay is observed as a displaced vertex. The presented results [1] are a search for a displaced neutralino decay with the RPV coupling λ'_{2ij}. In this scenario, a muon and two hadronic jets from the neutralino decay are looked for within the range of the ATLAS inner tracking detector up to $\sim O(10)$ cm away from the IP, which is shown in figure 1. A high transverse momentum (p_T) muon signature is used for triggering and background rejection. The vertex with a high associated track multiplicity is more efficiently identified. Since Standard Model (SM) processes do not produce displaced multi-track vertices at large distance from IP, small SM backgrounds are expected.

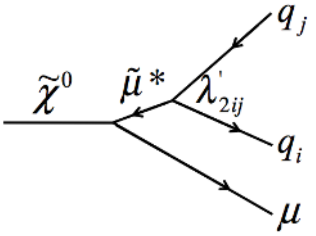

Figure 1. Diagram of the lightest neutralino $\tilde{\chi}^0$ decaying into a muon and two jets via a virtual smuon.

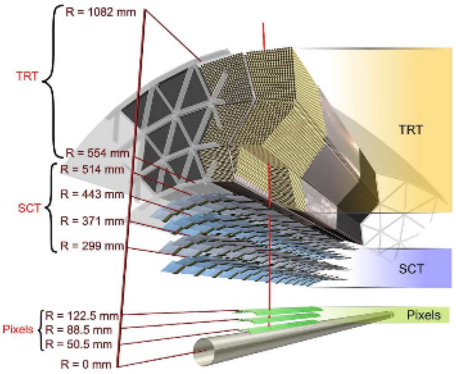

Figure 2. Sketch of the ATLAS inner detector [2].

2 ATLAS detector

The ATLAS detector [2] consists of several layers of subdetectors. From the interaction point (IP) outwards there is an inner detector (ID), measuring the tracks of charged particles, electromagnetic and hadronic calorimeters, and an outer muon spectrometer (MS). As shown in figure 2, the ID operates in a 2 Tesla magnetic field and consists of a pixel detector, a semiconductor tracker (SCT), and a transition radiation tracker (TRT). It extends from a radius of about 45 mm to 1100 mm and to $|z|$ of about 3100 mm and provides tracking and vertex information for charged particles within the pseudorapidity region $|\eta| < 2.5$.

The pixel detector consists of three layers in the barrel and three disks in each of the endcaps. The barrel pixel layers are placed at radii of 50.5 mm, 88.5 mm, and 122.5 mm, which are of particular relevance to this work. The SCT comprises four double layers in the barrel, and nine forward disks on either side. The TRT is positioned at larger radii, comprising straw-tube elements interleaved

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with transition radiation material for electron identification.

3 Data and simulation

The data used in this analysis were collected between March and October 2011. After the application of beam, detector, and data quality requirements, the total luminosity considered corresponds to 4.4 fb^{-1}.

Signal events are generated with Pythia 6 [3]. The processes of squark pair-production, with each squark (antisquark) decaying into a long-lived lightest neutralino and a quark (antiquark) are considered. The signal Monte Carlo (MC) samples are labeled according to the masses of the squark and neutralino, respectively: MH (medium-mass or 700 GeV squark, heavy or 500 GeV neutralino), ML (medium-mass squark, light or 100 GeV neutralino), and HH (heavy squark or 1 TeV sqark and heavy neutralino).

4 Event selection and vertex selection

Events are triggered by a high-p_T muon trigger with no inner detector track requirement. A primary vertex (PV), originating from the pp collision is required and must contain a minimum of 5 tracks and have a z position (z_{PV}) within 200 mm. A muon candidate is required to have been reconstructed in both the MS and the ID with $p_T > 50$ GeV, $|\eta| < 1.07$, and transverse impact parameter $|d_0| > 1.5$ mm.

The default tracking algorithm assumes that tracks originate from close to the PV, and hence will have reduced reconstruction efficiency for signal tracks which originate from a displaced vertex (DV). To recover some of these lost tracks, the silicon-seeded tracking algorithm is re-run with looser cuts on d_0. This procedure is called "re-tracking". Figure 3 shows the vertex reconstruction efficiency as a function of the radial position of the vertex (r_{DV}) when using standard tracking and re-tracking for MH sample. As shown in the figure, the re-tracking leads big improvement on vertex reconstruction efficiency.

DV finding and reconstruction algorithms construct 2-track "seed" vertices with tracks satisfying $p_T > 1$ GeV and $|d_0| > 2$ mm. Multi-track vertices are formed from combinations of seed vertices in an iterative process [1].

The DVs are found from the above procedure and then are required to satisfy the following selections:

- The DV is found in the regions $|r_{DV}| < 180$ mm and $|z_{DV}| < 300$ mm,
- Transverse distance between DV and all PVs in the event ($|r_{PV} - r_{DV}|$) > 4 mm,
- A muon passes within 0.5 mm of reconstructed DV,
- The associated muon is not back-to-back with any of tracks in the DV,
- At least 5 tracks linked to the DV and the DV mass (m_{DV}) > 10 GeV,
- The DV does not coincide with a high-density material region.

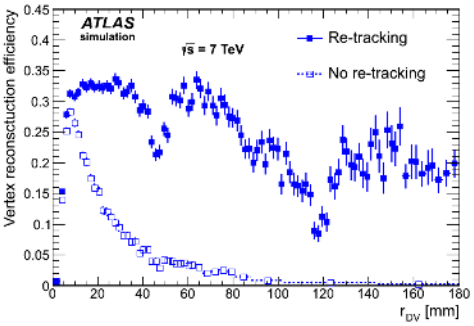

Figure 3. The vertex reconstruction efficiency as a function of r_{DV} after all cuts for MH sample, with and without re-tracking.

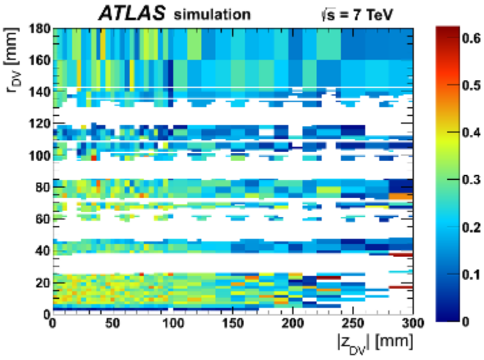

Figure 4. The efficiency as a function of the reconstructed DVs in ($|z_{DV}|$, r_{DV}) plane for signal MC sample MH.

5 Efficiency and systematic uncertaintites

The signal efficiency as a function of the reconstructed DV r_{DV} and z_{DV} is shown in figure 4 after applying the selections mentioned in section 4. This DV reconstruction efficiency depends on the efficiencies of track reconstruction and track selection. It is therefore affected by the following factors: (1) The number of tracks originating from the DV and their total invariant mass increase with the neutralino mass. (2) More tracks fail the $|d_0| > 2$ mm requirement for small r_{DV} or if the neutralino is highly boosted. (3) The reconstruction efficiency of tracks decreases with increasing values of $|d_0|$.

The total efficiency for the signal MC samples is shown in figure 5 as a function of the product of the speed of light (c) and the neutralino lifetime (τ). To calculate this efficiency, we generated the distributions of decay positions for different neutralino lifetime $c\tau$ using toy MC and combinded with a 2-dimensional efficiency map in ($|z_{DV}|, r_{DV}$) (figure 4) for vertices. The results shown in figure 5 include systematic corrections and uncertaintites. The uncertainties on efficiency come from statistics, muon and vertex reconstruction efficiencies and trigger efficiency. The following differences between data and MC are applied as corrections:

- Trigger efficiency difference between data and MC from Tag and Probe on $Z \to \mu\mu$.

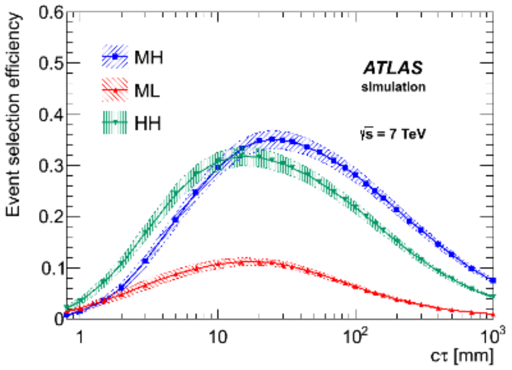

Figure 5. The event efficiency as a function of $c\tau$ for the three signal samples. The shaded region shows the uncertainties on the efficiency.

- Muon reconstruction efficiency difference between data and MC.
- Difference in z_{PV} distribution between data and MC.

6 Background estimation

In order to estimate the number of background vertices, we employ a fully data driven method. The possible sources of backgounds are purely random combinations of tracks and high-mass vertices from hadronic interactions. The former arises inside the beam pipe and the latter outside the beam pipe. The control samples with jet-triggered events and vertices with 4 GeV $< m_{DV} <$ 10 GeV are used to estimate the backgoud inside the beam pipe.

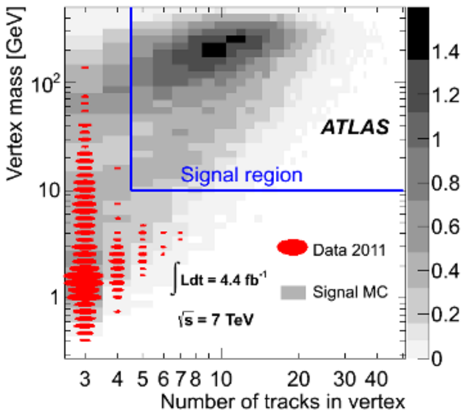

Figure 6. Vertex mass as function of vertex track multiplicity for DVs in events.

High-mass vertices from hadronic interactions can be formed by random track crossing at large angle. We obtained m_{DV} distributions of i) n-track vertices without large-angle tracks and ii) (n-1)-track vertices plus four-momentum of a randomly-selected track. The m_{DV} distributions are then normalized with the number of vertices in non-material regions from a maximum likelihood fit.

The total backgound estimate is $(4^{+60}_{-4}) \times 10^{-3}$ vertices in the signal region.

7 Result

The signal region is defined by high track multiplicity (n-track) and high mass of vertex. Figure 6 shows m_{DV} vs. n-track for the selected vertices in the data sample, including vertices that fail the requirements DV on m_{DV} and n-track this is overlaid with a distribution from signal MC. There is no vertices observed, satisfying all the DV selection criteria.

Based on this null observation, limits are calculated on the supersymmetry production cross section (σ) times the square of the branching ratio (BR^2) of the simulated signal decays for different combinations of squark and neutralino masses. Limits shown in figure 7 are established as a function of the $c\tau$ of the neutralino.

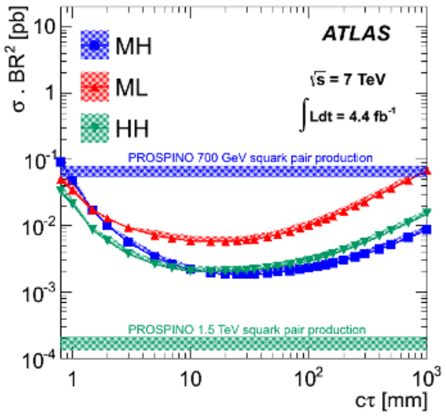

Figure 7. Upper limits on $\sigma\times$ BR^2 as a function of the neutralino lifetime for different combinations of squark and neutralino masses.

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