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ATLAS searches for low mass resonances-resolved signatures

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The discovery of the Higgs boson with the mass of about 125 GeV completed the particle content predicted by the Standard Model. Even though this model is well established and consistent with many measurements, it is not able to solely explain some observations. Many extensions of the Standard Model addressing such shortcomings introduce additional neutral bosons. The current status of searches for resolved, resonant signatures in the full LHC Run 2 dataset of the ATLAS experiment at 13 TeV is presented.

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1. Introduction

Additional scalars in beyond Standard Model (BSM) searches are mostly motivated by theoretical models such as Two-Higgs-Doublet-Models (2HDM), Axion Like Particles (ALPs), etc. which manifest scalar mixing with the SM Higgs boson, opening the Higgs portal to the Dark Sector. Their existence could solve the naturalness problem, the muon $(g-2)$ anomaly, provide dark matter candidates, etc. The five ATLAS [1] presented analyses in these proceedings used full LHC Run 2 proton-proton data, at $\sqrt{s}$= 13 TeV, $\mathcal{L}$ = 139 fb^{-1}, as listed in Table 1.

Table 1: List of the analyses presented in these proceedings.

Analysis	Particle(s)	Mass [GeV]	Reference	Section
2HDM multi-b multi-lepton	heavy Higgs/SUSY	200 - 1500	[2]	2
$t \to qX, X \to b\bar{b}$	X	20 - 160	[3]	3
$h \to 2a \to 2b2\mu$	a	16 - 62	[4]	4
"Boosted" di $-\gamma$ resonances	X/ALP a	10 - 70	[5]	5
di $-\gamma$ resonances	low-mass Higgs	66 - 110	[6]	6

2. 2HDM multi-b multi-lepton analysis

This analysis [2] is motivated by the general 2HDM (g2HDM), which has the alignment limit that extra scalars have vanishingly small mixing with the SM Higgs. A new scalar, the heavy Higgs boson, features Flavour-Changing-Neutral-Higgs (FCNH) couplings with top quarks, leading to two same sign (SS) tops, 3-top, 4-top production with the Feynman diagrams as shown in Figure 1(a), 1(b), 1(c). These are the first searches for g2HDM and for BSM 3-top production at the LHC. In addition, the R-parity-violating (RPV) SUSY model (shown in Figure 1(d)) is also of concern as motivated by the lepton flavour and muon $(g-2)$ anomalies.

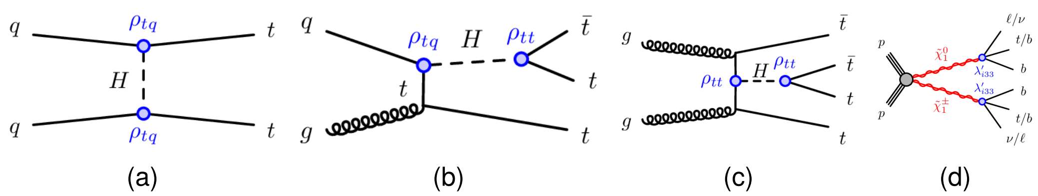
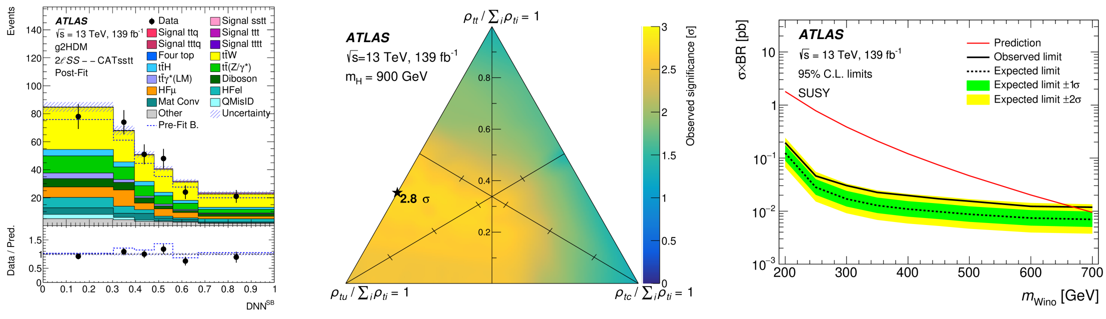


Figure 1: Feynman diagrams of (a): SS tops, (b): 3-top, (c): 4-top, (d): R-parity violation processes.

Final states include multi-(e/μ) and multi-jets with b-jets. Events are categorized into signal regions (SRs) based on the number of leptons (e/μ), the total lepton charge and a multi-output deep neural network (DNN) score, as shown in Figure 2(a). The irreducible prompt-lepton background includes $t\bar{t}W$, $t\bar{t}t\bar{t}$, $t\bar{t}Z/\gamma^*$ and VV production while the reducible background with non-prompt leptons arise from $t\bar{t}$, V+jets, single-top-quark production; dedicated control regions (CRs) are exploited to estimate them. The analysis is dominated by statistical uncertainties. A maximum-likelihood fit is performed in all SRs and CRs simultaneously. No significant excess is observed and the largest excess is 2.8 σ, at m_H = 900 GeV and ρ_{tt} = 0.6, ρ_{tc} = 0.0, ρ_{tu} = 1.1 as shown in Figure 2(b), where ρ_{tt}, ρ_{tq} ($q = u, c$ quarks) are the couplings of the heavy Higgs with the two quarks in the indices. An upper limit at 95% confidence level (CL) on cross section (XS) times branching ratio ($\mathcal{B}$) in the RPV SUSY model is shown in Figure 2(c).



(a) (b) (c)

Figure 2: (a): A DNN output score, (b): Observed significance in the phase space of FCNH couplings, (c): 95% CL upper limit on XS $\times\, \mathcal{B}$ of Wino in RPV SUSY model [2].

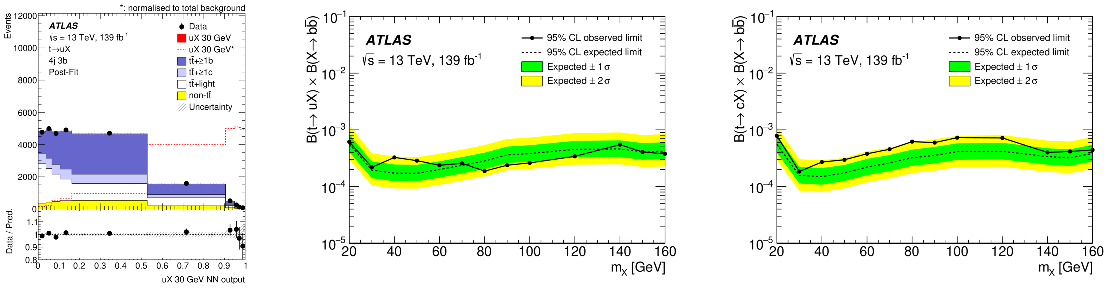
3. $t \to qX, X \to b\bar{b}$ analysis

The BSM version of the SM Flavour-Changing-Neutral-Current $t \to qH$ motivates this analysis [3]. The theoretical model uses the Froggatt-Nielsen mechanism where the X field is charged under the flavour charge (flavon) symmetry $\mathrm{U(1)_F}$, which is then broken leading to decays of a top-quark to up type quarks (u, c) and a scalar boson X where X decays to $b\bar{b}$. Only on-shell X from top-quark decay are considered.

The process of concern is top-quark pair production with one top quark decaying to exotic qX and the second top quark decaying to SM Wb. Final states include one e/μ and four or more jets. The main background originates from $t\bar{t}$ production in association with jets.

Events are categorized according to the multiplicities of jets and b-jets. Three SRs are $4j3b$, $5j3b$ and $6j3b$ while three CRs are $4j4b$, $5j \geq 4b$ and $6j \geq 4b$. A Neural Network (NN) is used to discriminate signal against background with the information from jets, lepton, their invariant masses and angular separation.

To correct mismodelling of MC predictions in $t\bar{t}$ and $W \to cb$, three additional regions: $2b1bl$-jet (with four, five, six jets in total) are defined where bl-jet is a looser required b-jet. Weights are derived based on ${H_T}^{\mathrm{all}}$, the scalar sum of the transverse momenta of all selected objects, to reweight kinematic distributions of those MC samples. A maximum-likelihood fit is performed on signal NN output distributions (as shown in Figure 3(a)) in the three SRs and on the total background yields in the three CRs. Dominating systematic uncertainties are $t\bar{t}$ modelling, jet energy scale and resolution, or jet tagging. No significant excess is observed, the highest local excess is 1.8 σ in the $t \to uX$ channel at $m_X = 40$ GeV. Limits at 95% CL on $\mathcal{B}(t \to u/cX) \times \mathcal{B}(X \to b\bar{b})$ are obtained and shown in Figure 3(b) and 3(c).



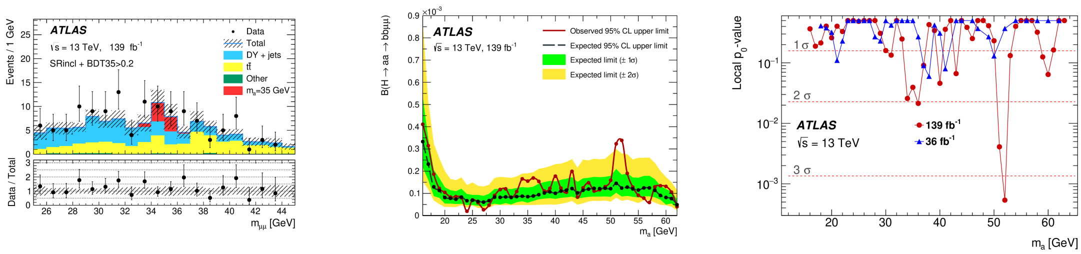
(a) (b) (c)

Figure 3: (a): A DNN output score. 95% CL upper limit on (b): $\mathcal{B}(t \to uX) \times \mathcal{B}(X \to b\bar{b})$ and on (c): $\mathcal{B}(t \to cX) \times \mathcal{B}(X \to b\bar{b})$ [3].

4. $h \to 2a \to 2b2\mu$ analysis

This analysis [4] considers the light scalar/pseudoscalar boson a that couples to the 125 GeV Higgs boson, motivated by the naturalness problem, the muon $(g-2)$ anomaly, etc. with on-shell a boson from Higgs boson decay. The final state includes a $b\bar{b}$ pair and a $\mu^+\mu^-$ pair as four fermions coming from a Higgs decay. The main background includes Drell-Yan (DY) $\mu^+\mu^-$ production in association with b-quarks, $t\bar{t}$ production where $W \to \mu\nu$. Their contribution is estimated using two corresponding dedicated CRs (DYCR and TCR), then validated in two validation regions (VRs). A kinematic likelihood (KL) fit exploiting the approximate equalness of $m_{\mu\mu}$ and m_{bb} improves the resolution of the $m^{\text{KL}}_{bb\mu\mu}$ distribution. The inclusive SR, CRs and VRs are made orthogonal on $m^{\text{KL}}_{bb\mu\mu}$ and missing transverse momentum ($E_{\text{T}}^{\text{miss}}$) distributions. A boosted decision tree (BDT) classifier is employed to separate signal versus background, with an example shown in Figure 4(a). After the inclusive selection, a SR for each dedicated m_a is narrowed down by requiring $m_{\mu\mu}$ approximately at m_a and a cut on the score of the BDT of the corresponding m_a mass hypothesis.

A maximum-likelihood fit is performed on the $m_{\mu\mu}$ distributions in SR and CRs. Dominating uncertainties are the statistical uncertainty and b-tagging ones. No significant excess is observed, the highest local (global) excess of 3.3 (1.7) σ is seen at $m_{\mu\mu}$ = 52 GeV as shown in Figure 4(c). An upper limit at 95% CL is set on $\mathcal{B}(h \to 2a \to 2b2\mu)$ as a function of m_a as shown in Figure 4(b).



(a) (b) (c)

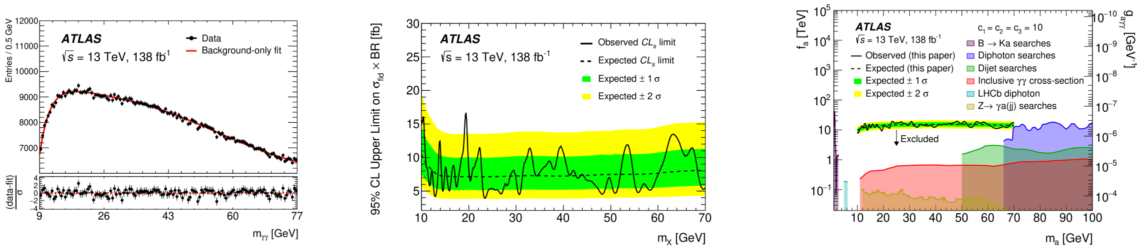
Figure 4: (a): $m_{\mu\mu}$ for BDT35 > 0.2. (b): 95% CL limit on BR$(h \to 2a \to 2b2\mu)$ and (c): $p_0$value [4].

5. "Boosted" di − γ resonances

New phenomena involving narrow resonances, X, within the mass range from 10 GeV to 70 GeV is of interest in this analysis [5]. The resonance X could be the Pseudo Nambu–Goldstone bosons (pNGBs) associated with spontaneously broken approximate global symmetries at the TeV scale or above, or ALPs. All resonances are considered with the narrow width approximation (NWA). The final state has a pair of closely spaced photons with large transverse momentum $p_T{}^{\gamma\gamma}$.

Analytic functions are used to describe signal/background components with the Double-sided Crystal Ball function used for signal. Additionally, a Gaussian Process fit is employed to smooth the background MC template to reduce statistical fluctuation. A fiducial volume of two photons with each photon's transverse energy (E_T^{γ}) greater than 22 GeV, $|\eta^{\gamma}| < 2.37$, $p_T{}^{\gamma\gamma} > 50$ GeV is defined.

A maximum-likelihood fit is performed on the $m_{\gamma\gamma}$ distribution in data (Figure 5(a)) and the analytic functions of signal/background. Dominating uncertainties are data statistics and background modelling. No significant excess is observed, the highest local (global) excess is 3.1 (1.5) σ, at $m_{\gamma\gamma}$ = 19.4 GeV. An upper limit at 95% CL is calculated for the fiducial production XS of the resonance X versus its mass, as shown in Figure 5(b). Similarly for ALPs as shown in Figure 5(c).



(a) (b) (c)

Figure 5: (a): $m_{\gamma\gamma}$ after all selections. 95% CL upper limit on the fiducial production XS of resonance X (b), and ALPs (c) where f_a is a decay constant which governs ALP coupling with SM field and $g_{a\gamma\gamma}$ is the coupling constant of a with di − γ [5].

6. di − γ resonances analysis

Compared to the "Boosted analysis", this one [6] covers the high-mass region and adds on a model-dependent search for an additional low-mass Higgs boson. It has a substantial Drell-Yan di-electron background with electron faking γ. Events are split into three categories based on γ conversion, then further split into three BDT categories in the model-dependent case to discriminate the continuum $\gamma\gamma$ background from the low-mass Higgs boson signal.

No significant excess is observed. The highest local excess for the model-independent case is 2.2 σ at $m_{\gamma\gamma}$ of 71.8 GeV, for the model-dependent case: with Large Width Approximation is of 1.7 σ at $m_{\gamma\gamma}$ of 85.2 GeV, while with NWA is of 1.7 σ at $m_{\gamma\gamma}$ of 95.4 GeV. An upper limit at 95% CL on the XS times $\mathcal{B}$ of the process is calculated and shown in Figure 6.

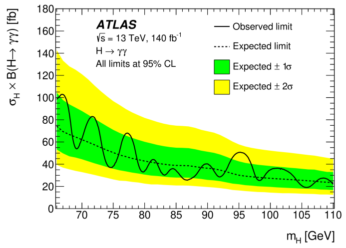


Figure 6: 95% CL upper limit on XS $\times \mathcal{B}$ versus mass of the low-mass Higgs boson [6].

7. Conclusion

Summaries are presented for five low-mass additional scalar resonance searches done at ATLAS with full LHC Run 2 data. No significant excess is seen but there are some interesting local excesses. The usage of multivariate techniques and especially machine learning brings an important boost to the analyses. Some searches are statistically limited. Run 3 analyses with more data, advanced analysis techniques are anticipated.

References

[1] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST **3** (2008) S08003.

[2] ATLAS Collaboration, *Search for heavy Higgs bosons with flavour-violating couplings in multi-lepton plus b-jets final states in pp collisions at 13 TeV with the ATLAS detector*, JHEP **12** (2023) 081, arXiv:2307.14759 [hep-ex].

[3] ATLAS Collaboration, *Search for a new scalar resonance in flavour-changing neutral-current top-quark decays $t \to qX$ ($q = u, c$), with $X \to b\bar{b}$, in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, JHEP **07** (2023) 199, arXiv:2301.03902 [hep-ex].

[4] ATLAS Collaboration, *Search for Higgs boson decays into a pair of pseudoscalar particles in the $bb\mu\mu$ final state with the ATLAS detector in pp collisions at $\sqrt{s}$=13 TeV*, Phys. Rev. D **105** (2022) 012006, arXiv:2110.00313 [hep-ex].

[5] ATLAS Collaboration, *Search for boosted diphoton resonances in the 10 to 70 GeV mass range using 138 fb^{-1} of 13 TeV pp collisions with the ATLAS detector*, JHEP **07** (2023) 155, arXiv:2211.04172 [hep-ex].

[6] ATLAS Collaboration, *Search for diphoton resonances in the 66 to 110 GeV mass range using pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, arXiv:2407.07546 [hep-ex].

[7] ATLAS Collaboration, *Search for heavy resonances in final states with four leptons and missing transverse momentum or jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, arXiv:2401.04742 [hep-ex].