Searches for Dijet Resonances with the ATLAS Detector

Wasikul Islam[1], *On behalf of the ATLAS Collaboration*

[1]Department of Physics, University of Wisconsin, Madison, WI 53706 USA

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Abstract

Many theories beyond the Standard Model (SM) predict new physics phenomena that decay hadronically to dijet or multijet final states. This document summarises some of the latest results from the ATLAS experiment using the Run 2 dataset, involving these final states.

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1 Introduction

Searches for resonances decaying into two jets are among the most powerful probes of new physics at hadron colliders and are of particular interest at the ATLAS experiment[1]. They are sensitive to a wide variety of models, including new gauge bosons (sequential Standard Model Z'/W'), excited quarks, composite states, dark matter mediators, technicolor particles, and exotic Higgs scenarios. Historically, such searches have been carried out by UA1/UA2 (CERN SppS), CDF/D0 (Tevatron), and, more recently, ATLAS and CMS at the LHC [2]. ATLAS has conducted inclusive di-jet resonance searches as well as analyses exploiting additional objects (leptons, photons) or advanced machine learning methods—both weakly supervised and unsupervised anomaly detection [3, 4]. These strategies are motivated by the need to overcome trigger limitations, extend sensitivity to low-mass regions, and ensure broad coverage across final states. This proceeding summarizes recent Run 2 results from ATLAS presented at Lepton-Photon 2025, covering inclusive searches, lepton- and photon-assisted analyses, paired di-jet topologies, and novel ML-driven approaches [2–7].

2 Dataset and Analysis Strategies

The ATLAS detector recorded 139 fb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV during Run 2. Across the full program, the combined di-jet resonance-mass coverage spans very low masses, such as a few hundred GeVs to very high masses such as 8 TeV: inclusive di-jet searches typically probe ∼1.1–8 TeV [2], while low-mass analyses using ISR photons or jets extend sensitivity down to 200–650 GeV [7]. Backgrounds to di-jet searches are dominated by QCD multijet production, which often yields a smoothly falling di-jet invariant mass (m_{jj}) spectrum.

Low-mass di-jet searches also benefit from Trigger-Level Analyses (TLA) [8], where events are recorded using high-level trigger (HLT) jet objects rather than full detector readout. This strategy enables significantly lower di-jet mass thresholds and higher data-taking rates, providing enhanced sensitivity in the 450–900 GeV region.

The main strategies considered in this document include:

- inclusive di-jet searches scanning m_{jj} from ∼1–8 TeV, sensitive to generic Gaussian-shaped signals [2],
- lepton- and photon-assisted searches, exploiting single-lepton or ISR-photon/jet triggers to overcome jet trigger thresholds and reduce QCD background [5, 7],
- paired di-jet topologies, probing heavy resonances Y decaying to two intermediate states X ($Y \to XX \to 4j$), with sensitivity to cascade decays not captured in single di-jet analyses [6], and
- weakly supervised and unsupervised ML methods, enabling model-agnostic anomaly detection using data-driven background estimation [3, 4].

3 Inclusive and Lepton-Assisted Searches

Inclusive di-jet resonance searches provide the most general test of new two-body resonances. With Run 2 data, ATLAS excludes excited quarks (q^*) below 6.7 TeV and sequential Z' bosons below 2.7 TeV [2]. Sensitivity is extended by introducing lepton-assisted searches: single-lepton triggers with thresholds $p_T > 24$ GeV for muons and $p_T > 26$ GeV for electrons enable exploration of the low mass regions otherwise inaccessible due to jet trigger prescales [5]. In these events, the background is further suppressed by requiring an isolated lepton, leading to reduced multijet contamination [5].

The analysis considers three- and four-body invariant masses, such as $m_{jj\ell}$ and $m_{jj\ell\ell}$, which probe new particles decaying to di-jets in association with a W/Z boson or a charged lepton [5]. The smoothly falling background is modeled with empirical fit functions of the form

$$f(x) = p_1(1-x)^{p_2}x^{p_3+p_4\ln x+p_5\ln^2 x}, \quad x \equiv m_{jj}/\sqrt{s}. \tag{1}$$

The largest local deviation is observed in the *three-body* spectrum at $m_{jj\ell} \sim 3.5$ TeV, with a local significance of 3.5σ (global 1.5σ) [5]. Exclusions in this lepton-trigger program include limits on W'/Z' scenarios and the simplified dark matter models and—importantly—the first ATLAS limits on a composite lepton model and W_{kk}-radion model [5].

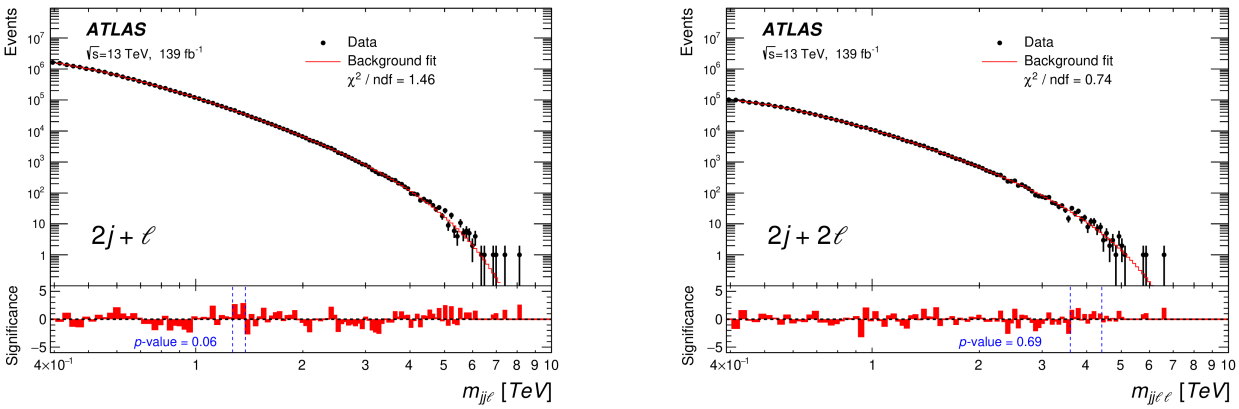

Figure 1: $m_{jj\ell}$ and $m_{jj\ell\ell}$ distributions from the ATLAS di-jet+lepton search, showing data compared to the smooth background fit [5].

4 Paired Di-jet Resonances

A novel search investigates heavy resonances decaying through intermediate states: $Y \to XX \to 4j$ [6]. This topology yields two di-jet systems per event, reconstructed into the tetrajet invariant

mass m_{4j} and the average di-jet mass $\langle m_{jj}\rangle$; the analysis organizes events in slices of the dimensionless variable $\alpha \equiv \langle m_{jj}\rangle/m_{4j}$ to stabilize the background shape [6]. Simultaneous smooth fits are performed to both spectra [6]. No significant deviations are found; localized excesses include one at $m_{4j} \simeq 3.2$ TeV in $0.24 < \alpha < 0.26$ with global significance 0.53σ, and another at $\langle m_{jj}\rangle \simeq 800$ GeV in $0.26 < \alpha < 0.28$ with global significance 1.98σ [6]. Upper limits at 95% CL are set on $Y \to XX$ production across a wide range of m_Y and m_X/m_Y; the highest observed m_{4j} reaches 6.6 TeV with $\langle m_{jj}\rangle \approx 2.2$ TeV [6]. This is the first ATLAS search dedicated to paired di-jet resonances [6].

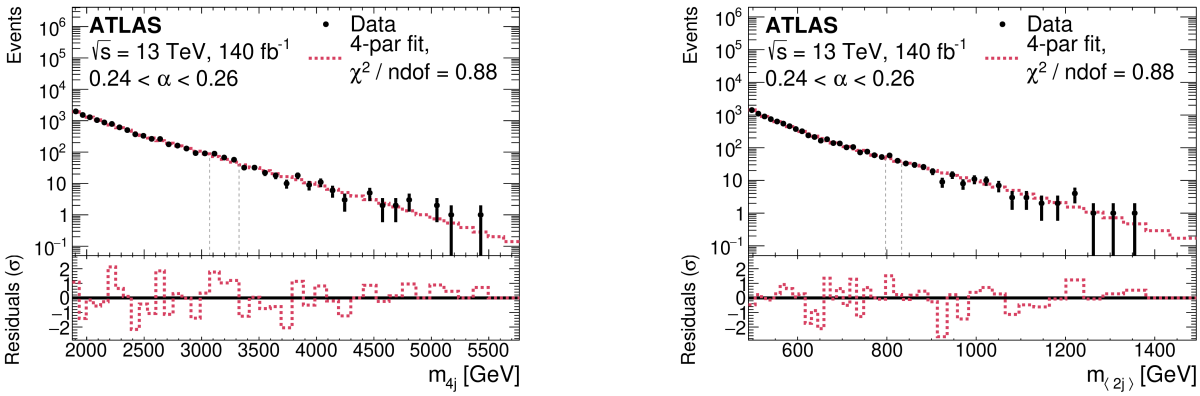

Figure 2: Distributions from the paired di-jet resonance search: tetrajet mass m_{4j} (left) and average di-jet mass $\langle m_{jj}\rangle$ (right), shown in a representative α slice for $0.24 < \alpha < 0.26$ [6].

5 Low-Mass Searches with ISR Objects

Dedicated ISR-assisted analyses explore resonance masses between 200 and 650 GeV, a region inaccessible to inclusive jet triggers [7]. Events are selected with either a high-p_T photon or an additional jet recoiling against the di-jet system. Both inclusive and b-tagged final states are studied, the latter providing sensitivity to resonances decaying preferentially to b-quarks [7]. No significant deviations are found; strong upper limits are placed on benchmark Z' models and model-independent Gaussian signals [7]. These results substantially improve constraints in the low-mass region and complement the inclusive high-mass program [7].

6 Machine Learning Approaches

Beyond traditional bump hunts, machine learning has been deployed to enhance sensitivity and broaden model coverage.

6.1 Weak Supervision

A weakly supervised strategy, Classification Without Labels (CWoLa), trains classifiers on mass sidebands and then applies them in the signal window [3]. The methods use the subjettiness ratios $\tau_{21} = \tau_2/\tau_1$ and $\tau_{32} = \tau_3/\tau_2$, where lower values correspond to jets with clearer two- or three-prong structure.

Two complementary implementations are used: SALAD, which learns weights to correct simulation to data, and CURTAINs, which learns discriminative transformations from adjacent intervals [3]. In the 2.6–5.0 TeV window of the di-jet invariant mass m_{jj} (after classifier selection), both approaches find no significant local excess and set competitive 95% CL limits, demonstrating robust, data-driven background modeling [3].

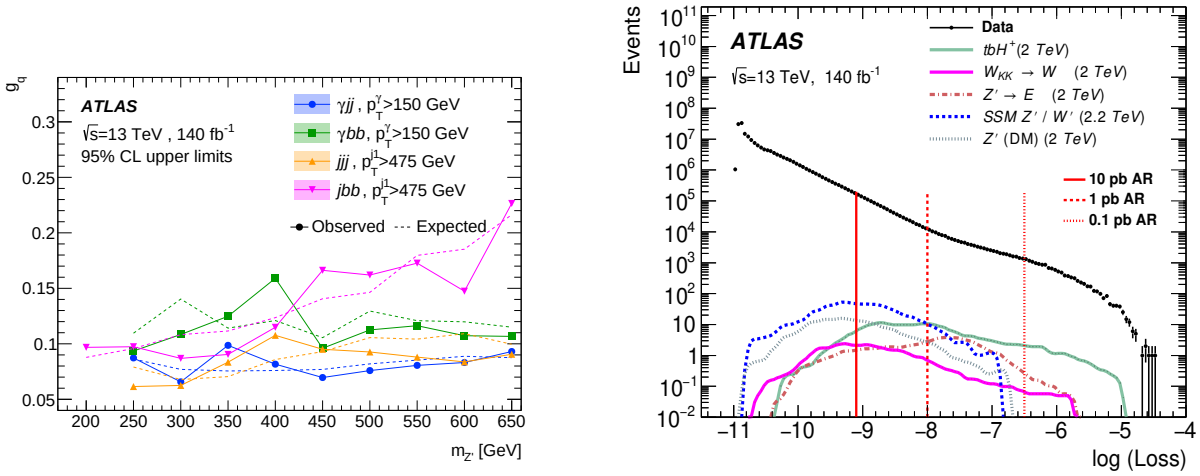

Figure 3: Comparison of ATLAS di-jet resonance searches: (a) representative di-jet invariant mass distribution in the ISR-assisted low-mass search, showing data and fitted background [7], and (b) autoencoder reconstruction loss distribution for collision data and representative BSM signals in the event-level anomaly detection search [4].

6.2 Event-Level Anomaly Detection

An anomaly detection using an unsupervised machine learning approach trains an autoencoder on ∼1% of collision data using 1287 input observables spanning jets, leptons, and photons [4]. The reconstruction loss defines "anomaly regions" corresponding to effective cross sections of 10 pb, 1 pb, and 0.1 pb, providing complementary sensitivities [4]. Bump hunts in nine final states ($m_{jj}, m_{jb}, m_{bb}, m_{j\ell}, m_{j\gamma}$, etc.) reveal no significant excess; nonetheless, limits improve by factors of 2–3 below 1 TeV compared to earlier selections [4]. Local fluctuations (e.g., 2.9σ at 4.8 TeV and 2.8σ at 1.2 TeV) are consistent with expectations once the look-elsewhere effect is considered [4].

Systematic uncertainties are dominated by the jet energy scale and resolution, which influence both the signal acceptance and the fitted background spectra. Additional contributions come from luminosity, trigger efficiency, and the choice of background parameterization. For ML-based approaches, uncertainties from model training and potential mismodelling of high-dimensional correlations are included. All uncertainties are propagated for limit setting.

7 Conclusions

ATLAS has carried out a comprehensive program of di-jet resonance searches with the full Run 2 dataset [2–7]. These cover inclusive di-jet mass spectra, ISR-assisted low-mass regions, three- and four-body final states with leptons, cascade decays to four jets, and both weakly supervised and unsupervised machine learning approaches. No significant excess has been observed across any search channel. Exclusion limits summarized here combine the latest results with earlier Run 2 constraints shown for context: excited quarks below 6.7 TeV and SSM Z' bosons below 2.7 TeV from inclusive searches [2]; W'/Z' scenarios and radion constraints, and first composite-lepton limits from lepton-assisted searches [5]; paired di-jet limits across m_Y and m_X/m_Y [6]; improved low-mass constraints with ISR photons/jets [7]; and ML-based limits from weak supervision and event-level anomaly detection [3, 4]. Novel ML methods, particularly anomaly detection, have demonstrated improved sensitivity and will be central to Run 3 analyses. Future efforts will extend these strategies to boosted topologies, trigger-level analyses, and model-agnostic searches, ensuring broad and robust sensitivity to new physics.

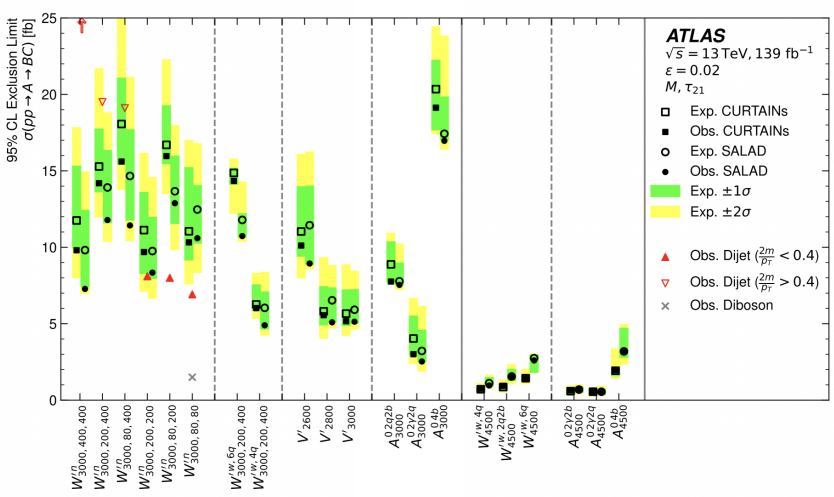

Figure 4: 95% CL upper limits from weakly supervised anomaly detection searches, compared to traditional di-jet analyses [3].

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