Searches for Physics Beyond the Standard Model in Monojets- and Monophoton-Events with the ATLAS Detector

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Abstract. Various models for new physics not described by the Standard Model predict event topologies with large missing transverse energy due to invisible new particles. Such events can be identified in the detector if they are accompanied by an energetic photon or a jet with high transverse energy. This article presents results from searches for new physics with both signatures in proton-proton collision data with the ATLAS detector at the LHC. The focus is on the analyses using the full 2011 data set with an integrated luminosity of \( \mathcal{L} = 4.7 \text{ fb}^{-1} \) at a center of mass energy of \( \sqrt{s} = 7 \text{ TeV} \) but the article also includes an update of the monojet analysis with \( \mathcal{L} = 10.5 \text{ fb}^{-1} \) of data recorded in 2012 at \( \sqrt{s} = 8 \text{ TeV} \). The results are translated into exclusion limits on parameters of different theoretical models.

1. Introduction

A variety of models for physics beyond the Standard Model (BSM) include the production of new particles that do not interact in the detector. Such events can be tagged, however, if in addition - for example - a jet or a photon with high transverse momentum \( p_T \) is produced, recoiling against the invisible particles. This leads to event topologies with large missing transverse energy \( E_T^{\text{miss}} \). Among the theories predicting such event signatures are models for large extra dimensions (LED) [1, 2], pair production of weakly interacting massive particles (WIMP), candidates for dark matter [3], and supersymmetry (SUSY) scenarios [4, 5, 6].

Analyses with both final states have been performed with proton-proton collision data at the ATLAS experiment [8] at the LHC and since no significant deviation from the Standard Model (SM) prediction is observed, exclusion limits are set on the respective model parameters: the Planck scale of the Arkani-Hamed, Dimopoulos, Dvali (ADD) model for LED [2], the suppression scale of an effective theory used to describe the WIMP pair production and on the mass of the gravitino which is produced in association with a squark or a gluino in gauge-mediated SUSY breaking (GMSB) scenarios [7].

2. Mono-jet Analysis

The monojet analysis was performed with \( \mathcal{L} = 4.7 \text{ fb}^{-1} \) of data recorded at \( \sqrt{s} = 7 \text{ TeV} \) in 2011 [9] and updated with \( \mathcal{L} = 10.5 \text{ fb}^{-1} \) of \( \sqrt{s} = 8 \text{ TeV} \) data recorded in 2012 [10]. This update includes, for the first time, the GMSB scenario as a new interpretation in addition to the WIMP
and ADD model. In the following, the event selection as well as the determination of background contributions are outlined and the results are presented.

2.1. Event Selection
At first, a basic preselection of good quality data with potentially interesting events is applied: All data taken with a completely functional detector are being used, events have to have at least one reconstructed primary vertex and have to be selected by a trigger which accepts events with a missing transverse energy of more than 80 GeV. This trigger has an efficiency above 95% for an offline reconstructed $E_T^{\text{miss}}$ higher than 120 GeV. Events are required to have an $E_T^{\text{miss}}$ above this threshold and at least one jet within $|\eta| < 2.0$ with $p_T > 120$ GeV as well. Jets are reconstructed with the anti-Kt algorithm with a distance parameter of $R = 0.4$. Events with more than one additional jet with $p_T > 30$ GeV and $|\eta| < 4.5$ are rejected.

Multijet events can contribute to the background if a mis-measurement of one of the jets gives rise to fake $E_T^{\text{miss}}$, which then typically is aligned with the direction of the jet. To suppress such events, sub-leading jets which survive the jet veto have to be well separated from the direction of $E_T^{\text{miss}}$, a vector, which is ensured by requiring that their azimuthal distance be larger than 0.5: $|\Delta\phi(E_T^{\text{miss}}, \text{jet}_2)| > 0.5$. Contributions from the production of $Z$ or $W$ bosons in association with jets are reduced by rejecting any event containing a reconstructed electron or muon. The search is performed in 4 signal regions (SR), defined by symmetric lower bounds on the leading jet $p_T$ and the $E_T^{\text{miss}}$ with values of 120 GeV, 220 GeV, 350 GeV, and 500 GeV, labelled SR1 - SR4, respectively.

2.2. Estimation of Background Contributions
The main (and irreducible) background contribution is the production of $Z$ bosons together with jets where the boson decays to two neutrinos, $Z(\nu\bar{\nu})$+jets. Other significantly contributing processes are $W(\ell\nu)$+jets ($\ell = e, \mu, \tau$) with the decay leptons escaping detection or - in case of $W(\tau\nu)$+jets - the $\tau$ decaying hadronically. $Z/\gamma^*(\ell^+\ell^-)$+jets ($\ell = e, \mu, \tau$) contribute when both leptons are not identified or are outside the detector acceptance. Together, those make up for about 97% of the total background. The remaining contribution are QCD multijet events, non-collision backgrounds such as muons from cosmic rays or beam halo, as well as top quark and diboson production ($WW/ZZ/WZ$). The top and diboson backgrounds are taken directly from the simulation while the other contribution are estimated in a data driven way. For the determination of the $W/Z$+jets background contributions, control regions (CR) orthogonal to the signal regions are defined by requiring good quality reconstructed electrons or muons in the event and otherwise applying the same cuts on jets and the signal regions are defined by requiring good quality reconstructed electrons or muons in the event has to have an $E_T^{\text{miss}}$ above this threshold and at least one jet within $|\eta| < 2.0$ with $p_T > 120$ GeV as well. Jets are reconstructed with the anti-Kt algorithm with a distance parameter of $R = 0.4$. Events with more than one additional jet with $p_T > 30$ GeV and $|\eta| < 4.5$ are rejected.

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A $W(\mu\nu)$+jet control region is defined by requiring exactly one good muon with a $p_T$ greater than 20 GeV and rejecting additional electrons or muons. In addition, the transverse mass - defined as $m_T = \sqrt{2p_T E_{T}^{\text{miss},\mu}(1 - \cos\Delta\phi(\ell, E_{T}^{\text{miss},\mu})))$, with $p_T$ of the lepton - has to fulfill $40\text{ GeV} < m_T < 100\text{ GeV}$ and the $E_{T}^{\text{miss}}$ corrected for the muon contribution, $E_{T}^{\text{miss},\mu}$, should be larger than 25 GeV.

For the $Z(\mu^+\mu^-)$+jets CR exactly two oppositely charged muons are selected, restricting the invariant mass of the muon pair around the $Z$-mass peak, $66\text{ GeV} < m_{\mu^+\mu^-} < 116\text{ GeV}$. Similarly, control regions in the electron channel are defined: The $W(e\nu)$+jets CR uses events which have been selected by an electron trigger and which contain exactly one good electron with $p_T > 25$ GeV. An overlap removal between jets and the electron in the event is performed and the same invariant mass cut as for the muon channel is applied. The $E_{T}^{\text{miss}}$ in the event has to be larger than 25 GeV.
Finally, there is a $Z(e^+e^-)+$jets control region of events selected by an electron trigger and containing exactly two oppositely charged electrons and no muons. The electrons have to have $p_T > 25$ and 20 GeV, respectively. Again, a jet-electron overlap removal is performed and the cut on the invariant mass of the lepton pair is applied as for the muon channel.

Fig. 1 shows the distribution of the leading muon $p_T$ in the $Z(\mu^+\mu^-)+$jets CR, while in Fig. 2 the $E_T^{miss}$ distribution in the $W(\mu\nu)+$jets CR is displayed. Good agreement between data and simulation is observed.

The selected data in a control region has to be corrected for background contributions to this control region (from multijet events or other electroweak processes). By applying transfer factors to this corrected number, the contribution of a given background process in the signal region can be estimated. These transfer factors are based on ratios of event numbers predicted by simulation which allows for a significant reduction of systematic uncertainties compared to using simulation only. For example, the dominating $Z(\nu\bar{\nu})++$jets background contribution in the signal region is estimated from the $W(\mu\nu)+$jets control region as

$$N(Z(\nu\bar{\nu})+jets)_{signal} = \left(C \cdot \frac{1 - f_{EW}}{f_{EW}} \cdot \frac{N(|Z(\nu\bar{\nu})+jets|_{signal}}{N(|W(\mu\nu)+jets|_{signal}} \right)$$

where $N_{data}$ is the number of data events observed in the CR, $N_{CR}$ is the number of non-electroweak background events in the CR and $f_{EW}$ the remaining fraction of events from electroweak processes other than $W(\mu\nu)+$jets. The predicted number of events in the SR is $N(Z(\nu\bar{\nu})+jets)_{signal}$, while $N(W(\mu\nu)+jets)_{CR,jet,E_T^{miss}}$ is the number of $W(\mu\nu)+$jets events in the CR from simulation after applying only the SR selection of jets and $E_T^{miss}$. The ratio of the two is the transfer factor. The factor $C$ accounts for differences in the lepton selection between signal and control region.

Di-jet or tri-jet events can enter the signal region if the energy of one of the sub-leading jets is measured badly so that its $p_T$ falls below the threshold of 30 GeV. To estimate this contribution from data, two control regions are defined: For the first region, the $\Delta\phi$-cut between the second jet and the $E_T^{miss}$ is inverted, for the second region a third jet above 30 GeV is required which again is aligned with the missing $E_T$: $\Delta\phi(jet3,E_T^{miss}) < 0.5$. The $p_T$ distributions of these
sub-leading jets are extrapolated below the 30 GeV threshold to get an estimate of the multijet contribution in the signal region.

\[ \int L dt = 4.7 \text{ fb}^{-1} \]

**Figure 3.** $E_T^{\text{miss}}$ distribution in SR1. The background prediction is shown in comparison to the data. For illustration purposes shapes from ADD and WIMP signal simulations are shown as well (dashed lines) [9].

**Figure 4.** $p_T$ distribution in SR1. The background prediction is shown in comparison to the data. For illustration purposes shapes from ADD and WIMP signal simulations are shown as well (dashed lines) [9].

### 2.3. Results

As can be seen from the $E_T^{\text{miss}}$ and $p_T$ distributions (Figs 3 and 4, respectively) good agreement between data and prediction from the SM is observed. Therefore, limits on model parameters for the different theoretical interpretations are derived using the CLs method [11].

Fig. 5 shows the 95%CL limits from SR4 on the fundamental Planck scale in 4+n dimensions, $M_D$, as a function of the number of extra dimensions, $n$. The expected limit is shown as a black dashed line with the $\pm 1\sigma$ error band in gray, while the red solid line marks the observed limit. The theoretical uncertainties have not been included as nuisance parameters in the limit calculation. Instead, their impact is illustrated by the red dotted lines which show the observed limit recomputed after varying the signal cross section up and down within the theoretical uncertainties. The comparison with the violet line, which indicates the limits obtained from the monojet analysis performed with 2010 data [12], shows an increase in sensitivity.

The WIMP interpretation is based on the assumption that the interaction between dark matter and SM particles is mediated by a new particle, too heavy to be directly produced at the LHC. This allows for an effective field theory approach with 14 different operators for the contact interaction, assuming WIMPs are Dirac fermions. One characteristic operator is D5 (following the naming scheme from [13]), which describes a vector interaction with a quark-antiquark pair in the initial state. The 90%CL lower limit on the suppression scale of the effective theory, $M_\star$, for D5 is shown in Fig. 6 as a function of the WIMP mass. For these limits the results from SR3 are used. The colour scheme is the same as described for Fig. 5, the gray shaded area (in the bottom right corner) marks the region where the effective theory is not valid any more. In addition, a green line indicates the thermal relic limit, i.e. those values of $M_\star$ that for a given WIMP mass $m_\chi$ result in the correct cross section to yield the total relic density of dark matter in the universe as measured by the WMAP satellite [14]. This means that above this green line, annihilation channels other than the one considered by the given operator must also be open. The lower limits on $M_\star$ can be translated into upper limits on WIMP-nucleon scattering [13] and these can be compared to direct detection experiments which are sensitive to spin-dependent and
Figure 5. 95%CL lower limits from SR4 on the fundamental Planck scale $M_D$ as function of the number of extra dimensions. The expected limit is shown as a black dashed line with a gray $\pm 1\sigma$ error band. The red solid line shows the observed limit with the impact of theoretical uncertainties illustrated by the red dotted lines. For comparison the observed limit from the 2010 analysis is shown [9].

Figure 6. 90%CL lower limits from SR3 on the suppression scale $M_\ast$. The colour coding is the same as in fig. 5. The gray shaded area marks the region where the effective theory is not valid. The green line indicates those values of $M_\ast$ that for a given value of $m_\chi$ result in the measured relic density [9].

to spin-independent interactions. In Fig. 7 the limits for operators describing spin-independent interactions are compared to other collider limits as well as limits from direct searches, again as a function of the WIMP mass. It can be seen that the colliders have a higher sensitivity at small WIMP masses (of the order of MeV). For spin-dependent interactions on the other hand, colliders are competitive over a large range of WIMP masses, as Fig. 8 illustrates.

The monojet analysis was updated with 10.5 fb$^{-1}$ of 8 TeV data with only minor changes to the analyses strategy and cuts. Again, no significant excess over the SM prediction was observed as can be seen from the $E_T^{\text{miss}}$ distribution in the first signal region (Fig. 9). A new theoretical interpretation has been included in the analysis: the associated production of a gravitino together with a squark or a gluino, assuming a GMSB scenario. Lower limits on the gravitino mass for different squark/gluino mass configurations can be derived. Fig. 10 shows the limit for the degenerate case as a function of the squark/gluino mass. The dashed-dotted line defines the validity of the narrow-width approximation (NWA) used to derive the decay rate of a squark/gluino to a gravitino and a parton. For comparison, the current limit from LEP on the gravitino mass assuming very heavy squarks/gluino is shown (solid red line).

3. Monophoton Analysis
The monophoton analysis has been performed at the ATLAS experiment with 4.7 fb$^{-1}$ of 7 TeV data [15]. In the following the event selection, background determination and results are presented.

3.1. Event Selection
The 4.7 fb$^{-1}$ remain after applying quality criteria on the data. Out of these, events are selected using an $E_T^{\text{miss}}$ trigger with a threshold of 70 GeV and requiring at least one primary vertex. The photon is required to be within $|\eta| < 2.37$ where the transition region between barrel and endcap ($1.35 < |\eta| < 1.52$) is excluded. At most one jet with $p_T > 30$ GeV and $|\eta| < 4.5$ is allowed in
Figure 7. 90%CL upper limits on the spin-independent WIMP-nucleon scattering cross section for different collider and direct searches as a function of the WIMP mass. Solid lines are the observed limits without theory uncertainties, the dotted lines show the impact of the theoretical uncertainties. The ATLAS limits are calculated considering the four light quark flavours assuming equal coupling strength to WIMPs for all flavours [9].

Figure 8. 90%CL upper limits on the spin-dependent WIMP-nucleon scattering cross section for different collider and direct searches as a function of the WIMP mass. Solid lines are the observed limits without theory uncertainties, the dotted lines show the impact of the theoretical uncertainties. The ATLAS limits are calculated considering the four light quark flavours assuming equal coupling strength to WIMPs for all flavours [9].

the event. The signal region is defined by requiring the $E_T^{\text{miss}}$ and the $p_T$ of the photon to be larger than 150 GeV. The photon, $E_T^{\text{miss}}$ and jet (if present) have to be well separated, which is ensured by applying the following cuts: $|\Delta \phi (E_T^{\text{miss}}, \gamma)| > 0.4$, $|\Delta \phi (E_T^{\text{miss}}, j)| > 0.4$ and $|\Delta R (\gamma, j)| > 0.4$. As in the monojet analysis a veto on any reconstructed electron or muon is applied.

3.2. Background Estimation
The dominant background contribution is events with a photon and a Z boson where the latter decays into two neutrinos. Further contributions are W/Z + $\gamma$ events with lost electrons, muons or hadronically decaying taus, and W/Z+jet events where an electron or jet is mis-identified as a photon. The remaining backgrounds consist of top, diboson (WW/ZZ/WZ), $\gamma\gamma$, $\gamma + j$ and multijet processes. Non-collision backgrounds are found to be negligible. The contributions from top, diboson and $\gamma\gamma$ are taken from the simulation while for the $W/Z$, $\gamma + j$ and multijet backgrounds the same data-driven techniques as in the monojet analysis are used.

3.3. Results
As in the monojet search no significant deviation from the SM prediction is observed as illustrated by Fig. 11. Hence, lower limits on $M_D$ are derived for the ADD model. These are shown in Fig. 12 as a function of the number of extra dimension in comparison to results from other experiments. Upper limits on the WIMP-nucleon scattering cross section are also derived as was done for the monojet analysis. The 90%CL bounds are shown in Fig. 13 as a function of the WIMP mass in comparison to other collider and direct search experiments both for spin-independent and spin-dependent interactions.
Figure 9. Distribution of $E_T^{\text{miss}}$ in SR1 for the 8 TeV monojet analysis. The data are shown in comparison to the SM prediction. For illustration purposes signal simulation for all three theoretical interpretations are also shown as dashed lines [10].

Figure 10. 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 theoretical uncertainty on the observed limit (solid line). The expected limit (dashed line) is shown with its ±1σ and ±2σ error bands. The solid red line denotes the current limit from LEP [10].

Figure 11. Distribution of $E_T^{\text{miss}}$ in the signal region for the monophoton analysis. The data are shown in comparison to the SM prediction. The band around the total background prediction includes uncertainties on the data-driven background estimates and statistical uncertainties on the MC samples. For illustration purposes signal simulations for the theoretical interpretations are also shown as dashed lines [15].

Figure 12. Observed (solid lines) and expected (dashed-dotted lines) 95% CL limits on $M_D$ as a function of the number of extra dimensions in the ADD model. The dashed lines around the observed limit indicate the impact of the ±1σ NLO theoretical uncertainty on the limit computation. The shaded band indicates the expected ±1σ range of limits in the absence of a signal. The results are compared with previous results [15].
4. Conclusion

The ATLAS experiment has performed analyses with monojet and monophoton signatures with proton-proton collision data at center of mass energies of 7 TeV and 8 TeV. Data-driven techniques were used to determine the largest background contributions from Standard Model processes. No excess over the SM predictions is observed and the results are used to set limits on model parameters for different BSM scenarios: the ADD model of large extra dimensions, associated squark(gluino)+gravitino production in gauge-mediated SUSY breaking and WIMP pair production.

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