Search for Exotic mono-jet and mono-photon signatures with the ATLAS detector

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Abstract. Mono-jet and mono-photon signatures are final states in a variety of scenarios beyond the Standard Model, such as the Large Extra Dimension models, gauge-mediated SUSY breaking scenarios, and models with pair production of Weakly Interacting Massive Particles considered as dark matter candidates. The produced exotic particles do not interact with the detector, resulting in missing transverse energy. The results of searches, performed in the ATLAS experiment at the LHC, for new physics in final states with an energetic jet or photon and large missing transverse energy are presented. The mono-jet search is performed using both 4.6 fb−1 of 7 TeV and 10.5 fb−1 of 8 TeV data, while the mono-photon results correspond to 4.6 fb−1 of 7 TeV data.

1 Introduction

Event topologies with one high transverse momentum \( p_T \) jet or photon and large missing transverse energy are important final states for searches for new phenomena beyond the Standard Model (BSM) at the LHC. The large missing transverse energy can be a signature of weakly interacting particles not yet discovered. In order to tag such events, the processes are required to be accompanied by jets or photons. The BSM scenarios resulting in such final states include supersymmetry [1–3], Large Extra Dimensions (LED) scenarios [4, 5], and a general model for production of dark-matter weakly interacting massive particles (WIMP) [6]. In case the experimental studies of mono-jet and mono-photon events are consistent with Standard Model expectations, constraints will be set on the production of light gravitinos in association with gluinos or scalar quarks in the gauge-mediated SUSY breaking GMSB SUSY scenarios, the Planck scale of the LED model of Arkani-Hamed, Dimopoulos, Dvali (ADD), and the suppression scale in the pair production of WIMPs.

2 Mono-jet Analysis

The ATLAS [11] mono-jet analysis has been performed with 4.6 fb−1 of 7 TeV data [7], and has been updated with 10.5 fb−1 of 8 TeV data [8]. In the following, event selections, background determination methods, and the results are presented.

2.1 Event Selection

All data passing detector quality requirements are considered for the analysis. Events are required to pass a trigger that selects events with missing transverse momentum \( E_T^{\text{miss}} \) above 80 GeV. This trigger is more than 95% efficient for offline reconstructed \( E_T^{\text{miss}} \) above 120 GeV, and its efficiency is determined using an unbiased data sample with muons in the final state. Events should further satisfy a set of offline pre-selection and kinematic criteria as follows:

- Events are required to have a reconstructed primary vertex.

- Events should have \( E_T^{\text{miss}} > 120 \) GeV and at least one jet with \( p_T \) above 120 GeV and \( |\eta| < 2 \). Events with more than two jets with \( p_T \) above 30 GeV and in the region \( |\eta| < 4.5 \) are rejected. Furthermore, a cut on the azimuthal separation between \( E_T^{\text{miss}} \) and the second jet (if present) is required, in order to reduce the QCD multi-jet background contribution where the large \( E_T^{\text{miss}} \) originates from the mis-measurement of a jet: \( |\Delta \phi(E_T^{\text{miss}}, \text{2nd jet})| > 0.5 \).

- Events are required to have no identified electrons or muons.

Four signal regions are defined with increasing symmetric lower thresholds of 120, 220, 350, and 500 GeV on the leading jet \( p_T \) and \( E_T^{\text{miss}} \), referred to as SR1 - SR4.
The measured transverse mass in the W(\(\mu\nu\)+jets) control region, for the first signal region selection, compared to the background predictions. For illustration purposes, the ALPGEN W/Z+jet predictions from simulation are multiplied by a global scale factor 1.01 which brings the simulation predictions close to the data in the control region, allowing for a direct comparison of the shapes [8].

### 2.2 Background Determination

The background to mono-jet events is dominated by Z(\(\ell\ell\))+jets and W(\(\ell\nu\))+jets processes (\(\ell = e, \mu, \tau\)). It also includes contributions from Z(\(\ell\ell\)) (\(\ell = e, \mu, \tau\)), QCD multi-jet, top, and diboson (WW, WZ, ZZ) processes. The W/Z+jets backgrounds, as well as the QCD multi-jet and non-collision backgrounds, are determined using data-driven techniques. Backgrounds from top and dibosons are determined using simulation samples.

Data control regions, orthogonal to the mono-jet signal regions, with identified electrons or muons in the final state and with the same requirements on the jets and \(E_T^{\text{miss}}\), are defined to determine the W/Z+jets backgrounds. This reduces significantly the large theoretical and experimental systematic uncertainties associated with methods purely based on simulation.

The W(\(\mu\nu\))+jet data control regions are defined using muons with \(p_T\) above 7 GeV, and a transverse mass cut: 40 GeV < \(m_T\) < 100 GeV. The Z(\(\mu\nu\))+jets data control regions are defined requiring the presence of two oppositely charged muons with an invariant mass cut: 76 GeV < \(m_{\mu\mu}\) < 116 GeV. The W(\(e\nu\))+jets data control regions are defined using an electron above 20 GeV in \(p_T\). Figures 1 and 2 show the transverse mass and invariant mass distributions in the W(\(\mu\nu\))+jets and Z(\(\mu\nu\))+jets control regions.

To each data control region, simulation-based transfer factors are applied in order to get the background contribution in the mono-jet signal regions. As an example, the largest background Z(\(\ell\ell\))+jets in the signal region is determined from the W(\(\mu\nu\))+jets data control region according to:

\[
N(Z(\ell\ell)+jets)_{\text{signal}} = \frac{N_{\text{data}}}{N_{\text{control}}^{\text{background}} + N_{\text{control}}^{\text{background}}} \times \frac{N_{\text{MC}}(Z(\ell\ell)+jets)_{\text{signal}}}{N_{\text{MC}}(W(\mu\nu)+jets)_{\text{control}}},
\]

where \(N_{\text{MC}}(Z(\ell\ell)+jets)_{\text{signal}}\) is the background predicted by simulation in the signal region, and \(N_{\text{data}}/N_{\text{control}}\) is the ratio of simulated events for the process in the signal region over simulated events for the process in the control region, respectively. The latter refers to the top and diboson processes and is based on simulation. The transfer factor for each background process is defined as the ratio of simulated events for the process in the signal region over the total number of simulated events in the control region.

The contribution of QCD multi–jet events to mono-jet signal regions comes from those events for which the energy of a jet is badly measured such that the \(p_T\) of the jet falls below the 30 GeV jet definition threshold, therefore passing the selection cuts. Two types of data control regions are defined. For both types, all the selection cuts are applied except that the second jet above 30 GeV in \(p_T\) is required to be along the \(E_T^{\text{miss}}\) direction in the first type \(|\Delta \phi(E_T^{\text{miss}}, 2\text{nd jet})| < 0.5\), and a third jet above 30 GeV in \(p_T\) is required along the \(E_T^{\text{miss}}\) in the second type, \(|\Delta \phi(E_T^{\text{miss}}, 3\text{rd jet})| < 0.5\). Extrapolation of the \(p_T\) distribution of these jets below the 30 GeV jet definition threshold gives an estimate of this background in the signal region.

### 2.3 Results

Good agreement is observed between data and the Standard Model predictions within the total background uncertainties, and model-independent 90% and 95% confidence level (CL) upper limits on the visible cross section, defined as the production cross section times acceptance times efficiency (\(\sigma \times A \times e\)), are set using the CLs approach [9], as shown in Fig. 3 for the 8 TeV mono-jet analysis. Values of \(\sigma \times A \times e\) above 2.8 pb, 0.16 pb, 0.05

**Figure 1.** The measured transverse mass in the W(\(\mu\nu\))+jets control region, for the first signal region selection, compared to the background predictions. For illustration purposes, the ALPGEN W/Z+jet predictions from simulation are multiplied by a global scale factor 1.01 which brings the simulation predictions close to the data in the control region, allowing for a direct comparison of the shapes [8].

**Figure 2.** The measured di-muon invariant mass in the Z(\(\mu\nu\))+jets control region, for the first signal region selection, compared to the background predictions. For illustration purposes, the ALPGEN W/Z+jet predictions from simulation are multiplied by a global scale factor 0.97, which brings the simulation predictions close to the data in the control region, allowing for a direct comparison of the shapes [8].
The model-independent observed (solid lines) and expected (dashed lines) 95% CL upper limits on $\sigma \times A \times \epsilon$ for different signal regions. The shaded areas around the expected limit indicate the $\pm 1\sigma$ and $\pm 2\sigma$ expected limits [8].

The predicted ADD signal yields as a function of the Planck scale $M_D$ for the degenerate case, the upper limits on the ADD signal yields as a function of the Planck scale $M_D$, and the lower limits on the WIMP suppression scale $M^*$ for operator D5 of the effective theory used to calculate the cross sections. The lower limits on $M^*$ can further be translated to upper limits on the WIMP-nucleon scattering cross section, as shown in Fig. 7 using the $M^*$ limits of the 7 TeV mono-jet analysis.

The upper limits on the cross section can be translated to limits on a model parameter. Figures 4-6 show the resulting lower limits on the gravitino mass in the GMSB SUSY scenario for the degenerate case, the upper limits on the ADD signal yields as a function of the Planck scale $M_D$ and the lower limits on the WIMP suppression scale $M^*$ for operator D5 of the effective theory.

The grey and blue bands around the expected limit are the $\pm 1\sigma$ and $\pm 2\sigma$ expected limits. The dashed-dotted line defines the validity of the narrow-width approximation (NWA) used to obtain the decay rate of the gluino and squark to a gravitino and a parton. The solid red line denotes the current limit from LEP on the gravitino mass assuming very heavy squarks/gluinos [8].

The model-independent observed (solid line) and expected (dashed line) 95% CL lower limits on the gravitino mass as a function of the squark mass for degenerate squark/gluino masses. The dotted line indicates the impact of the $\pm 1\sigma$ LO theoretical uncertainty on the observed limit. The shaded bands around the expected limit indicate the expected $\pm 1\sigma$ and $\pm 2\sigma$ expected limits. The dashed-dotted line defines the validity of the narrow-width approximation (NWA) used to obtain the decay rate of the gluino and squark to a gravitino and a parton. The solid red line denotes the current limit from LEP on the gravitino mass assuming very heavy squarks/gluinos [8].

For the degenerate SUSY scenario for the degenerate case, the upper limits on the ADD signal yields as a function of the Planck scale $M_D$, and the lower limits on the WIMP suppression scale $M^*$ for operator D5 of the effective theory used to calculate the cross sections. The lower limits on $M^*$ can further be translated to upper limits on the WIMP-nucleon scattering cross section, as shown in Fig. 7 using the $M^*$ limits of the 7 TeV mono-jet analysis.
3 Mono-photon Analysis

The ATLAS mono-photon analysis has been performed with the 4.7 fb$^{-1}$ 7 TeV data [10]. In the following, the event selections, background determination methods, and results are presented.

3.1 Event Selection

The data are collected using a trigger that selects events with $E_T^{miss}$ above 70 GeV. Events are further required to have $E_T^{miss}$ above 150 GeV. A photon is also required with $p_T > 150$ GeV and $|\eta| < 2.37$, excluding the calorimeter barrel/end-caps transition regions ($1.37 < |\eta| < 1.52$). Events with more than one jet with $p_T > 30$ GeV and $|\eta| < 4.5$ are rejected, while those with one such jet are kept in order to increase the signal acceptance and reduce systematic uncertainties related to the modelling of initial-state radiation. The reconstructed photon, $E_T^{miss}$, and jet (if present) are required to be well separated in the transverse plane with $|\Delta \phi(E_T^{miss}, \gamma)| > 0.4$, $|\Delta \phi(E_T^{miss}, jett)| > 0.4$, and $|\Delta R(\gamma, jett)| > 0.4$. No identified electrons or muons should be present in the final state.

3.2 Background Determination

As in the mono-jet analysis, the background to mono-photon events is dominated by $Z(\nu \nu)\gamma$. It also receives contributions from $W/Z + \gamma$ events with unidentified electrons, muons or hadronic $\tau$ decays, and $W/Z+jets$ events with an electron or a jet misreconstructed as a photon. In addition, there is a small contribution from top-quark, $\gamma\gamma$, diboson ($WW, ZZ, WZ$), $\gamma$+jets, and multi-jet processes.

3.3 Results

The data are found to be in good agreement with the Standard Model background-only hypothesis. The results are expressed in terms of model-independent 90% and 95% CL upper limits on the visible cross section, using the $CL_s$ approach. Values of $\sigma \times A \times \epsilon$ above 5.6 fb and 6.8 fb are excluded at 90% CL and 95% CL, respectively. The results can further be translated to 95% CL lower limits on the scale $M_D$ in the ADD scenario, and 90% CL upper limits on the WIMP-nucleon scattering cross sections, as shown in Fig. 8 and 9, respectively.
4 Conclusion

The ATLAS mono-jet and mono-photon analyses have been performed with the 7 and 8 TeV LHC pp collision data. Data-driven techniques have been used to determine the largest Standard Model backgrounds in both analyses. As good agreement has been observed between data and the expected Standard Model backgrounds, the results are interpreted as upper limits on the visible cross sections in various kinematic regions. These limits can further be used to constrain some BSM models that result in the mono-jet or mono-photon signatures, such as the ADD large extra dimensions scenario, the pair production of WIMP dark matter candidates, and the production of a gravitino in association with a squark/gluino, with the further decay of the squark/gluino to a gravitino and a parton, in GMSB scenarios.

References