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Heavy resonance searches

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This proceeding from the LHCP2023 conference summarizes analyses of heavy resonance searches in particle physics, conducted using 140 fb^{-1} data from the ATLAS and CMS experiments at the LHC Run 2. Focusing on Beyond Standard Model (BSM) theories, various phenomena such as Two-Higgs-Doublet models, Heavy Vector Triplets, and vector-like quarks are explored. Employing advanced machine learning techniques and statistical methods, the analysis covers a range of final states. The results align closely with Standard Model predictions, setting stringent limits on the explored BSM theories.

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1. Introduction

Standard Model (SM) is extremely successful for particle physics, yet it is not without its shortcomings. Issues such as the hierarchy problem, the unification of gravity, and the mysteries of dark matter and energy suggest the presence of phenomena not accounted for by the SM, leading to the proposal of Beyond Standard Model (BSM) theories. Among the diverse strategies for uncovering new physics, the search for heavy resonances stands out as a promising method to probe these theoretical extensions.

High energy collider experiments like ATLAS and CMS at the LHC have carried out many heavy resonance searches covering wide range of models since last LHCP [1] [2]. In this letter, some of the latest ATLAS and CMS results will be introduced. These results are all based on LHC Run-2 pp collision at $\sqrt{s}$ = 13 TeV with 140 fb^{-1} good-for-physics data collected [3] [4].

2. ATLAS and CMS analyses

ATLAS carried out an anomaly detection in two-body final states of jet + Y [5], where Y may be a lepton (electron or muon), a photon, or another jet. The analysis utilized an AutoEncoder (AE), an unsupervised machine-learning technique, to explore the deviation from SM. Trained with 1% of randomly selected events, the AE was instrumental in flagging anomalous events characterized by high loss values. Three anomaly regions (ARs) are defined based on the loss values for in-depth analysis (Figure 1). The invariant mass spectra is examined in each AR to detect localized excesses. No significant resonance-like signals were observed in these ARs. The largest excess with a local significance of 2.9σ was identified by BumpHunter in 10 pb AR at an invariant mass $m_{j\mu}$ of 4.8 TeV with a width of 0%.

ATLAS also carried out a generic $Y \to XH$ search in hadronic final states [6], exploring scenarios involving two large-radius (large-R) jets: J_H (one with a larger H_{bb} score) and J_X (the other one). Three distinct signal regions were defined: The Anomaly Region, with an Anomaly Score greater than 0.5, as determined using a variational recurrent neural network (VRNN); The Two-prong Merged (Resolved) Region, targeting the benchmark $X \to q\bar{q}$ decay. In the merged region, m_Y was constructed using two large-R jets, while in the resolved region, m_Y was computed with the large-R Higgs jet combined with the two small-radius (small-R) X jets. A simultaneous fit was conducted for both the merged and resolved two-prong signal regions. The most notable excess was observed in the anomaly signal region (SR), showing a global significance of 1.43%. Despite this, no significant deviations from the Standard Model were detected.

An CMS analysis focusing on Vector-like quarks (VLQs) was carried out in $T' \to tH$ [7], where H decays into two photons. VLQs are hypothetical spin-1/2, colored particles, with both left- and right-handed components uniformly transforming under the Standard Model (SM) gauge group. Depending on the decay mode of t, the analysis is divided into leptonic category and hadronic category. No statistically significant excesses were observed in the analysis. The T' quark was excluded up to a mass of 960 GeV for $\kappa_T = 0.25$ and $\Gamma/M_{T'} < 5\%$, where $\Gamma/M_{T'}$ represents the relative decay width, and κ_T denotes the coupling to third-generation quarks.

VLQs can manifest as SU(2) singlets (T) or (B), doublets ($X\ T$) or ($T\ B$), or triplets. The topology of $T \to Ht/Zt$ is analyzed by ATLAS [8] with T decaying into a leptonically decaying

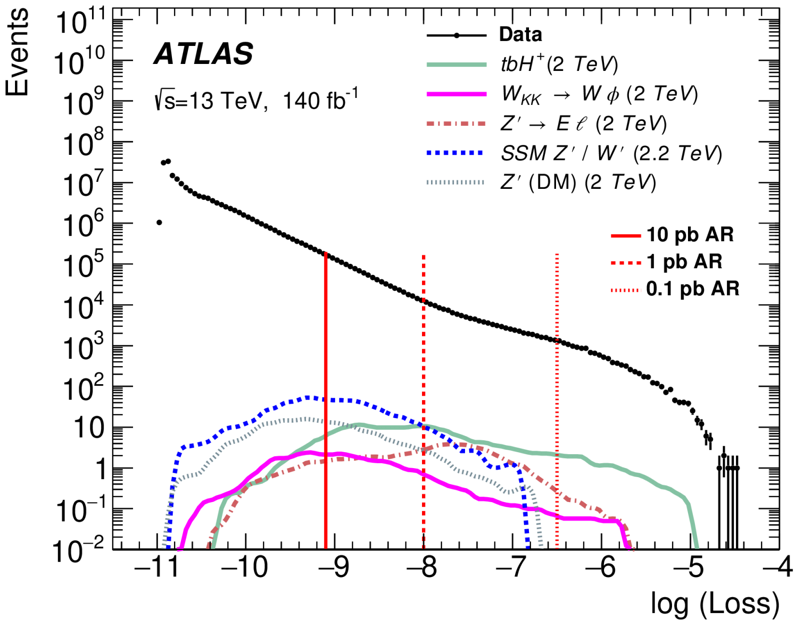

Figure 1: Distributions of the anomaly score from the AE for data and five benchmark BSM models.

top quark plus a hadronically decaying H or Z boson. The analysis involves small-R b-jets and reclustered (RC) jets, which are constructed from small-R jets and characterized as 't-tagged', 'H-tagged', or 'V-tagged'. No significant excess was observed. For the singlet T, masses below 2.1 TeV are excluded for $\kappa \geq 0.6$, and $\kappa > 0.3$ is excluded for masses equal to 1.6 TeV, where κ is the universal coupling strength; For the doublet T, masses below 1.68 TeV are excluded for $\kappa \geq 0.75$, and $\kappa > 0.55$ is excluded for masses equal to 1.0 TeV (Figure 2).

CMS searched for the process of $W' \rightarrow bt$ in leptonic final states [9]. Z' and W' bosons are predicted by various BSM theories. The jet from top decay is identified using the criterion that $M_{\ell\nu j}$ is closest to the top mass, in proximity to the lepton, and is the p_{T}-subleading jet. Categorization is based on the b-tagging condition of the top jet and the W' jet. The comparison between observed data and Standard Model predictions shows good agreement. The largest local (global) significance of $2.6(2.0)\sigma$ was observed for a W' boson at 3.8 TeV with a relative width of 1%.

Conventional inclusive Z' search is challenged by a large Drell–Yan background, hence CMS carried out an analysis focusing on $Z' \rightarrow \mu\mu$ process with the presence of additional b-jets [10]. By imposing $\min(m_{\mu b}) > m_{\mathrm{top}}$, the $\bar{t}t$ background is substantially reduced by two orders of magnitude. For model-independent limits, f_{2b} (the fraction of $N_b \geq 2$) is varied when performing the fit, and the $m_{\mu\mu}$ distribution for both signal and background is parameterized. No significant excess was found. The result is interpreted into lepton flavor-universal model: $g_\nu = g_\ell$ and g_b scales both $Z'bb$ and $Z'sb$ interactions, while δ_{bs} exclusively scales the $Z'sb$ interaction, and the restriction of $\Gamma(Z') < \sigma_m/2$ is applied. Most of parameter space of this lepton flavor-universal model is excluded according to this study, as shown in Figure 3.

ATLAS carried out a Lepton-flavour-violation (LFV) $e\mu$ or $\ell\tau$ resonance search [11]. LFV is predicted by many BSM theories, potentially observable from Z' decay or from $\tilde{\nu}_\tau$ decay in

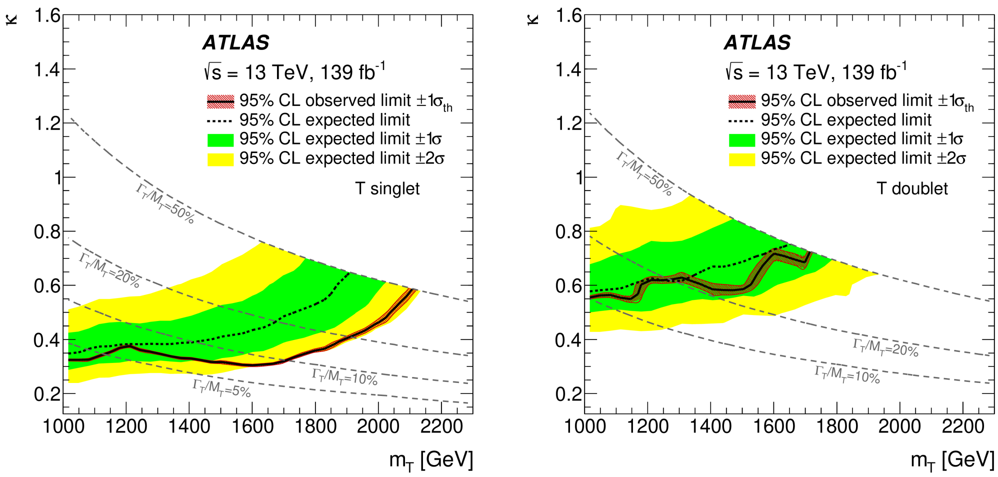

Figure 2: Observed (solid black line) and expected (dashed black line) 95% CL exclusion limits on the universal coupling constant κ as a function of the T-quark mass in the SU(2) singlet and SU(2) doublet scenarios. All values of κ above the black contour lines are excluded at each mass point.

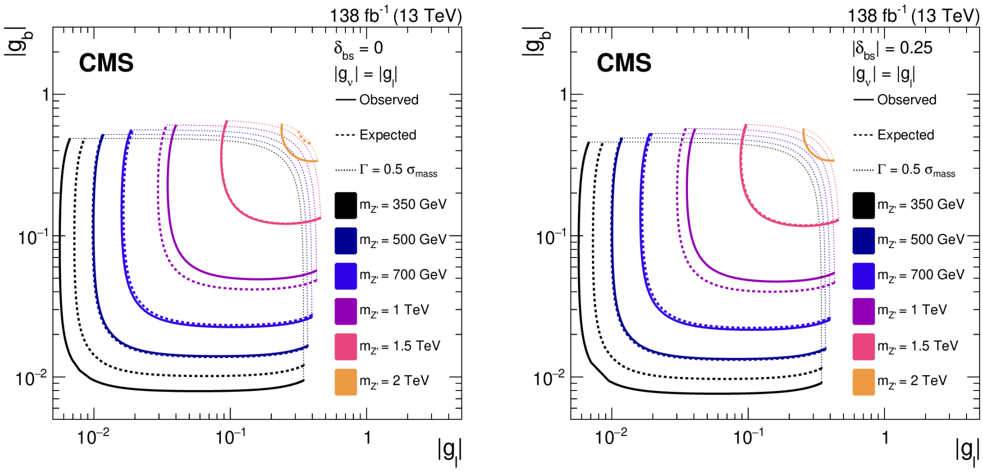

Figure 3: Observed (solid) and median expected (dashed) exclusion limits at 95% CL in the $|g_b| - |g_\ell|$ plane for the LFU model. The scenarios considered have $|\delta_b s|$ values of either 0 (left) or 0.25 (right). In all cases, we assume $|g_\nu| = |g_\ell|$

R-Parity-violating (RPV) Supersymmetry (SUSY). The analysis requires exactly two opposite-sign leptons: $e\mu$, $e\tau_{\text{had}}$ or $\mu\tau_{\text{had}}$. The $\tilde{\nu}_\tau$ is reconstructed from $E_{\text{T}}^{\text{miss}}$ and the direction of τ_{had}. The two leptons are also expected to be back-to-back in ϕ. The data is found to be consistent with the Standard Model.

CMS carried out a dark matter particles search in $W^+W^- + E_{\text{T}}^{\text{miss}}$ [12]. A dark Higgs boson singlet s as a Majorana Dark Matter (DM) particle, and a massive spin-1 vector boson Z' decaying to stable χ, under a new U(1) local gauge symmetry, are examined. Two lepton-multiplicity channels are defined: The 2-lepton channel focuses on $e\mu$ or μe with opposite-sign leptons and $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV; The semi-leptonic channel involves one lepton plus at least 2 jets, with $E_{\mathrm{T}}^{\mathrm{miss}} > 60$ GeV. No significant deviation from the Standard Model was observed. This represents the first exploration by CMS of the dark Higgs model. For $m_\chi = 200$ GeV, the results exclude $m_s < 350$ GeV for $m_{Z'} = 700$ GeV and $m_{Z'} < 2200$ GeV for $m_s = 160$ GeV.

Flavour-changing neutral currents (FCNCs) are processes that do not occur at tree level within the SM but are predicted by various BSM theories, such as the Froggatt-Nielsen mechanism. ATLAS carried out a search for FCNCs $t \to qX$ interaction [13], where X represents a non-SM Higgs field. The analysis requires exactly one electron or muon, with at least four jets. Events are categorized by the number of jets and b-jets, specifically into 4j 3b, 5j 3b, and 6j 3b categories. A Neural Network score is employed for the signal extraction fit. The expected and observed 95% CL upper limits for BR($t \to uX$) $\times$ BR($X \to b\bar{b}$) and BR($t \to cX$) $\times$ BR($X \to b\bar{b}$) are shown in Figure 4. While no significant excess above the SM predictions was found, there is a roughly 2σ excess observed over the entire range of m_X for $t \to cX$, and a local excess of 1.8σ at $m_X = 40$ GeV for $t \to uX$.

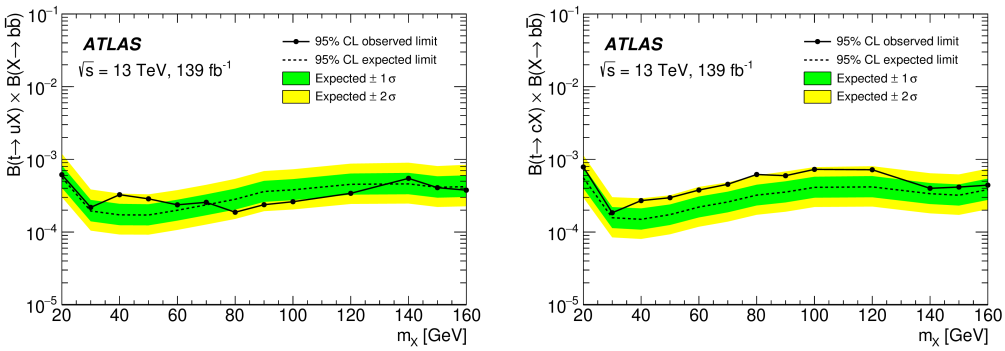

Figure 4: Expected and observed 95% CL upper limits for BR($t \to uX$) $\times$ BR($X \to b\bar{b}$) and BR($t \to cX$) $\times$ BR($X \to b\bar{b}$).

A Two-Higgs-doublet (2HDM) $A \to ZH \to \ell\ell tt$ or $\nu\nu bb$ search is carried out by ATLAS [14], where $H \to tt$ leads to a semi-leptonic decay. 2HDM predicts five Higgs bosons post-electroweak symmetry breaking: h, H, A, H^+, H^-, with h being the observed Higgs boson. A hierarchy where $m_A > m_H$ is favoured in this analysis. A parameter $\tan\beta$ is defined as the ratio of the vacuum expectation values of the two doublets. The $\ell\ell bb$ final state requires p_{T}^{V} (or $E_{\mathrm{T}}^{\mathrm{miss}}$) greater than 150 GeV and at least 2 jets, with exactly 2 b-tagged for gluon-gluon fusion (ggF) processes, or more than 2 b-tagged for b-associated (bbA) production. The $\ell\ell tt$ state requires 3 leptons and at least 4 jets with exactly 2 of them are b-tagged. No significant deviations from the SM is observed. The largest local significance of 2.85σ was observed at $(m_A, m_H) = (650, 450)$ GeV for the $\ell\ell tt$ final state. This marks the first search of $\nu\nu bb$ at the LHC for high m_{bb} and the first exploration of $\ell\ell tt$ at the LHC 13 TeV.

Excited b^* quarks are predicted in compositeness models, suggesting that excited states of quarks may have masses around the 1 TeV scale. CMS carried out an analysis looking for $b^* \to Wt$ process [15], which complements previous excited b^* searches by focusing on the scenario where the W decays leptonically. Scenarios with Right-Handed (RH), Left-Handed (LH), or Vector-Like (VL) b^* quarks are investigated. The event selection requires exactly one lepton (either electron or muon), at least one b-tagged small-R jet, and exactly one W-tagged large-R jet. No significant excess was found in the analysis.

CMS also carried the first generic search for new particles decaying to three hadronic jets [16]. The analysis includes searches for the Kaluza-Klein gluon (G_{KK}) decaying to three gluons via a radion: $X \to Y(gg)g$, for an excited quark (q^*) decaying to three quarks via a vector boson: $X \to Y(qq)q$, and for a right-handed Z boson (Z_R) decaying directly to three gluons: $X \to 3g$. Two resonance widths are considered: nominal ($\Gamma_X \sim 3\%$) and narrow ($\Gamma_X \sim 0.01\%$). The search was conducted in the range ρ_m from 0.2 to 0.8, where ρ_m is the mass ratio between Y and X. The largest local significance of $2.1(2.2)\sigma$ was observed at 4.1 TeV for nominal (narrow) width. The current sensitivity is insufficient to constrain the Z_R model and no significant excesses were observed. The observed limits at 95% CL as a function of m_X and ρ_m on $\sigma \times BR(X \to Y(gg)g) \times A$ and $\sigma \times BR(X \to Y(qq)q) \times A$ are shown in Figure 5.

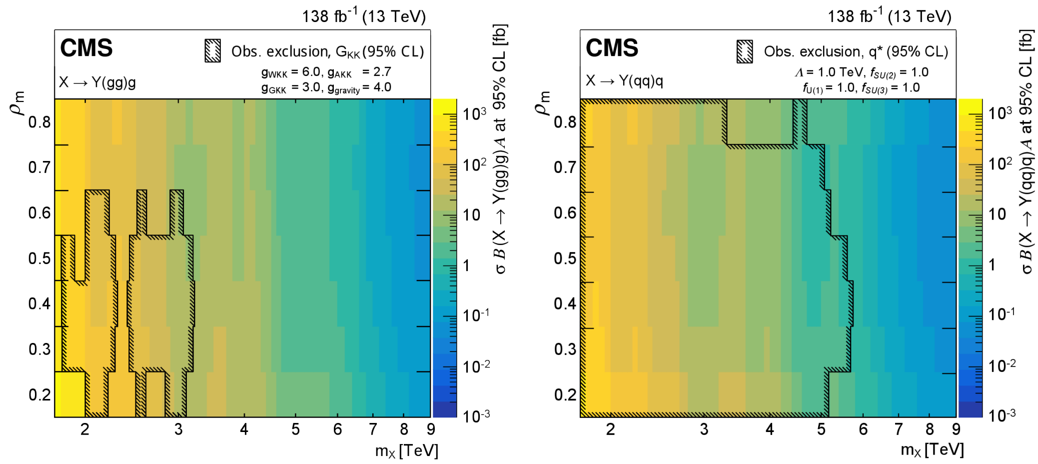

Figure 5: Observed limits at 95% CL as a function of m_X and ρ_m on $\sigma \times BR(X \to Y(gg)g) \times A$ (left) and $\sigma \times BR(X \to Y(qq)q) \times A$ (right). Only 2016 data are used to derive limits below 2.0 TeV because of the higher trigger thresholds in 2017 and 2018.

3. Summary

Heavy resonance search remains an active area of new physics search. New models and particles beyond the SM are explored at ATLAS and CMS, yet no significant deviation beyond SM is observed until now. The exclusion limits on BSM theories have been extended thanks to the larger statistics and new Techniques such as Machine Learning being widely developed and implemented in the analyses. Regarding future prospects, the ATLAS and CMS data analysis will persist into LHC Run 3, accompanied by the advancement of analysis techniques and the exploration of additional theoretical frameworks.

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