Searches for new physics with jets in ATLAS

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Abstract. We present the latest results of searches for new physics beyond the Standard Model with jets in the final state using the ATLAS detector. These analyses are performed with the full LHC 2010 data from proton-proton collisions at a center-of-mass energy of 7 TeV. The results are based on an integrated luminosity of 33 to 37 pb$^{-1}$ depending on the analysis. No significant discrepancy is found with the expected Standard Model predictions. New limits on various models are set beyond the reach of previous experiments.

1. Introduction

The Standard Model (SM) describes most of the current high energy physics data well. It accommodates three families of leptons and quarks that couple via the exchange of four bosons. The mass of these particles is generated via the spontaneous symmetry breaking mechanism at the cost of predicting a new particle, the Higgs boson, which has not been observed yet. Even if the Higgs boson is observed, there are still many open questions not explained within the Standard Model such as the apparent asymmetry of matter-anti-matter in the visible universe or what is the mechanism that generates the mass of fermions. Since 2009, the Large Hadron Collider (LHC) has been producing proton-proton collisions to investigate some of these questions. The data recorded by the ATLAS experiment during 2010 includes 45 pb$^{-1}$ at a center-of-mass energy of 7 TeV. Therefore, we are now accessing a new energy regime where new physics could potentially appear.

In this note, we will present the search for new physics in final states containing jets. The analysis try to be model-independent when possible and the results are then interpreted within different models. Section 3 shows the results on the dijet final state where we are looking for new resonances and new interactions by analyzing the dijet mass spectrum and angular distributions. Section 4 shows the search for a heavy fourth generation quark $(Q_4)$ in final states with two $W$ bosons and jets. And finally, Section 5 shows a search for 1$^{st}$ and 2$^{nd}$ generation leptoquark (LQ) pair production in leptons-plus-jets signatures.

2. Detector description

The ATLAS detector is described in detail elsewhere [1]. The beam-line is surrounded by a tracking detector that uses silicon pixel, silicon strip, and straw tubes and is embedded in a 2 T magnetic field. The tracking system covers the pseudorapidity $|\eta| < 2.5$. It is surrounded by electromagnetic and hadronic calorimeters covering $|\eta| < 3.2$, which are
complemented by a forward hadronic calorimeter covering $3.1 < |\eta| < 4.9$. The luminosity calibration has been determined during dedicated van der Meer beam scans to a precision of 3.4\% [3, 4].

3. Dijet signatures

The aim of this analysis is to search for massive objects and new interactions by studying the dijet invariant mass and angular distributions. Previous ATLAS results used $3.1 \text{ pb}^{-1}$ [5] while the results presented here use an order of magnitude more of data, $36 \text{ pb}^{-1}$ integrated luminosity. The dijet inclusive cross-section has been measured in ATLAS up to dijet masses of 4.1 TeV [6] testing the Standard Model in a new unexplored regime.

The dijet invariant mass spectrum is sensitive to new phenomena: potential new physics could show up as a local excess of events in the dijet mass spectrum. This analysis starts with a basic event pre-selection that requires a primary vertex with more than 4 charged tracks and at least 2 jets with $p_T^1 > 60$ GeV and $p_T^2 > 30$ GeV. For the dijet analysis [7], we use all 2010 data that pass a first-level inclusive jet trigger which has an efficiency larger than 99\% for jet pairs with $m_{jj} > 500$ GeV.

For the resonance search additional event selection cuts are applied. Only events with a leading jet with transverse momentum larger than 150 GeV, dijet invariant mass, $m_{jj}$, larger than 500 GeV, $|\eta_j| < 2.5$ and $\Delta \eta_{jj} < 1.3$ are used.

This analysis looks for resonances in the dijet invariant mass with a data-driven method that models the rapidly falling smooth distribution of the SM dijet background shape using the formula:

$$f(x) = p_1(1-x)^{p_2}x^{p_3+p_4\ln x} \quad \text{with} \quad x = m_{jj}/\sqrt{s},$$

where $p_i$ are the parameters of the fit, $\sqrt{s}$ is the center-of-mass energy and $m_{jj}$ the invariant mass of the two leading jets. This formula has been empirically shown to model the shape of SM dijet background [8, 9]. After the fit, a $\chi^2$ test is performed, resulting in a p-value of 0.88 which is indeed in good agreement with the QCD expected shape. An additional test is performed using a BUMPHUNTER algorithm [10]. This algorithm searches for a signal window with an excess of events. The largest discrepancy is found in the region $995 \text{ GeV} < m_{jj} < 1253 \text{ GeV}$ with a p-value of 0.39 which is still very good agreement between the data and the fit to a smooth rapidly falling distribution. Figure 1 shows the observed dijet mass distributions fitted using Eq. 1. Overlaid to the distribution are the predicted signals for excited quarks ($q^*$) with masses of 1000, 1700 and 2500 GeV normalized to $36 \text{ pb}^{-1}$. The bin-by-bin significance of the data-background difference is shown in the lower panel.

We do not find any discrepancy with the Standard Model prediction and are able to set new exclusion limits in several models. Using Bayesian credibility intervals, we exclude the production of an excited quark $q^*$ with masses below 2.15 TeV (see Figure 2) and the production of an axigluon with masses below 2.10 TeV. We also set limits on “low multiplicity” quantum black hole models (QBH) [6, 11]. This model produces threshold effects in $m_{jj}$ with long tails to higher dijet masses that compete with the SM dijet background. Since, the cross-section is very large just above the threshold it is possible to extract limits given the resulting resonance-like signal shape. The resulting limits are shown in Table 1.
Figure 1: Observed dijet mass distribution (filled dots) and the fitted function (solid line). The bin-by-bin significance of the data-background difference is shown in the lower panel.

| Extra Dimensions | Observed Limit [TeV] | Expected Limit [TeV] |
|------------------|----------------------|----------------------|
| 2                | 3.20                 | 3.18                 |
| 3                | 3.38                 | 3.35                 |
| 4                | 3.51                 | 3.48                 |
| 5                | 3.60                 | 3.58                 |
| 6                | 3.67                 | 3.64                 |
| 7                | 3.73                 | 3.71                 |

Table 1: The 95% C.L. observed and expected lower limits on the allowed quantum gravity scale, $M_D$, for various numbers of extra dimensions.

As a novelty, in this analysis, we also set up model-independent limits by using a simplified Gaussian method. Our signal template is a Gaussian with mean ($\mu$) that varies between 600 GeV and 4000 GeV and sigma ($\sigma$) between 3% and 15%. We set production cross-section limits as a function of the dijet mass to facilitate comparisons with other hypotheses. Figure 3 shows the 95% C.L. limits as a function of the resonance mass expressed in terms of number of events observed after applying all event selection criteria. Points in the same mass bin correspond to different resonance widths.
For the analysis on the angular distributions the starting point is the sample obtained with the pre-selection described above. We define 2 variables:

\[ y_B = \frac{1}{2}(y_1 + y_2) \quad \text{and} \quad y^* = \frac{1}{2}(y_1 - y_2), \]

where \( y_i \) is the rapidity of jet \( i \). We then select events with \(|y_B| < 1.1, |y^*| < 1.7\) and \(|y_1,2| < 2.8\). The dijet invariant mass is required to be \( m_{jj} > 500 \) GeV. Figure 4 shows the distribution of the angular variable \( \chi \) defined as

\[ \chi = \exp(|y_1 - y_2|), \]

for several dijet mass bins. This variable is shown to be relatively flat for the expected QCD background. In the Figure we compare the QCD prediction with a quantum black hole scenario with quantum gravity mass scale of \( M_D = 3 \) TeV and six extra dimensions.

Figure 5 shows the fraction of dijets produced centrally versus the total number of observed dijets for a specified dijet mass range:

\[
F_{\chi}(m_{jj}^{min} + m_{jj}^{max}]/2) = \frac{N_{\text{events}}(|y^*| < 0.6, m_{jj}^{min}, m_{jj}^{max})}{N_{\text{events}}(|y^*| < 1.7, m_{jj}^{min}, m_{jj}^{max})}.
\]

This variable is sensitive to mass-dependent changes. In the Figure, the observed data \( F_{\chi}(m_{jj}) \) are compared with QCD predictions and with the predicted distribution for a contact interaction model with the compositeness scale \( \Lambda = 5.0 \) TeV. The data are compatible with the background-only hypothesis and exclusion limits are set from this analysis, see Ref. [7]. In particular, we exclude contact interactions for \( \Lambda < 9.5 \) TeV at 95% C.L.

![Figure 4: The \( \chi \) distributions for several dijet mass bins shifted up by the value shown in the legend.](image)

![Figure 5: The \( F_{\chi}(m_{jj}) \) function versus dijet invariant mass.](image)
4. WWjj signatures

In this note, we also show a search for pair production of fourth generation quarks, $Q_4$, decaying $Q_4 \to Wq$ where the quark type $q$ could be $u, d, c, s$ or $b$. We assume a $u_4$ model for the analysis but the results are directly applicable to more exotic quark models (i.e. quarks with charges $-1/3, -4/3$ decaying into $Wq, q$ being a light quark) [12]. We analyze the case of both $W$ bosons decaying into $l\nu$: therefore the final state will contain two oppositely charged leptons, jets and missing transverse energy from the undetected neutrinos.

The initial event selection suppresses most of the background contribution from $Z/\gamma^*$ production; this selection requires:

- At least 2 jets with $p_T > 20$ GeV and $|\eta| < 2.5$.
- For same flavor events ($ee$ and $\mu\mu$):
  - Missing transverse energy $E_T^{\text{miss}} > 40$ GeV.
  - Dilepton invariant mass, $m_{ll} > 15$ GeV, as the Monte-Carlo does not include contribution from lower invariant masses.
  - Dilepton invariant mass must fall outside a $m_Z$ window, $m_{ll} < 81$ GeV or $m_{ll} > 101$ GeV.
- For different flavor events ($e\mu$):
  - Scalar sum of transverse energy from leptons and jets $H_T^{\text{jet}, \text{leptons}} > 130$ GeV.

Figure 6 shows the missing transverse energy for the data (points) and the expected signal and backgrounds for the 3 leptonic channels $ee, \mu\mu$ and $e\mu$ after this baseline selection. Afterwards, a more refined selection uses the mass reconstruction to suppress the dominant top quark pair background.

We can reconstruct both neutrinos by assuming that the two neutrinos are the only contribution to the $E_T^{\text{miss}}$ and that they are approximately collinear with the leptons. In order to do this, we vary $|\Delta\eta(\nu l)|$ and $|\Delta\phi(\nu l)|$ independently between 0 and 1 and reconstruct the invariant masses of the two $lq$ systems. We choose the values of $|\Delta\eta(\nu l)|$, $|\Delta\phi(\nu l)|$ and the jet assignment that minimize the difference of the two reconstructed collinear masses ($M_{\text{collinear}}$) in the event. Figure 7 shows the distribution of the sum of transverse energy versus collinear mass for background (left) and signal of a heavy quark with mass $M_{Q_4} = 350$ GeV for the sum of the $ee, \mu\mu$ and $e\mu$ channels. These distributions indicate that it is possible to remove a significant fraction of the background events by applying a triangular cut dependent on $H_T = H_T^{\text{jet, leptons}} + E_T^{\text{miss}}$ and $M_{\text{collinear}}$. Table 2 shows the final selection cuts for each $Q_4$ mass.

| $Q_4$ Mass [GeV] | Final selection                           |
|------------------|------------------------------------------|
| 250              | $H_T > 500 - 0.7 \times M_{\text{collinear}}$ |
| 300              | $H_T > 600 - 0.5 \times M_{\text{collinear}}$ |
| 350              | $H_T > 600 - 0.2 \times M_{\text{collinear}}$ |
| 400              | $H_T > 700 - 0.3 \times M_{\text{collinear}}$ |
Figure 6: Missing transverse energy, $E_T^{\text{miss}}$ after dilepton selection in ee, $\mu\mu$ and $e\mu$ channels.

Figure 7: Sum of transverse energy $H_T$ versus $M_{\text{collinear}}$ for background (left) and for a heavy quark $Q_4$ with mass $m_{Q_4} = 350$ GeV (right) for the sum of ee, $\mu\mu$ and $e\mu$ channels.

Figure 8 shows the collinear mass distribution after the final selection cuts. The data are consistent with the expectation from the Standard Model and we set a lower limit on the $Q_4$ mass of $m_{Q_4} > 270$ GeV at 95% C.L., see Figure 9. These limits are applicable to $u_4$-type quarks as well as other exotic quark models.

Figure 8: Reconstructed collinear mass ($M_{\text{collinear}}$) for the sum of ee, $\mu\mu$ and $e\mu$ channels after applying the final cuts for expected signal of $m_{Q_4} = 250$ GeV.

Figure 9: 95% confidence level observed and median expected cross-section upper limits compared to the theoretical prediction.
5. Leptons plus jets signatures

We have also investigated the production of leptoquark pairs decaying into leptons plus jets. Leptoquarks are particles that carry both lepton and baryon number; these particles are predicted by theories such as substructure theories, grand unification and extended technicolor. The cross-section times branching ratios for the leptoquark-mediated processes \( pp \rightarrow lljj \) and \( l\nu jj \) can be written as \( \sigma_{LQ} \times \beta^2 \) and \( \sigma_{LQ} \times 2\beta(1-\beta) \) respectively, where \( \beta \) is the branching fraction for a single leptoquark to decay into a charged lepton and a quark. The production rates also depend strongly on the leptoquark mass \( M_{LQ} \) and therefore the final production limits will be shown as a function of these two parameters \( M_{LQ} \) and \( \beta \).

The main backgrounds for the channel \( lljj \) are \( Z + \text{jets} \) and \( t\bar{t} \) production and for the channel \( l\nu jj \), \( W + \text{jets} \) and \( t\bar{t} \) production. For leptoquark pair production we expect a signal peak in the invariant mass of jet-lepton (and jet-neutrino) pair together with large \( S_L^T \), where \( S_L^T \) is the scalar sum of the transverse momentum of the two charged leptons and jets; in the case of the \( l\nu jj \) channel the missing transverse energy is used on the calculation. Figure 10 shows the \( S_L^T \) distribution for the \( eejj \) final state after all selections. Figure 11 shows the invariant mass (lepton-jet) distribution for the \( e\nu jj \) channel after all selections. In both cases, the data are indicated by the points and the Standard Model backgrounds are shown with cumulative distributions. The expected LQ signals for various masses are also shown.

![Figure 10: \( S_L^T \) distribution for the \( eejj \) final state signal region.](image)

![Figure 11: \( M_{LQ} \) distribution for the \( e\nu jj \) final state signal region.](image)

The data match the background-only prediction. Figures 12 and 13 show the 95% C.L. exclusion region obtained from the combination of the two electron channels (left) and the two muon channels (right) in the \( \beta \) versus \( M_{LQ} \) plane. The gray area indicates the D0 exclusion limit and the thick dotted line the CMS exclusion. The dotted and dotted-dashed lines show the individual limits for the \( lljj \) and the \( l\nu jj \) channels, respectively. The combined expected limit is indicated by the dashed line. The combined observed limit is indicated by the solid line. We set 95% C.L. observed lower limits for first (second) generation leptoquark masses of \( M_{LQ} > 376(422) \) GeV and \( M_{LQ} > 319(362) \) GeV for \( \beta = 1.0 \) and \( \beta = 0.5 \) respectively.

6. Results and conclusions

ATLAS has searched for new physics in final states with jets using between 33 and 37 pb\(^{-1} \) of LHC data which correspond to the full data sample recorded in 2010. We are exploring a new physics regime at the TeV scale. No discrepancies with the Standard Model were found, new limits at 95% C.L. set for several models (see Table 3).
**Table 3:** Summary of exclusion limits from events with jets in the final state.

| Final state           | Model                          | Limit [TeV] |
|-----------------------|--------------------------------|-------------|
| Dijets                | Excited quarks ($q^*$)         | 2.64        |
|                       | QBH $n = 6$                    | 3.67        |
|                       | Axigluons                      | 2.10        |
|                       | Contact Interactions           | 9.50*       |
| WWjj                  | 4th generations heavy quarks ($Q_4$) | 0.270     |
| Leptons (MET) + jets  | $1^{st}$ generation LQ ($\beta = 1$) | 0.376    |
|                       | $2^{nd}$ generation LQ ($\beta = 1$) | 0.422    |

*6.7 TeV Bayesian Limit

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