New Physics with the ATLAS detector: experimental prospects

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Abstract. During 2010 the ATLAS detector has collected 45 pb$^{-1}$ of proton-proton collisions at $\sqrt{s} = 7$ TeV. These data have been used for a wide range of searches such as high-mass final states and contact interactions. Early inclusive SUSY searches have been also performed for a wide range of final states. The most recent results of searches of physics beyond the Standard Model with the ATLAS detector are presented. Prospects for physics searches with $\sim 1$ fb$^{-1}$ of data will be discussed together with the most relevant performance results.

1. Introduction

During the data taking period of 2010, the LHC has delivered proton-proton ($pp$) collisions at $\sqrt{s} = 7$ TeV for a total integrated luminosity of 48 pb$^{-1}$, reaching the peak instantaneous luminosity of $2.1 \times 10^{32}$ cm$^{-2}$s$^{-1}$. Further details on the luminosity measurement and beam conditions can be found in Ref. [1]. The ATLAS detector [2], a general purpose detector optimized for a wide range of physics processes involving high-$p_T$ leptons, jets and missing energy, has been used to search for evidence of new physics beyond the Standard Model (SM). During the 7 TeV run in 2010, it has collected 45 pb$^{-1}$ of data, which correspond to a data-taking efficiency of 93.6%.

Recent experimental results from ATLAS will be presented, discussing their implications in the context of several theoretical models, which predict new phenomena at the TeV scale.

2. Search for new physics in final states containing two jets

The production and properties of dijet events in high energy collisions at the LHC have been measured in ATLAS [3] showing good agreement between data and QCD expectations. Detailed analyses have been performed to search for new physics in the dijet final states. In particular, in the following sections, we report on results for the search of resonances and for deviations in several sensitive observables, which should account for quark contact-interactions.

In the following, jets are reconstructed by using the anti-kT jet clustering algorithm [4] with a radius parameter $R = 0.6$. Detailed studies on the jet reconstruction and calibration have been performed using Monte Carlo (MC) simulated events, test beam and collision data [5, 6].

2.1. Dijet resonances

Several extensions beyond the SM predict the presence of new particle states with heavy masses accessible at LHC energies and decaying into two energetic partons. Such states include an
excited composite quark $q^*$, in models postulating quark substructure [7, 8, 9]. This is the benchmark model that will be used for the present study.

Particularly sensitive to such new objects is the dijet invariant mass observable, defined as \( m_{jj} = \sqrt{(E_1 + E_2)^2 - (p_1 + p_2)^2} \), where \( E \) and \( p \) are the jet energy and three-momentum, respectively. Several experiments have examined \( m_{jj} \) distributions in search of new resonances. Recently, 1.13 fb\(^{-1}\) of \( pp \) collision data at \( \sqrt{s} = 1.96 \) TeV collected at the Fermilab Tevatron collider, excited quarks \( q^* \) with a mass of \( 260 < m_{q^*} < 870 \) GeV have been excluded [10].

In ATLAS, the analysis technique [11] consisted of a model-independent search for a narrow dijet mass resonance on top of a smooth and rapidly falling spectrum, relying on the measured \( m_{jj} \) distribution to estimate the background level to this new possible signal. In the absence of an observed new physics signal, upper limits were determined on products of cross section (\( \sigma \)) times signal acceptance (\( \mathcal{A} \)). The analysis is based on a data sample corresponding to an integrated luminosity of 3.1 pb\(^{-1}\).

The lowest unprescaled jet-trigger was used, which retains events with a jet satisfying the requirement \( p_{Tj}^\ell > 150 \) GeV. Events were required to have a primary vertex reconstructed from at least three tracks with \( p_T \) above 150 MeV and be compatible with the average beam spot position. Events with at least two jets were retained if the highest \( p_T \) jet (the “leading” jet) satisfied \( p_{Tj}^\ell > 150 \) GeV and the next-to-leading jet satisfied \( p_{Tj}^2 > 30 \) GeV. The two leading jets were required to satisfy several quality criteria [12] and to lie outside detector regions where the jet energy was not yet measured in an optimal way, such as the interval \( 1.3 < |\eta^{jet}| < 1.8 \). Finally, both jets were required to be in the pseudorapidity region \( |\eta^{jet}| < 2.5 \), and their pseudorapidity difference was required to satisfy \( |\eta^{j1} - \eta^{j2}| < 1.3 \). The final event sample was selected by requiring the dijet invariant mass to satisfy \( m_{jj} > 200 \) GeV in order to eliminate any potential kinematic bias in the \( m_{jj} \) distributions from the selection requirements on the jet candidates.

The invariant mass distribution is shown in Fig. 1 together with the estimated QCD background, which is obtained by fitting the data with a function of the form \( f(x) = p_1(1-x)p_2 \cdot x^{p_3+p_4 \ln x} \), where \( x = m_{jj}/\sqrt{s} \) and \( p_i \) are free parameters [10]. The presence or absence of detectable \( m_{jj} \) resonances in this distribution was determined by performing several statistical tests of the background-only hypothesis [11].

In the absence of any observed discrepancy with the zero-signal hypothesis, a Bayesian approach was used to set 95% confidence level (CL) upper limits on \( \sigma \cdot \mathcal{A} \) for hypothetical new particles decaying into dijets with \( |\eta^{jet}| < 2.5 \). For more details on the statistical treatment see Ref. [11]. The effects of the systematic uncertainties (jet energy scale, background fit, integrated luminosity, and jet energy resolution), were incorporated as nuisance parameters into the likelihood function used to extract the limit, as reported in in Ref. [11]. Figure 2 depicts the resulting 95% CL upper limits on \( \sigma \cdot \mathcal{A} \) as a function of the \( q^* \) resonance mass after incorporation of systematic uncertainties. A 95% CL \( q^* \) mass exclusion region was determined to be \( 0.50 < m_{q^*} < 1.53 \) TeV.

### 2.2. Quark Contact Interactions

This analysis [13] focuses on dijet angular distributions, which have been shown by previous experiments [14, 15, 16, 17] to be sensitive measures for testing the predictions of QCD and for searching for new processes. Dijet angular distributions are well suited to the analysis of early LHC data, since they are little affected by the main systematic uncertainties associated with the jet energy scale (JES) and the luminosity. QCD calculations predict that high-\( p_T \) dijet production is dominated by \( t \)-channel gluon exchange, leading to angular distributions that are peaked at \( |\cos \theta^*| \) close to 1, where \( \theta^* \) is the polar scattering angle in the two-parton center-of-mass (CM) frame. By contrast, models of new processes characteristically predict angular distributions that would be more isotropic than those of QCD.

The highest exclusion limits on quark contact interactions set by any previous experiment [17],
Figure 1. The data (D) dijet mass distribution (filled points) fitted using a binned background (B) distribution (histogram). The predicted $q^*$ signals for excited-quark masses of 500, 800, and 1200 GeV are overlaid, and the bin-by-bin significance of the data-background difference is shown.

Figure 2. The 95% CL upper limit on $\sigma \cdot A$ as a function of dijet resonance mass (black filled circles). The black dotted curve shows the expected 95% CL upper limit and the light and dark yellow shaded bands represent the 68% and 95% credibility intervals of the expected limit, respectively.

for several statistical analyses, ranges from 2.8 to 3.1 TeV at 95% CL for the compositeness scale $\Lambda$. The reference model assumed here is one with isoscalar left-left interaction with positive interference.

The variable $\chi$, used in the first angular distributions considered in this study, is derived from the rapidities of the two jets defining the dijet topology ($y_1$ and $y_2$). For a given scattering angle $\theta^*$, the corresponding rapidity in the CM frame (in the massless particle limit) is $y^* = \frac{1}{2}(y_1 - y_2)$. Defining $\chi \equiv \exp |y_1 - y_2| = \exp 2|y^*|$, the evaluation of $dN/d\chi$ in QCD events shows that this distribution is almost constant in $\chi$. By contrast, the angular distributions characteristic of new processes are more isotropic in $\theta^*$, leading to additional dijet events at low $\chi$.

The second angular distribution considered is the dijet centrality ratio, $R_C$. For this analysis, the detector is divided into two pseudorapidity regions: central and non-central. $R_C$ is defined as the ratio of the number of events in which the two highest $p_T$ jets both fall into the central region ($|\eta_{1,2}| < 0.7$) to the number of events in which the two highest $p_T$ jets both fall into the non-central region ($0.7 < |\eta_{1,2}| < 1.3$). Since new processes are expected to produce more central activity than QCD, their signal would appear as an increase in $R_C$ above some $m_{jj}$ threshold, with the increase being directly related to the cross section of the new signal.

Vertex and trigger requirements are as those discussed in Sec. 2.1. Events with at least two jets are retained if the highest $p_T$ jet (the “leading” jet) satisfies $p_T > 60$ GeV and the next-to-leading jet satisfies $p_T > 30$ GeV. The two selected jets are required to satisfy quality criteria [12]. They are also required to be found within the pseudorapidity region $|\eta| < 2.8$, where the jet energy scale is known to highest precision.

The benchmark process considered in this analysis is a quark contact interaction, which may be used to model the onset of kinematic properties that would characterize quark compositeness: the hypothesis that quarks are composed of more fundamental particles. The model Lagrangian...
for this benchmark process is a four-fermion contact interaction, the analog of the Fermi four-fermion interaction used to describe effects of the weak interaction. The effects of the contact interaction would be expected to appear below or near a characteristic energy scale $\Lambda$.

The JES represents the dominant uncertainty for this analysis. Typical values of the JES uncertainty in the considered phase space are between 5% and 7%. The resulting bin-wise uncertainties are up to 9% for the $\chi$ observable, and up to 7% for the $R_C$ observable. The dominant sources of theoretical uncertainty on the QCD cross section and the PDF uncertainties. Since no signal of new physics processes is observed in the $\chi$ (Fig. 3) and $R_C$ distributions, limits have been obtained on the compositeness scale $\Lambda$ of quark contact interactions, based on analyses of the $\chi$ distributions. The contact term hypothesis is tested in the highest dijet mass bin in Fig. 3, which begins at $m_{jj} = 1200$ GeV. For the $\chi$ distribution in this mass bin, the parameter $F_\chi$ is defined as the ratio of the number of events in the first four $\chi$ bins to the number in all $\chi$ bins. The upper boundary of the fourth bin is at $\chi = 3.32$. A frequentist analysis is employed, as reported in Ref. [13].

The observed limit on $\Lambda$ is 3.4 TeV. This limit is found from the point where the $F_\chi$ 95% CL contour crosses the measured $F_\chi$ value, which is shown in Fig. 4. All values of $\Lambda$ less than this value are excluded with 95% CL. The expected limit, found from the crossing at the QCD prediction, is 3.5 TeV. This corresponds to a distance scale of $\sim 6 \cdot 10^{-5}$ fm.

Figure 3. Normalized $\chi$ distributions for different mass intervals. Shown are the QCD predictions with systematic uncertainties (bands), and data points with statistical uncertainties. The prediction for QCD with an added quark contact term with $\Lambda = 3.0$ TeV is shown for the highest mass bin.

Figure 4. The dashed horizontal line is the measured $F_\chi$ and the solid horizontal line is the QCD prediction, with a band to illustrate a 1-$\sigma$ variation of the expected limit. The dotted curve is the 95% CL exclusion contour for $F_\chi$ with quark contact interactions, used to set the exclusion limit on $\Lambda$.

3. High-mass states with electron plus missing transverse energy

One extension to the SM common to many models is the existence of additional, heavy gauge bosons [18]. It is common to use $W'$ to denote any charge $\pm 1$, spin 1 particle outside the SM and here that convention is used. The analysis has been performed on the search for a $W'$ boson
decaying to an electron and a neutrino, whose production is inferred from Missing Transverse Energy ($E_T^{miss}$) [19]. Measurements at the Fermilab Tevatron experiments [20, 21] rule out the existence of a $W'$ with massless than 1 TeV assuming the Sequential SM, i.e. the same couplings as those for the SM $W$ boson.

Although ATLAS has not yet recorded enough luminosity to improve on this value, a limit on $\sigma \cdot B$ (the product of the production cross section and the branching fraction) is set in the electron decay channel over the mass range between 150 and 600 GeV. This limit is based on collision data equivalent to an integrated luminosity of only 317 nb$^{-1}$.

The kinematic variable used to identify the $W'$ is the transverse mass $m_T = \sqrt{p_T E_T^{miss} (1 - \cos \varphi)}$ which has a Jacobian peak which falls sharply above the boson mass. Here $p_T$ is the electron transverse momentum and $\varphi$ is the angle between the transverse components of the electron momentum and the missing momentum.

The main background to the $W'$ signal comes from the SM $W$ boson. Other backgrounds are $Z$ bosons decaying into two electrons where one electron is not reconstructed, $W$ or $Z$ decaying to tau leptons where the tau subsequently decays to an electron, and QCD and $t\bar{t}$ production where a light or heavy hadron decays into an electron or a jet is misidentified as an electron.

Events are required to be triggered by an electron with $p_T > 20$ GeV and to have a primary vertex reconstructed from at least three tracks with $p_T$ above 150 MeV and longitudinal distance less than 15 cm from the center of the collision region. Spurious tails in $E_T^{miss}$ arising from calorimeter noise are suppressed by checking the quality of each reconstructed jet and discarding events with any jet which has a shape indicating possible noise contamination following standard ATLAS criteria for jet cleaning [12]. Events are required to have a candidate electron defined as follows.

A candidate electron is one reconstructed with $E_T > 20$ GeV, $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$ and satisfying the ATLAS “medium” electron requirement, which is defined in Ref. [2]. In addition, a fiducial cut is made to remove events with electrons near problematic regions of the electromagnetic calorimeter. In addition, the inner detector track associated with the electron is required to be close to the primary vertex, specifically with transverse distance of approach satisfying $|p_{0\text{PV}}| < 1$ mm and longitudinal distance at this point $|z_{0\text{PV}}| < 5$ mm. Events are required to have exactly one candidate electron.

To suppress QCD sources of background, the electron is required to be isolated, defining the isolation by $R_{isol} = \sum_{p_T > 0} \frac{p_T^{trk}}{p_T}$ and requiring $R_{isol} < 0.05$. Here $p_T^{trk}$ is the electron transverse momentum and the sum in the numerator is over the transverse momenta of the inner detector tracks with $p_T^{trk} > 1.0$ GeV in a cone $\Delta R < 0.30$ ($\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \varphi)^2}$) around the direction of the electron, excluding the track associated to the electron itself. For the final selection, additionally $E_T^{miss}$ is required to exceed 25 GeV.

The $m_T$ spectrum (Fig. 5) shows no evidence for the existence of a $W'$ and the data are used to set limits on $\sigma \cdot B$ for a series of $W'$ masses ranging from 150 to 600 GeV. Limits are obtained by counting the number of events with $m_T > 0.7 \cdot m_{W'}$.

A single-bin likelihood analysis is performed to set a limit at each mass using the observed number of events. Limits for 95% CL exclusion are calculated as described in Ref. [19]. Inputs to this calculation include the observed number of events, the signal efficiencies and uncertainties. The systematic uncertainties used in the limit calculations include the uncertainty on the number of background events, the event selection efficiency uncertainties, and the uncertainty on the integrated luminosity. These are assumed to be uncorrelated. Results are shown in Fig. 6. The intersection between the limits and these values provides a 95% CL estimate upper limit on the $W'$ mass in the SSM model. Using linear interpolation between the points, a limit of 465 GeV is obtained at 95% CL.
Figure 5. Transverse mass spectra after the final selection. Points are ATLAS data and the filled histograms show the Monte Carlo background from QCD, $t\bar{t}$, W and Z boson contributions. Open histograms are $W'$ signals added to the background.

Figure 6. Limits on $W'$ production. Limits and the Pythia SSM predictions are shown on log scale.

4. Diphoton events with large missing $E_T$

In the SM, the production in $pp$ collisions of diphoton ($\gamma\gamma$) events with large $E_T^{\text{miss}}$ is mainly due to $W/Z + \gamma\gamma$ processes. Taking into account the branching ratios of $W/Z$ decays involving at least one neutrino, the cross sections are only a few femtobarns for 7 TeV $pp$ collisions. In contrast, some new physics models predict much larger $\gamma\gamma + E_T^{\text{miss}}$ rates.

Universal Extra Dimension (UED) models [22] postulate the existence of additional spatial dimensions in which all SM particles can propagate, leading to the existence for each SM particle of a series of excitations, known as a Kaluza-Klein (KK) tower. The same signature exists in gauge mediated supersymmetry with a gravitino as a LSP and Bino as NLSP. This analysis considers the case of a single TeV$^{-1}$ sized UED, with compactification radius $R$. The masses of the states of successive levels in the tower are separated by $\sim 1/R$.

The UED model considered is defined by specifying $R$ and $\Lambda$, the ultraviolet cut-off used in the calculation of radiative corrections to the KK masses. This analysis treats $R$ as a free parameter and sets $\Lambda$ such that $\Lambda \cdot R = 20$.

The reconstruction of photons is described in detail in Ref. [23]. To select photon candidates, EM calorimeter clusters were required to pass several quality criteria and to lie outside problematic calorimeter regions. Photon candidates were required to have $|\eta| < 1.81$ and to be outside the transition region $1.37 < |\eta| < 1.52$ between the barrel and the end-cap calorimeters. The analysis uses a “loose” photon selection [2]. The loose selection provides a high photon efficiency with modest rejection against the background from jets.

The data sample analysed corresponds to an integrated luminosity of 3.1 pb$^{-1}$. The events selected had to satisfy a trigger requiring at least one loose photon candidate with $E_T > 20$ GeV, and had to contain at least one reconstructed primary vertex consistent with the average beam spot position and with at least three associated tracks. Events were retained if they had at least two photon candidates, each with $E_T > 25$ GeV. In addition, a photon isolation cut was applied, where in the $E_T$ in a radius of 0.2 in the $\eta - \phi$ space around the center of the cluster (excluding the cells belonging to the photon cluster) had to be less than 35 GeV. The background was evaluated entirely using data.

Given the good agreement between the measured $E_T^{\text{miss}}$ spectrum and the expected background (Fig. 7), a limit was set on $1/R$ in the specific UED model considered here. A Bayesian approach was used to calculate a limit based on the number of observed and expected events.
with $E_{\text{T}}^{\text{miss}} > 75$ GeV, as explained in detail in Ref. [24]. A Poisson distribution was used as the likelihood function for the expected number of signal events, and a flat prior was used for the signal cross section [24]. The observed 95% CL exclusion region is $1/R < 728$ GeV, as shown in Fig. 8.

![Figure 7. $E_{\text{T}}^{\text{miss}}$ spectrum for the $\gamma\gamma$ candidates, compared to the total SM background as estimated from data. Also shown are the expected UED signals for $1/R = 500$ GeV and 700 GeV.](image1)

![Figure 8. 95% CL upper limits on the UED production cross section, and the LO theory cross section prediction, as a function of 1/R. The shaded band shows the pdf uncertainty.](image2)

5. SUSY searches
A wide range of SUSY searches have been performed with the first LHC data. The available data sample has been used to make a first study of the backgrounds and to optimize the analysis. Results from inclusive searches of SUSY signals are to be published. The expected sensitivity with an integrated luminosity of around 500 pb$^{-1}$ has also been estimated [25]. With such a luminosity, the most promising final states for the search of SUSY are the one including 4 jets and 0 leptons (Ref. [26]), for which discovery of squarks up to a mass of $\sim 700$ GeV and gluinos to a mass of $\sim 600$ GeV is possible in the scenario of minimal Supergravity with R-parity conservation [27]. With increasing luminosity, starting from $\sim 1$ fb$^{-1}$, will become important final states including leptons (Ref. [28]). Also final states with b-jets are expected to be really sensitive to SUSY scenarion (Ref. [29]).

6. Conclusion
The most recent results for the search of new physics with the ATLAS experiment have been shown after the detector has collected a total integrated luminosity of 40 pb$^{-1}$ at $\sqrt{s} = 7$ TeV. The detector is working nicely and the physics performance are under control and are being improved quickly. With this first round of analysis, several limits on Exotics physics processes have been extended beyond the results of previous experiments. Several benchmark searches are being refined and are expected to give interesting results once the full available luminosity will be analyzed. The optimization of the analysis strategies and
the improving of the understanding of the detector will allow for several sensitive searches with
the data expected in the next year of LHC running.

References
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