91. Dynamical Electroweak Symmetry Breaking: Implications of the H^0

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91.1 Introduction and Phenomenology

In theories of dynamical symmetry breaking, the electroweak interactions are broken to electromagnetism by the vacuum expectation value of a composite operator. This is typically a bilinear operator made of fermions charged under a strongly-coupled extension of the standard model. In these theories, the longitudinal components of the massive weak bosons are identified with composite Nambu-Goldstone bosons. They arise from the spontaneous dynamical breaking of a global symmetry that envelops the electroweak gauge one. Viable theories must also explain (or at least accommodate) the presence of a composite scalar state to be identified with the 125 GeV H^0 scalar boson [1,2] – a state unlike any other observed previously.

Theories of dynamical electroweak symmetry breaking can be classified by the nature of the composite singlet state to be associated with H^0 and the corresponding dimensional scales f, the analog of the pion decay-constant in QCD, and Λ, the scale of the underlying strong dynamics.[1] Of particular importance is the ratio v/f, where $v^2 = 1/(\sqrt{2}G_F) \approx (246\,\mathrm{GeV})^2$, since this ratio measures the expected size of deviations from typical standard model predictions – for instance, in some models, deviations of the composite Higgs couplings to other particles. In all models, new states are predicted below the scale Λ, and we describe the basic possibilities below.

91.1.1 *Technicolor-like models, $v/f \simeq 1$, $\Lambda \simeq 1$ TeV*

Technicolor models [8,9], based on a scaled-up version of two-flavor QCD, provided the first example of dynamical electroweak symmetry breaking. Models based on different dynamics have been proposed and studied, e.g. [10–14]. Such technicolor-like theories incorporate a new asymptotically free gauge interaction ("hypercolor") and charged massless fermions ("hyperfermions") transforming under a vectorial representation of the gauge group. The ensuing global chiral symmetry is spontaneously broken by the formation of a hyperfermion condensate, just as the approximate chiral symmetry in QCD is broken down to isospin by the formation of a quark condensate. The $\mathrm{SU}(2)_W \times \mathrm{U}(1)_Y$ interactions are embedded in the global hyperfermion chiral symmetries in such a way that the chiral condensate leaves only the electromagnetic $\mathrm{U}(1)_{em}$ unbroken.[2] The theories naturally provide the Nambu-Goldstone bosons "eaten" by the W and Z bosons. There would also typically be additional light states (scalars, analogous to pions) and heavy ones (e.g. vector mesons, analogous to the ρ and ω mesons in QCD) with masses in the TeV range [18,19]. The original technicolor was Higgsless, hence predicting the WW and ZZ scattering amplitudes to be strong at energies of order 1 TeV [20].

There are various possibilities for the scalar H^0 in technicolor-like models. First, the H^0 could be identified as an accidentally light singlet scalar resonance, analogous to the σ state expected in pion-scattering in QCD [21–23]. Alternatively, the H^0 could be identified as a dilaton, a pseudo-Nambu-Goldstone boson of scale invariance in theories of "walking technicolor" [24–29]. In both cases, the decay constant of the composite scalar requires tuning to obtain viable couplings to other

[1] In a strongly interacting theory "Naive Dimensional Analysis" [3,4] implies that, in the absence of fine-tuning, $\Lambda \simeq g^* f$ where $g^* \lesssim 4\pi$ is the typical size of a strong coupling in the low-energy theory [5,6]. This estimate is modified in the presence of multiple flavors or colors [7] .

[2] For a review of technicolor models, see [15–17].

standard model couplings, see e.g. [30].[3] Other possibilities exist, but are less viable in reproducing the standard model [31, 32].

In all of these cases one expects large deviations in the Higgs self-couplings, while the measurements of the H^0 couplings to other particles, which match the standard model predictions at a few percent level [33], impose the most challenging constraints. Technicolor-like models would also predict new states at a few TeV, such as a ρ-like vector resonances below 4 TeV [34], and could accommodate for dark matter [14, 35].

91.1.2 *The Higgs doublet as a pseudo-Nambu-Goldstone Boson, $v/f < 1$, $\Lambda > 1$ TeV*

The challenge with the Higgs couplings can be diminished by use of the vacuum misalignment mechanism [36, 37] in models where the whole scalar quartet in the Higgs doublet arises as a set of (pseudo-)Nambu-Goldstone bosons [38, 39]. Composite Goldstone Higgs models must, therefore, feature a chiral condensate that preserves the embedded electroweak symmetry. Its breaking occurs by misalignment of the vacuum due to external couplings, such as the electroweak gauging, top couplings and hyperfermion masses [40]. Hence, the electroweak scale v emerges as an "angle", $\sin\theta \equiv v/f$.[4] In this case, the underlying dynamics can occur at energies exceeding $f \geq 1$ TeV (hence, $\Lambda \gtrsim 10$ TeV), at the price of some fine-tuning in the Higgs potential [41] – closely related to the "Little Hierarchy Problem" [42]. Furthermore, the couplings of the composite Goldstone H^0 naturally equal those of the standard model Higgs boson, up to corrections of the order of $(v/f)^2$: the ones to weak gauge bosons are in fact universal [43, 44], while the ones to fermions strongly depend on the fermion mass origin [45]. Hence, these theories feature a decoupling limit when $v/f \to 0$ at constant v, while also featuring a technicolor-like limit when $v/f \to 1$ [40].[5]

As the misalignment is due to gauge and top couplings, some model building efforts have been directed towards mitigating the fine tuning issue. For instance, "Little Higgs" theories [48–51] can be seen as realizations of a composite Goldstone Higgs, where misalignment occurs at higher loop order thanks to collective symmetry breaking. Another avenue involves the enlargement of the global symmetry, as in the case of "Maximal Symmetric Models" [52–54].

Composite Goldstone Higgs models typically require a larger global symmetry of the underlying theory than technicolor-like ones. Hence, additional relatively light (compared to Λ) scalar particles are present [55–57], some of which could play the role of dark matter [58–60]. In addition to these states, one would expect the underlying dynamics to yield additional scalar and vector resonances with masses of order Λ. Lighter resonances, with masses of order f, may play an important role in mitigating the little hierarchy problem in the Higgs potential [61], particularly spin-1 resonances of the weak gauge bosons [62] and fermionic top partners [63, 64]. The presence of a custodial symmetry [65, 66] constrains the couplings and quantum numbers of these light resonances, for instance requiring top partners of exotic charge $+5/3$ [66] or a charged vector resonance with similar branching ratios to WZ and WH. Colored top partners also provide additional contributions to Higgs production via gluon fusion [67] and to Higgs pair production [68, 69]. A precise measurement of the Higgs properties at the LHC and future colliders, therefore, provides strong constraints on this class of models, together with electroweak precision (which currently yields the strongest bounds, $f \gtrsim 1$ TeV) and direct searches for light resonances.

The larger symmetry of the underlying composite Higgs theory also allows for more exotic states to appear (e.g. [70–72]), including colorless top partners in composite twin Higgs models [73, 74]. The phenomenology of the additional scalar and fermionic states is rather different. Lacking color,

[3] For the dilaton, this would require that chiral and scale symmetries are broken by the same condensate.

[4] Equivalently, misalignment can be described as a vacuum expectation value of the pseudo-Nambu-Goldstone Higgs, whose potential is dynamically generated by loops of top quarks and weak gauge bosons, as well as the hyperfermion mass terms.

[5] For a review of composite Goldstone Higgs models, see [46, 47].

the production of these particles at the LHC will be suppressed and their decays may lead to long-lived signatures.

91.1.3 *Top-Condensate, Top-Color, Top-Seesaw and related theories, $v/f < 1$, $\Lambda >$ 1 TeV*

A third alternative is offered by strongly interacting theories where a fine-tuning in the coupling strength allows a hierarchy between the dynamical scale and the electroweak scale. This scenario is only possible if the electroweak (quantum) phase transition is continuous (second order) in the strength of the strong dynamics [75]. Similarly to the Goldstone Higgs scenario, the tuned underlying strong interactions generate a light composite Higgs bound state, whose couplings match those of the standard model Higgs boson up to corrections of order $(1 \text{ TeV}/\Lambda)^2$. Hence, a precise measurement of the H^0 couplings gives rise to lower bounds on the scale Λ. By construction, the theory has a decoupling limit $\Lambda \to \infty$, at the price of arbitrary fine adjustment of the interaction strength.

Concrete realizations often posit the top-quark itself as strongly interacting at high energies [76, 77], potentially through an extended color gauge sector [78–80]. In these theories, top-quark condensation (or the condensation of an admixture of the top with additional vector-like quarks) is responsible for electroweak symmetry breaking, and the H^0 is identified with a bound state involving the third generation of quarks. The mechanism of top condensation has also been combined to technicolor like theories to explain the large top mass [81]. Theories of top condensation typically include an extra set of massive color-octet vector bosons (top-gluons), and an extra $U(1)$ interaction (giving rise to a top-color Z′) which couple preferentially to the third generation and whose masses define the scale Λ of the underlying physics.

91.1.4 *Extra-dimensions, CFTs and holography*

Theories with compact extra-dimensions [82] lead to low energy effective theories of “resonances”, which are hard to distinguish from composite states. In these scenarios, the electroweak gauge symmetry can be broken by boundary conditions, leading to both technicolor-like scenarios [83,84] and Goldstone Higgs ones [85,86]. A dictionary between extra dimensions and composite models can be established for both the gauge [85] and fermion [87,88] sector, motivated by the Ad-S/CFT correspondence [89] (dubbed holography).

A more formal application of holography would require the composite sector to behave as a strongly coupled conformal theory, where the gravity dual can be used as an analog computer to predict low energy properties of the composite resonances. This technique has been applied to technicolor-like models [34, 90, 91], composite Goldstone Higgs scenarios with top partners [92] and top-color models [90].

91.1.5 *Flavor*

In addition to the electroweak symmetry breaking dynamics described above, which gives rise to the masses of the W and Z bosons, additional interactions must be introduced to generate the masses of the standard model fermions. As they are typically induced by higher order terms (such as four-fermion interactions), small fermion masses are natural while a challenge is posed by the top mass, the only one which is close to the electroweak scale. Two broad classes have been suggested for these new interactions.

In “extended technicolor” (ETC) theories [93, 94], the gauge interactions in the underlying strongly interacting theory are extended to incorporate flavor. This extended gauge symmetry is broken down (possibly sequentially, at several different mass scales) to the residual hypercolor responsible for electroweak symmetry breaking. The massive gauge-bosons corresponding to the broken symmetries mediate interactions between mass operators for the quarks/leptons and the corresponding bilinears of hyperfermions, giving rise to the masses of the ordinary fermions via the electroweak symmetry breaking condensate.

In the "partial compositeness" class [95], the additional flavor-dependent interactions arise from mixing between the ordinary elementary quarks and leptons and (massive) composite operators in the strongly-interacting underlying theory. At low energies, fermionic resonances that couple largely to heavy fermions appear, with masses in the multi-TeV range. The main advantage of partial compositeness is that the coupling of the composite operators may be enhanced at low energy by large anomalous dimensions.[6]

Since the flavor interactions must give rise to quark and lepton mixing, a generic composite theory would give rise to large flavor-changing neutral-currents [94]. In ETC theories, these constraints are typically somewhat relaxed if the theory incorporates approximate generational flavor symmetries [97], the theory has a slowly running coupling constant or "walks" [24–28], or if $\Lambda > 1$ TeV [98]. In theories of partial compositeness, the masses of the ordinary fermions depend on the scaling-dimension of the operators corresponding to the composite fermions with which they mix. This leads to a new mechanism for generating the mass-hierarchy of the observed quarks and leptons that, potentially, ameliorates flavor-changing neutral current problems [99–103]. Alternatively, one can assume that the underlying flavor dynamics respect flavor symmetries ("minimal" [104, 105] or "next-to-minimal" [106] flavor violation) that suppress flavor-changing neutral currents in the two light generations [107]. Additional considerations apply when extending these arguments to potential explanation of neutrino masses (see, for example, [108]).

While most analyses of composite flavor rely on low energy effective theories, generating the necessary interactions in a complete model remains a challenge, often requiring multiple mechanisms at once (typically partial compositeness for the top, and bilinear ETC-like interactions for the light fermions). Theories of top partial compositeness have been defined in terms of hyperfermions [109], leading to possible ultra-violet completion which involve partial unification of the hypercolor interactions [110–112]. An alternative idea consists in adding Yukawa-like interactions with strongly interacting scalars, leading to "fundamental partial compositeness" for all fermions [113, 114]. Finally, one could assume that the theory flows to a conformal field theory above Λ, however no concrete and fully self-consistent model of this kind has been constructed yet.

91.1.6 *Theoretical Considerations*

Since the underlying low-energy dynamics in these theories is strongly coupled, there are no straightforward calculation techniques that can be applied to analyze their properties. Instead, most phenomenological studies depend on the construction of a "low-energy" effective theory describing additional scalar, fermion, or vector boson degrees of freedom, which incorporates the relevant symmetries and, when available, dynamical principles. In some cases, motivated by the AdS/CFT correspondence [89], the strongly-interacting theories described above have been investigated by analyzing a dual compactified five-dimensional gauge theory.

More recently, progress has been made in investigating strongly-coupled models using lattice gauge theory (see e.g. [115–120]). These calculations offer the prospect of establishing which strongly coupled theories of electroweak symmetry breaking have a particle with properties consistent with those observed for the H^0 – and for establishing concrete predictions for these theories at the LHC [121].

91.1.7 *Summary*

The theoretical ideas and models reviewed here motivate searches for a wide variety of new states. Heavy vector bound states decaying to dibosons and additional scalar states appear naturally in both technicolor-like (91.1.1) and Goldstone Higgs models (91.1.2). Light W' and Z' states

[6] For a review, see [47, 96].

are typically required in models featuring collective symmetry breaking, together with vector-like fermions that couple strongly to the top quark. The latter are also required by partial compositeness to generate a large mass for the top and address the flavor problem (91.1.5). Top-condensate and related models (91.1.3) predict the existence of colorons which preferentially couple to third-generation quarks. In all cases, realistic models that have a well-defined underlying model often predict the existence of more exotic states, such as exotic-color fermions and vectors, and colorless top partners. Finally, the new states discussed here also occur in extra-dimensional models (91.1.4)), which is understandable given that many strongly-coupled theories can be viewed as compactified five-dimensional gauge theories via duality. We turn now to a review the status of experimental searches related to dynamical electroweak symmetry breaking.

91.2 Experimental Searches

As discussed above, the extent to which the couplings of the H^0 conform to the expectations for a standard model Higgs boson constrains the viability of each of these models. Measurements of the H^0 couplings, and their interpretation in terms of effective field theory, are summarized in the H^0 review in this volume. In what follows, we will focus on searches for the additional particles that might be expected to accompany the singlet scalar: extra scalars, fermions, and vector bosons. In some cases, detailed model-specific searches have been made for the particles described above (though generally not yet taking account of the demonstrated existence of the H^0 boson).

In most cases, however, generic searches (e.g. for extra W' or Z' particles, extra scalars in the context of multi-Higgs models, or for fourth-generation quarks) are quoted that can be used – when appropriately translated – to derive bounds on a specific model of interest.

The mass scale of the new particles implied by the interpretations of the low mass of H^0 discussed above, and existing studies from the Tevatron and lower-energy colliders, suggests that only the Large Hadron Collider has any real sensitivity. A number of analyses already carried out by ATLAS and CMS use relevant final states and might have been expected to observe a deviation from standard model expectations – in no case so far has any such deviation been reported. The detailed implications of these searches in various model frameworks are described below.

Except where otherwise noted, all limits in this section are quoted at a confidence level of 95%. The searches at $\sqrt{s} = 8$ TeV (Run 1) are based on 20.3 fb^{-1} of data recorded by ATLAS, and an integrated luminosity of 19.7 fb^{-1} analyzed by CMS. The datasets collected at $\sqrt{s} = 13$ TeV during Run 2 of the LHC since 2015 are based on analyses with varied integrated luminosities ranging from $\sim$2-140 fb^{-1}.

91.2.1 *Searches for Z' or W' Bosons*

Massive vector bosons or particles with similar decay channels would be expected to arise in Little Higgs theories, in theories of Technicolor, or models involving a dilaton, adjusted to produce a light Higgs boson, consistent with the observed H^0. These particles would be expected to decay to pairs of vector bosons, or to third generation quarks, or to leptons. The generic searches for W' and Z' vector bosons listed below can, therefore, be used to constrain models incorporating a composite Higgs-like boson.

A general review of searches for Z' and W' bosons is also included in this volume [122, 123]. In the context of the dynamical electroweak symmetry breaking models, we emphasize their decays to third generation fermions by including a detailed overview, while also briefly summarizing the other searches.

$Z' \to \ell\ell$:

ATLAS [124] and CMS [125] have both searched for Z' production with $Z' \to ee$ or $\mu\mu$. No deviation from the standard model prediction was seen in the dielectron and dimuon invariant mass spectra, by either the ATLAS or the CMS analysis, and lower limits on possible Z' boson masses were set. A $Z'_{\rm SSM}$ with couplings equal to the standard model Z' (a "sequential standard model" Z') and a mass below 5.1 TeV was excluded by ATLAS, while CMS set a lower mass limit of 5.15 TeV. The experiments also place limits on the parameters of extra dimension models and in the case of ATLAS on the parameters of a minimal walking technicolor model [24–28], consistent with a 125 GeV Higgs boson [126]. For a general review of searches in these channels see the PDG review of Z prime in this volume [122].

In addition, both experiments have also searched for Z' decaying to a ditau final state [127,128]. An excess in $\tau^+\tau^-$ could have interesting implications for models in which lepton universality is not a requirement and enhanced couplings to the third generation are allowed. This analysis led to lower limits on the mass of a $Z'_{\rm SSM}$ of 2.4 and 2.1 TeV from ATLAS and CMS respectively.

$Z' \to q\overline{q}$:

The ability to relatively cleanly select $t\bar{t}$ pairs at the LHC together with the existence of enhanced couplings to the third generation in many models makes it worthwhile to search for new particles decaying in this channel. Both ATLAS [129] and CMS [130] have carried out searches for new particles decaying into $t\bar{t}$.

Both ATLAS and CMS searched for $t\bar{t}$ in the all hadronic mode [131] [132] in both the resolved and boosted regions. No evidence of resonance production were seen and limits were produced for various models including the Z' boson in topcolor-assisted technicolor which excludes masses less than 3.1 to 3.6 TeV (ATLAS) depending on the details of the model and 3.3, 5.25, and 6.65 TeV for widths of 1, 10 and 30 percent relative to the mass of the resonance .

ATLAS also presented results on the lepton plus jets final state, where the top quark pair decays as $t\bar{t} \to WbWb$ with one W boson decaying leptonically and the other hadronically; CMS used final states where both, one or neither W decays leptonically and then combined the results. The $t\bar{t}$ invariant mass spectrum was analyzed for any excess, and no evidence for any resonance was seen. ATLAS excluded a narrow ($\Gamma/m = 1.2\%$) leptophobic top-color Z' boson with masses between 0.7 and 2.1 TeV and with $\Gamma/m = 3\%$ between 0.7 and 3.2 TeV. CMS set limits on leptophobic Z' bosons for three different assumed widths $\Gamma/m = 1.0\%$, $\Gamma/m = 10.0\%$, and $\Gamma/m = 30.0\%$ of 3.9 TeV to 4.0 TeV and exclude RS KK gluons up to 3.3 TeV.

Both ATLAS [133] and CMS [134] have also searched for resonances decaying into $q\overline{q}$, qg or gg using the dijet invariant mass spectrum. Excited quarks are excluded up to masses of 6.7 TeV and model-independent upper limits on cross sections with a Gaussian signal shape were set. CMS excluded string resonances with masses below 7.9 TeV, scalar diquarks below 7.5 TeV, axigluons and colorons below 6.6 TeV, excited quarks below 6.3 TeV, color-octet scalars below 3.7 TeV, W' bosons below 3.6 TeV, Z' bosons with SM-like couplings below 2.9 TeV and between 3.1 TeV and 3.3 TeV, Randall–Sundrum Gravitons below 2.6 TeV.

$W' \to \ell\nu$:

Both LHC experiments have also searched for massive charged vector bosons. In this section we include a summary of the results, with emphasis on final states with third generation fermions, while the details on other decays are discussed in the mini-review of W' [123]. ATLAS searched for a heavy W' decaying to $e\nu$ or $\mu\nu$ and found no excess over the standard model expectation. A sequential standard model (SSM) W' boson (assuming zero branching ratio to WZ) with mass less than 7 TeV was excluded [135] using the 139 fb^{-1} dataset at $\sqrt{s} = 13$ TeV. Model independent cross-section limits as a function of mass were also set. Based on a similar dataset, the CMS experiment excluded a SSM W' boson with mass up to 5.7 TeV [136] and presented upper limits on the production of generic W' bosons decaying into this final state using a model-independent approach.

CMS [137] has carried out a complementary search in the $\tau\nu$ final state. As noted above, such searches place limits on models with enhanced couplings to the third generation. No excess was observed and limits between 2.0 and 2.7 TeV were set on the mass of a W' decaying preferentially to the third generation; a W' with universal fermion couplings was also excluded for masses less than 2.7 TeV.

$W' \to t\bar{b}$:

Heavy new gauge bosons can couple to left-handed fermions like the SM W boson or to right-handed fermions. W' bosons that couple only to right-handed fermions (W'_R) may not have leptonic decay modes, depending on the mass of the right-handed neutrino. For these W' bosons, the tb ($t\bar{b} + \bar{t}b$) decay mode is especially important because in many models the W' boson is expected to have enhanced couplings to the third generation of quarks relative to those in the first and second generations. It is also the hadronic decay mode with the best signal-to-background. ATLAS and CMS have performed searches for W' bosons via the $W' \to tb$ decay channel in the lepton+jets and all-hadronic final state.

The CMS lepton+jets search [138–141], $W' \to tb \to Wbb \to \ell\nu bb$, proceeded via selecting events with an isolated lepton (electron or muon), and at least two jets, one of which is identified to originate from a b-quark. The mass of the W' boson (M_{tb}) was reconstructed using the four-momentum vectors of the final state objects ($bb\ell\nu$). The distribution of M_{tb} is used as the search discriminant. A search [141] using $35.9\,\mathrm{fb}^{-1}$ of data, collected at $\sqrt{s} = 13$ TeV, led to an exclusion of W'_R bosons with masses below 3.4 TeV (3.6 TeV) if $M_{W'_R} >> M_{\nu_R}$ ($M_{W'_R} < M_{\nu_R}$), where M_{ν_R} is the mass of the right-handed neutrino.

The CMS search for $W' \to tb$ decays using the all-hadronic final state focused on W' masses above 1 TeV [140, 142]. In this region, the top quark gets a large Lorentz boost and hence the three hadronic products from its decay merge into a single large-radius jet. Deep neural network(DNN) algorithms are used to identify the jet initiated by the bottom quark. Techniques including DNN, which rely on substructure information of the jets [143] are employed to identify boosted all hadronic W boson and top quark [142] decays. The W' candidate mass was computed from back-to-back boosted top-tagged jet and a low mass b-tagged jet. From this all-hadronic search, W' bosons were excluded for masses up to 3.4 TeV [142].

ATLAS has searched for W'_R bosons in the $t\bar{b}$ final state both for lepton+jets [144] and all-hadronic [145] decays of the top. No significant deviations from the standard model were seen in either analysis and limits were set on the $W' \to t\bar{b}$ cross section times branching ratio and W' bosons with with both purely right and purely left-handed coupling and limits are set between 0.5 and 6 TeV for different values of the coupling strength.

In addition, the above studies also provided upper limits on the W' effective couplings to right- and left-handed fermions. In Fig. 91.1 (bottom) the upper limits on W' couplings normalized to the SM W boson couplings derived by ATLAS [145] are shown. The top panel of Fig. 91.1 shows the upper limits for arbitrary combinations of left- and right-handed couplings of the W' boson to fermions set using a model independent approach by CMS [141].

91.2.2 *Searches for Resonances decaying to Vector Bosons and/or Higgs Bosons*

Both ATLAS and CMS have used the data collected at $\sqrt{s} = 13$ TeV to search for resonances decaying to pairs of bosons. Overall no significant excesses were seen in the full datasets that were analyzed and the results are interpreted in models with heavy vector triplets (HVT) [147], models with strong gravity and extra spatial dimensions, and model independent limits as a function of mass are set. For a full review of models including extra spatial dimensions and the interpretation of many of these results in that context please see the review of extra dimensions in this volume [82].

Utilizing data collected at $\sqrt{s} = 13$ TeV, ATLAS [148] and CMS [149], have both looked for a

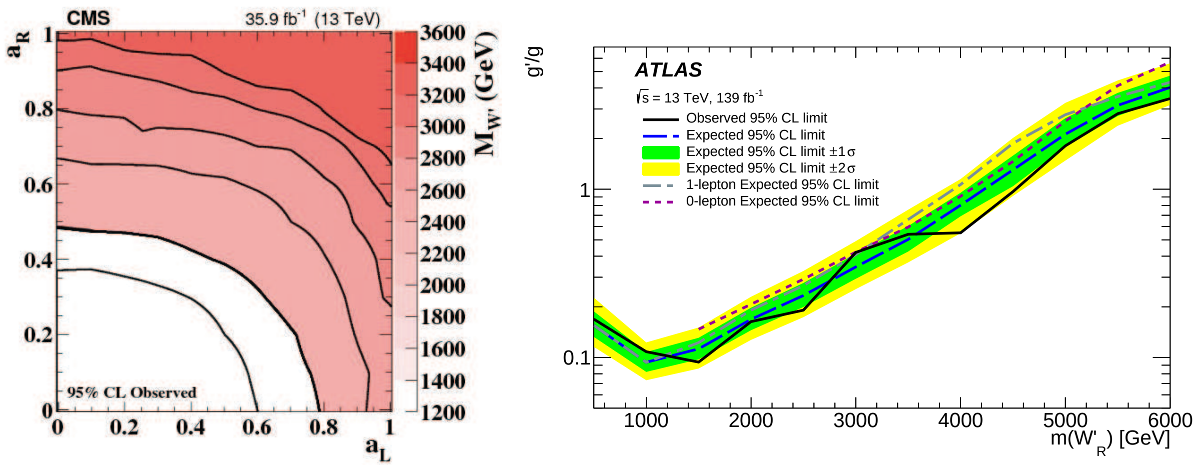

Figure 91.1: Left panel: Observed limits on the W' boson mass as function of the left-handed ($a_{\rm L}$) and right-handed ($a_{\rm R}$) couplings. Black lines represent contours of equal W' boson mass [141]. Right panel: Observed and expected regions, on the g$'$/g vs mass of the W' boson plane, that are excluded at 95% CL, for right-handed W' bosons [146] showing the exclusion of the values of a hypothetical right-handed coupling of a heavy W particle.

resonant state decaying into VV (with $V = W$ or Z) , VH (with H representing the SM Higgs boson), and HH. ATLAS has searched in the $qqqq$, $\nu\nu qq$, $l\nu qq$, $llqq$, $l\nu l\nu$, $ll\nu\nu$, $l\nu ll$, $llll$, $qqbb$ $\nu\nu bb$, $l\nu bb$, and $llbb$ final states and combined the results . While CMS analyzed the $qqqq$, $\nu\nu qq$, $l\nu qq$, $llqq$, $ll\nu\nu$, $\nu\nu bb$, $l\nu bb$, $llbb$, $bbbb$, $\tau\tau bb$, and $qq\tau\tau$ final states.

The combined limits are expressed both as limits on the cross-section as a function resonance mass as well as constraints on the coupling of the heavy boson triplet to quarks, leptons, and the Higgs boson.

$X \to WZ$:

ATLAS searched for new heavy resonances decaying into WZ in the channels $WZ \to qqqq$ [150] , $l\nu qq$ [151], and $l\nu ll$ [152]. In the fully leptonic channel , the invariant mass of the W Z pair is obtained by considering all possible four lepton permutations in each event. The dominant background is Standard Model continuum WZ production, ZZ production where one lepton is not identified or falls outside the detector acceptance, and top quark plus vector boson production. No resonant production is seen in data and lower limits on the mass of a HVT decaying into WZ are set at 2260 (2460) GeV assuming a coupling constant of $g_V = 1$ ($g_V = 3$). In the $WZ \to l\nu qq$ mode, ATLAS searches in both the cases that the quarks are observed as individual jets (resolved) and where they merge into one jet in the detector (boosted) which probe the low and high p_T regime of the Z boson. No significant excess is seen in either channel and combined lower mass limits are placed at 2900 (3000) GeV for $g_V = 1$ ($g_V = 3$) in the HVT model. In the all hadronic decay mode, ATLAS searched for two high p_T hadronically decaying vector bosons looking for a resonant structure. No excess is seen and limits are placed exclude 1200-3000 (1200-3300) GeV for $g_V = 1$ ($g_V = 3$) in the HVT model.

CMS searched for new heavy resonances in the ZV final state using the semi-leptonic decay channels excluding W' masses up to 1800 GEV in HVT two models with $g_V = 1$ and 3 and in the ZZ channel excludes gravitons up to 1200 GeV. The CMS collaboration searched for $VV \to qqqq$ [153] in the large R dijet search. The W and Z boson are identified through the mass of the large R jet and substructure variables. No excess is seen and limits are set for charged HVT bosons with masses lower than 3200 (3800) GeV for $g_V = 1$ ($g_V = 3$). Cross-section limits as function of mass are reported for the charged spin-1 resonance interpretation and are placed at 44.4 fb at 1.4 TeV to 0.7 pb at 4 TeV. In the $\nu\nu qq$ final state [154], the CMS collaboration searched for a charged spin 1 resonance decaying into a VZ final state with a Z boson decaying into a pair of neutrinos and the other boson decaying into two collimated quarks reconstructed as a large R-jet. The transverse mass of the VZ candidate is reconstructed and utilized to search for evidence of resonant VZ production. No excess is seen and lower mass limits are placed on the charged resonance at 3100 (3400) GeV for $g_V = 1$ ($g_V = 3$) . In the $2l2q$ final state, the CMS collaboration searched for a heavy resonance decaying into ZV [155] looking for events with one large R-jet consistent with the hadronic decay of a vector boson and a Z boson reconstructed in the charged lepton decay channel (e or μ). Limits are set for a HVT W' with a lower mass of 2270 (2330) for $g_V = 1$ ($g_V = 3$) .

$X \to WW$:

ATLAS searched for a new heavy resonance decaying into WW in the channels $WW \to qqqq$ [150] , $l\nu qq$ [151], and $l\nu\nu$ [156]. In the case where both Ws decay leptonically, ATLAS utilized the transverse mass of the two lepton and two neutrino final state and searched for an excess in this distribution between 200 GeV and 5 TeV. No excess is seen and a HVT is excluded for masses below 1300 GeV. Vector boson fusion is also considered and cross-section limits as a function of mass are placed ranging from 1.3 pb to 0.006 pb at 200 GeV to 3 TeV, respectively. In the $l\nu qq$ mode , ATLAS completed a companion analysis to the $WZ \to$ analysis discussed above and places lower mass limits of 2850 (3150) GeV for $g_V = 1$ ($g_V = 3$) in the HVT model. ATLAS also interprets the all hadronic mode analysis in the hypothesis that $WW \to qqqq$ and places limits on a HVT boson decaying into WW in the all hadronic mode between 1200 and 2200 (1200 and 2800) GeV for $g_V = 1$ ($g_V = 3$).

The CMS collaboration searched for $VV \to qqqq$ [153] in the large R dijet search. The W and Z boson are identified through the mass of the large R jet and substructure variables. No excess is seen and limits are set for charged HVT bosons with masses lower than 2700 (2800) GeV for $g_V = 1$ ($g_V = 3$). Cross-section limits as function of mass are reported for the uncharged spin-1 resonance interpretation and are placed at 41.6 fb at 1.4 TeV to 0.6 pb at 4 TeV.

$X \to VH$:

ATLAS searched for a new heavy resonance decaying into WH and ZH in the $qqbb$ (WH and ZH) [157], $l\nu bb$ (WH), $\nu\nu bb$ (ZH), $llbb$(ZH) [158] modes. In the all hadronic mode, ATLAS searched for boosted VH production looking for two large R jets where the larger invariant mass large R jet is interpreted as the Higgs boson decay products while the lesser invariant mass jet is taken to be the hadronically decaying vector boson requiring b-tagging on the Higgs boson subjets. The invariant mass is reconstructed and a search is performed for resonant production of ZH. None is found and limits from 1100 to 2500 (1300 to 3800 GeV) are placed for $g_V = 1$ ($g_V = 3$). ATLAS also searched for XH where the W or Z boson decays into $\nu\nu$, $l\nu$, and ll . The analysis searched for both resolved and merged (boosted) b-jets from the decay of the Higgs boson and defines the signal regions based on the number of reconstructed charged leptons (0,1,or 2). In the dilepton channel the invariant mass is explicitly reconstructed of the entire diboson system, the single lepton channel reconstructs the diboson final state constraining the lepton and missing transverse momentum utilizing the known W boson mass, while the 0 charged lepton channel reconstructs the transverse mass of the diboson system. No excess is seen in any channel and limits on the production of a HVT are placed at 2800 GeV (2930) GeV for $g_V = 1$ ($g_V = 3$).

The CMS Collaboration searched for a heavy resonance decaying into VH [159] searching for a resonances decaying into a Higgs boson and a hadronically decaying W or Z boson. The search identifies events with two large-R jets using substructure variables and requires one large-R jets is tagged with a pair of b-hadrons clustered in a single jet. The invariant mass of the VH bosons is reconstructed and evidence for resonance production is sought. No excess is seen and limits are placed. With $g_V = 1$ (3) a narrow W' resonance with $m_{W'} < 2470(3150)$ GeV and $m_{Z'} <$ 1150(1190).

The CMS collaboration searched for a heavy resonance decaying into a pair of boosted Higgs boson with $HH \to b\bar{b}WW^*$ in the single and dilepton channel [160]. Events are categorized according to lepton flavor and multiplicity, along with discriminators that characterize the compatibility with having jets arising from the decay of boosted Higgs and W bosons. The reconstructed Higgs and diHiggs mass distributions are fit and used as the final discriminators. No significant deviations in the 12 sub-categories are seen and 95% confidence limits on spin-0 bosons are set from 24.5 fb at 0.8 TeV to 0.78 fb at 4.5 TeV and spin-2 bosons from 16.7 fb at 0.8 TeV to 0.67 fb at 4.5 TeV. A similar search in the four b-quark final state is used to set limits range 9.74 to 0.29 fb and 4.94 to 0.19 fb in the spin-0 bosons and spin-2 gravitons (respectively) interpretation with masses of 1-3 TeV [161].

$X \to H\gamma$ or $V\gamma$:

Both CMS and ATLAS search for heavy resonances decaying into either a vector boson and a photon or a Higgs boson or a photon. These searched are motivated generically by the fact that new heavy gauge bosons are generically predicted to decay to either a Higgs boson or a vector boson and a photon by one loop decays [162]. ATLAS searched for for a heavy resonances decaying into a Higgs boson and a photon and sets limits from 0.7 to 4 TeV from 11.6 fb to 0.11 fb [163]. ATLAS searched for a heavy resonance decaying into XH where $XH \to qqbb$ [164] and sets limits from 1 to 4 TeV. CMS searched for a heavy resonance decaying into a W boson and a photon [165] setting limits for narrow resonances range between 0.17 fb at 6.0 TeV and 55 fb at 0.7 TeV.

Summary of Searches with Diboson Final States:

Both ATLAS [148] and CMS [149] provide plots summarizing the various searched results and limits combining. The results are shown in the context of HVT models and models of strong gravity with extra spatial dimensions. No excess is seen in any search and limits on the 4.3 (4.5) TeV (ATLAS) and (CMS). Inclusion of decays directly to fermions increase these limits to 5.3 (5.5) TeV and 5.0 (5.2) TeV from the ATLAS and CMS combinations, respectively. Both collaborations also place varying limits on the coupling strength as a function of HVT boson mass as well.

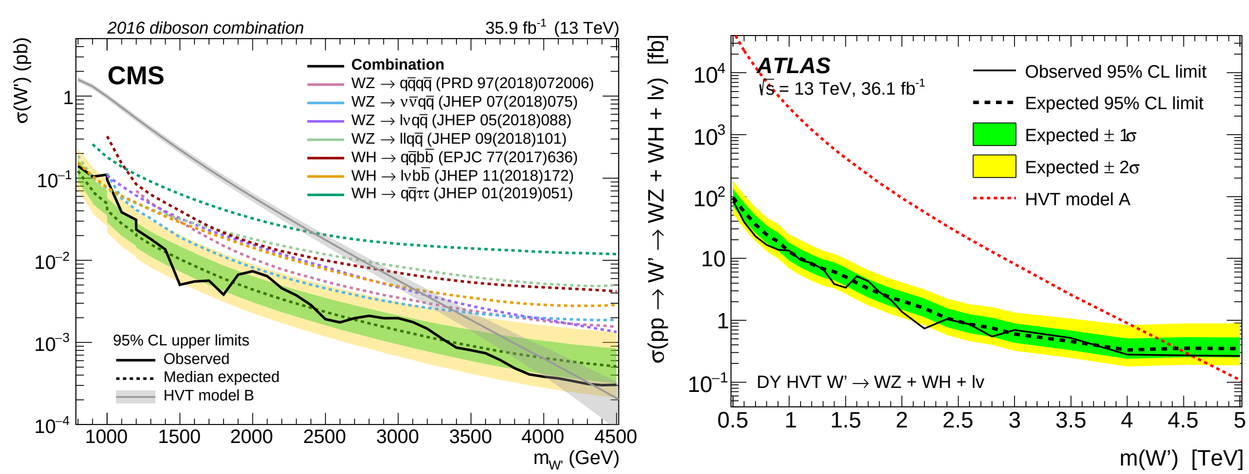

Figure 91.2: Left panel:Observed limits from W' to diboson from CMS [149]. Right panel: Observed limits from W' to diboson decays from ATLAS [148].

Searches for Triboson Resonances:

The CMS collaboration presents the first search for massive triboson resonances in both the semi-leptonic [166] and fully hadronic final state [167]. Three boson final states can be produced via the decay of Kaluza-Klein (KK) states decaying via $W_{KK} \to WR$ with $R \to WW$ where R is a scalar radion. The search utilizes novel deep neural networks to perform optimal separation between signal and background and searched for evidence of resonance structure in the triboson invariant mass-spectrum. No excesses above SM backgrounds are seen and W_{KK} and radion masses are excluded up to $M_{W_{KK}} = 3.4$ TeV and $M_R = 1$ TeV and up to $M_{W_{KK}} = 3.6$ TeV and $M_R = 0.35$ TeV . $M_{W_{KK}}$ below 3 TeV are excluded for $0.6 < \frac{M_R}{M_{W_{KK}}} < 0.7$ in the semi-leptonic final state and up to $M_{W_{KK}} = 3.0$ TeV and $M_R = 200$ GeV and up to $M_{W_{KK}} = 1.5$ TeV and $M_R = 1.5$ TeV in the fully hadronic final state.

91.2.3 *Vector-like third generation quarks*

Vector-like quarks (VLQ) have non-chiral couplings to W bosons, i.e. their left- and right-handed components couple in the same way. They therefore have vectorial couplings to W bosons. Vector-like quarks arise in Little Higgs theories, top-coloron-models, and theories of a composite Higgs boson with partial compositeness. In the following, the notation T quark refers to a vector-like quark with charge 2/3 and the notation B quark refers to a vector-like quark with charge −1/3, the same charges as the SM top and b quarks respectively. The exotic vector-like quarks $X_{5/3}$ and $Y_{-4/3}$ have charges 5/3, and −4/3 respectively. Vector-like quarks couple with SM quarks with Yukawa interactions and may exist as SU(2) singlets (T, and B), doublets [$(X_{5/3}, T)$,(T, B),$(B, Y_{-4/3})$], or triplets [$(X_{5/3}, T, B)$, $(T, B, Y_{-4/3})$]. At the LHC, VLQs can be pair produced via the dominant gluon-gluon fusion process. VLQs can also be produced singly by their electroweak effective couplings to a weak boson and a standard model quark. The single production rate is expected to dominate over the rate of pair production at large VLQ masses. T quarks can decay to bW, tZ, or tH^0. Weak isospin singlets are expected to decay to all three final states with (asymptotic) branching fractions of 50%, 25%, 25%, respectively. Weak isospin doublets are expected to decay exclusively to tZ and to tH^0 [168] with equal branching ratios. Analogously, B quarks can decay to tW, bZ, or bH^0. The $Y_{-4/3}$ and $X_{5/3}$ quarks decay exclusively to bW and to tW. While these are taken as the benchmark scenarios, other representations and decays to exotic new particles are possible [169–171], and hence the final results are interpreted for many allowed branching fraction combinations.

Given the multiple decay modes of the VLQs, the final state signatures of both pair produced and the singly produced VLQs are fairly rich with leptons, jets, b-jets, and missing energy. Depending on the mass of the VLQ, the top quarks and $W/Z/H^0$ bosons may be Lorentz boosted and identified using jet substructure techniques. Thus the searches are performed using lepton+jets signatures, multi-lepton and all-hadronic decays. In addition, T or B quarks with their antiparticles can result in events with same-sign leptons, for example if the decay $T \to tH \to bWW^+W^-$ is present, followed by leptonic decays of two same-sign W bosons. In the following subsections, while we describe the searches for each of the decay modes of the VLQs, the same analysis can be re-interpreted to obtain the sensitivity to a combination with varied branching fractions to the different decay modes.

In the following sections, the results obtained for T (B) quarks assuming 100% branching ratio to Wb (Wt) are also applicable to heavy vector-like $Y_{-4/3}$ ($X_{5/3}$) with charge 4/3 (5/3).

91.2.3.1 *Searches for T quarks that decay to W, Z and H^0 bosons*

$T/Y \to qW$:

ATLAS has searched for pair production of heavy T quarks that decay to a W boson and a light quark q [172]. The search focuses on the channel where one W decays to a lepton (electron or muon) , and one W decays hadronically leading to a large R jet. Thus the final state is a charged lepton, missing transverse energy, a large radius jet, and multiple small radius jets. The analysis uses the scalar sum of all the final state objects S_T to discriminate against background and searches in hypothetical reconstructed heavy quark mass. The analysis excludes T masses below 1530 GeV.

$T/Y \to bW$:

CMS has searched for pair production of heavy T quarks that decay exclusively to bW [173–175]. The analysis selected events with exactly one charged lepton, assuming that the W boson from the second T quark decays hadronically. Under this hypothesis, a 2-constraint kinematic fit can be performed to reconstruct the mass of the T quark as a narrow mass peak with a mass resolution of around 7%. In Refs. [174] and [175], the two-dimensional distribution of reconstructed mass vs S_T was used to test for the signal, where S_T is the scalar sum of the missing p_T and the transverse momenta of the lepton and the leading four jets. This analysis, when combined with the search in the fully hadronic final state [176] excluded new quarks that decay 100% to bW for masses below 0.89 TeV [175]. At times the hadronically-decaying W boson is produced with a large Lorentz boost, leading to the W decay products merged into a large-radius jet. Algorithms such as jet pruning [177] were used to remove contributions from soft, wide angle radiation, from large-radius jets, leading to better discrimination between jets from multijet events and those arising from decays of the heavy particles. If the mass of the boosted jet was compatible with the W boson mass, then the W boson candidate jet and its subjets were used in the kinematic reconstruction of the T quark. No excess over standard model backgrounds was observed. Upper limits on the production cross section as a function of the mass of T quarks were measured. By comparing them with the predicted cross section for vector like quark pair production, the strong pair production of T quarks was excluded for masses below 1.30 TeV (1.28 TeV expected) [173].

Another "cut-based" search for pair produced T quarks in the all-hadronic final state targeting the Wb decay mode [178], relies on mass reconstruction of two highest p_T Wb combinations using boosted W boson candidates with $p_T > 200$ GeV and b-tagged jets. H_T is used as the signal discriminator, with selected events divided into nine categories based on the multiplicity of W and b-jets in the event. From this search T quarks with pure Wb decays are excluded for masses below 1.04 TeV (1.07 TeV expected).

An analogous search has been carried out by ATLAS [179,180] for the pair production of heavy T quarks. It used the lepton+jets final state with an isolated electron or muon and at least four jets, including a b-jet, and required reconstruction of the T quark mass. Given that the mass range for the T quark being explored was from a 0.4 TeV to a couple of TeV, the W boson from the T quark may fall in two categories: those with a high boost leading to merged decay products, and others where the two jets from the W boson were resolved. In addition, the selection was optimized to require large angular separation between the high p_T W bosons and the b-jets.

The $T \to Wb$ candidates were constructed from both the leptonically and hadronically decaying W bosons by pairing them with the two highest p_T b-tagged jets in the event. The pairing of b-jets with W bosons which minimizes the difference between the masses of leptonically decaying T ($m_{lep}(T)$) and the hadronic T ($m_{had}(T)$) was chosen. Finally, $m_{lep}(T)$ was used as the discriminating variable in a signal region defined by high S'_T (here S'_T is defined as the scalar sum of the missing p_T, the p_T of the lepton and jets), and the opening angle between the lepton and the neutrino ($\Delta\ R(e,\nu)$). With the 36.1 fb^{-1} data collected during Run 2 at $\sqrt{s} = 13$ TeV, assuming 100% branching ratio to the Wb decay, the observed lower limit on the T mass was 1.35 TeV, and in the SU(2) singlet scenario, the lower mass limit was obtained to be 1.17 TeV [179].

A targeted search for a T quark, produced singly in association with a light flavor quark and a b quark and decaying into bW, was carried out by CMS at $\sqrt{s}$=13 TeV and a dataset corresponding to 2.3 fb^{-1} [181]. The analysis used lepton+jets events, with at least one b-tagged jet with large transverse momentum, and a jet in the forward η region. Selected events were required to have $S_T'' >$ 500 GeV, where S_T'' is defined as the scalar sum of the transverse momenta of the lepton, the leading central jet, and the missing transverse momentum. The invariant mass of the T candidate was used as the discriminating variable and was reconstructed using the four-vectors of the leptonically decaying W boson and the leading central jet. No excess over the standard model prediction was observed. As the VLQ width is proportional to the square of the coupling, upper limits were set on the production cross section assuming a narrow width VLQ with coupling greater than 0.5. For Y/T quarks with a coupling of 0.5 and a 100% branching fraction for the decay to bW the excluded masses were in the range from 0.85 to 1.40 TeV [181]. A similar search [182, 183] was performed by ATLAS for a singly produced T or $Y_{-4/3}$ quark decaying to Wb using a dataset corresponding to $36.1\,\mathrm{fb}^{-1}$. The search was performed using lepton+jets events with a high p_T b-tagged jet, and at least one forward jet. The reconstructed mass of the $T/Y_{-4/3}$ quark, was used as the discriminating variable and showed no excess above the expectation from SM. Interference effects with the SM background are included in the study. This search led to 95% CL upper limits on the mixing angle $|sin(\theta_L)|$ (C_L^{Wb}) in the range of 0.18–0.35 (0.25–0.49) for singlet T quark mass between 0.8–1.2 TeV. This search also provided limits as a function of the $Y_{-4/3}$ quark mass, on the coupling of the $Y_{-4/3}$ quark to bW, and the mixing parameter $|sin\theta_R|$ (C_R^{Wb}) for a $(B,Y_{-4/3})$ doublet model [182]. For VLQ masses between 0.08–1.8 TeV, the limits on $|sin(\theta_R)|$ (C_R^{Wb}) are in the range 0.17–0.55 (0.24–0.77), and for for $Y_{-4/3}$ quark mass between 0.9–1.25 TeV, the limits on $|sin\theta_R|$ are around 0.18–0.19 and below the constraints from electroweak precision observables. For $Y_{-4/3}$ quark in the triplets $(T,B,Y_{-4/3})$, limits on $|sin(\theta_L)|$ (C_L^{Wb}) are between 0.16–0.39 (0.31–0.78) for masses between 0.8 GeV–1.6 TeV [182].

<u>$T \to tH^0$:</u>

ATLAS has performed a search for $T\overline{T}$ production with $T \to tH^0$ [180,184]. Given the dominant decay mode $H^0 \to b\bar{b}$, these events are characterized by a large number of jets, many of which are b-jets. Thus the event selection required one isolated electron or muon and high jet multiplicity (including b-tagged jets). The sample is categorized by the jet multiplicity (5 and ≥6 jets in the 1-lepton channel; 6 and ≥7 jets in the 0-lepton channel), b tag multiplicity (2, 3 and ≥4) and mass-tagged jet multiplicity (0, 1 and ≥2). The distributions of m_{eff}, defined as the scalar sum of the lepton and jet p_T and the missing p_T, for each category were used as the discriminant for the final signal and background separation. No excess of events was found. Weak isospin doublet T quarks were excluded below 1.16 TeV.

A search by ATLAS for pair produced VLQs with an all-hadronic final state signature yields an exclusion of pure decays $T \to tH^0$ upto a T quark mass of 2.3 TeV [185].

The CMS search for $T\overline{T}$ production, with $T \to tH^0$ decays has been performed in lepton+jets, multilepton and all-hadronic final states. The lepton+jets analysis [186] emphasizes the presence of a large number of b-tagged jets, and combines it with other kinematic variables in a Boosted Decision Tree (BDT) to enhance signal to background discrimination. The multilepton analysis [186] was optimized for the presence of b-jets and the large hadronic activity. For $\mathcal{B}(T \to tH^0) = 1$, the combined lepton+jets and multilepton analyses led to a lower limit on T quark masses of 0.71 TeV. A search for $T \to tH^0$ in all-hadronic decays [187], optimized for a high mass T quark, and based on identifying boosted top quark jets has been carried out by CMS. This search aimed to resolve subjets within the jets arising from boosted top quark decays, including b tagging of the subjets. A likelihood discriminator was defined based on the distributions of H_T and the invariant mass of the two b-jets in the events for signal and background. No excess above background expectations was observed. Assuming 100% branching ratio for $T \to tH^0$, this analysis led to a lower limit of 0.75 TeV on the mass of the T quark.

Searches for T quarks at $\sqrt{s}$=13 TeV, based on a 2.6 fb^{-1} dataset [188] have been performed by CMS using the lepton+jets final state. This search has been optimized for high mass T quarks by exploiting techniques to identify W or Higgs bosons decaying hadronically with large transverse momenta. The boosted W channel excluded T quarks decaying only to bW with masses below 0.91 TeV, and the boosted tH channel excluded T quarks decaying only to tH for masses below 0.89 TeV.

A CMS search for $T \to tH^0$ with $H^0 \to \gamma\gamma$ decays has been performed [189] in pair production of T quarks. To identify the Higgs boson produced in the decay of the heavy T quark, and the subsequent $H^0 \to \gamma\gamma$ decay, the analysis focused on identification of two photons in events with one or more high p_T lepton+jets or events with no leptons and large hadronic activity. A search for a resonance in the invariant mass distribution of the two photons in events with large hadronic activity defined by the H_T variable showed no excess above the prediction from standard model processes. The analysis resulted in exclusion of T quark masses below 0.54 TeV. CMS also searches for a single vector like T decaying to either Z boson or a Higgs boson and a T quark [190] placing a limit of up to 1.4 TeV.

A search for single production of a vector-like quark either a singlet T with charge $\frac{2}{3}$ or a Y from a triplet (T,B,Y) with charge $-\frac{4}{3}$ decaying into W (l ν) and b-quark was performed by the ATLAS collaboration [191]. Limit on the coupling strength , κ ranges between 0.22 and 0.52 for masses from 1150 to 2300 GeV for the singlet interpretation while with the triplet assumption the limits on vary from 0.14 to 0.46 for masses from 1150 to 2600 GeV. A companion analysis [192] searches in the all hadronic final state for the same single production of a vector-like quark The observed lower limits on the masses of Y quarks with κ of 0.5 and κ of 0.7 and are 2.0 TeV and 2.4 TeV, respectively. For T quarks, the observed mass limits are 1.4 TeV for and 1.9 TeV for κ of 0.5 and κ of 0.7. The combination of these two analysis [193] results in a combined limit of κ 0.5 and m_T excluded for masses above 2.1 TeV, the most restrictive to date. ATLAS also searches for a a T quark decaying into Z t with the Z boson decaying leptonically into electron or muon pairs and the top quark resulting in a large-R top quark jet [194] which produces limits and excludes this decay up to 1.8 TeV.

A search for electroweak single production of T quarks decaying to tH^0 using boosted topologies in fully hadronic [195] and lepton+jets [196] in the final states has been performed by CMS. The electroweak couplings of the T quarks to the SM third generation quarks are highly model dependent, and hence these couplings determine the rates of the single T quark production. In both analyses, T quark invariant mass was reconstructed using the boosted Higgs boson jet and the top quark. Higgs boson jets were identified using jet substructure techniques and subjet b tagging. For the lepton+jets analysis, the top quark was reconstructed from the leptonically decaying W and the b jet, while in the all-hadronic analysis the top quark jet was tagged using substructure analysis. There was no excess of events observed above background. Exclusion limits on the product of the production cross section and the branching fraction $(\sigma(pp \to Tqt/b) \times \mathcal{B}(T \to tH^0)$ were derived for the T quark masses in the range 0.70-1.8 TeV. From the lepton+jets analysis, for a mass of 1.0 TeV, values of $(\sigma(pp \to Tqt/b) \times \mathcal{B}(T \to tH^0)$ greater than 0.8 and 0.7 pb were excluded assuming left- and right-handed coupling of the T quark to standard model fermions, respectively [196]. For the all-hadronic analysis, upper limits between 0.31 and 0.93 pb were obtained on $(\sigma(pp \to Tqt/b) \times \mathcal{B}(T \to tH^0)$ for T quark masses in the range 1.0-1.8 TeV [195]. ATLAS performs a similar search [197] for single production of vector-like T quarks decaying into a Higgs Boson and a top quark and places limits between 1 and 1.7 TeV depending on the coupling

<u>$T \to tZ$:</u>

Both ATLAS and CMS search for T quarks that decay exclusively into tZ in pp collisions at

$\sqrt{s} = 13$ TeV. No excesses were found in either search.

ATLAS performs a search [198] optimized for pair production of vector-like top quarks decaying into tZ where the Z boson subsequently decays into neutrino pairs, utilizing 139 fb^{-1} of data. The search selected events with one lepton, multiple jets, and significant missing transverse momentum. No significant excesses were found and lower limits on the mass of a vector like top quark were placed, excluding masses below 1.59 TeV (weak-isospin doublet) and 1.47 TeV (pure tZ mode).

Another search by ATLAS for pair produced T decaying to tZ has been carried out by reconstructing the high transverse momentum Z boson from a pair of opposite-sign same-flavor leptons, using events with two or three charged leptons [199]. The final analysis is based on three final state signatures. In the trilepton events, at least one b-tagged jet is required and H_T, formed from all hadronic jets and charged leptons, is used as the discriminating variable. In events with two leptons, at least 2 b-jets are requested and events with zero or one high p_T top-tagged jet, use H_T as the discriminator. The second dilepton analysis with two top-tagged high p_T jets focuses on hadronically decaying heavy resonances and the invariant mass of the Z boson and the highest p_T b-tagged jet is found to be a good discriminating variable. No excess was observed over the background expectations. Limits were placed at a heavy vector like top of 1.6 TeV.

ATLAS has subsequently carried out a search [200] for singly produced T quarks decaying to tZ where the Z boson decays into neutrino pairs. The search is carried out using 36.1 fb^{-1} of data in events with two different final state signatures: one with jets and significant missing p_T (0L) and the other with a single lepton, jets and missing p_T (1L). Events are divided into signal and dedicated W+jets and $t\bar{t}$ background control regions. The sensitivity to the T quark signal is extracted using distributions of missing p_T for the 1L and the distribution of T quark transverse mass constructed from missing p_T and the high p_T large-radius top-tagged jet, for 0L analysis. There is no excess found over the expected background and lower limits on the production of T singlets are obtained as a function of the left- and right-handed couplings $c_{L,W}$ and $c_{R,W}$ to top quarks and W bosons, where c_W above 0.7 is excluded for T quark mass of 1.4 TeV. The limits on c_W are also recasted into expected and observed 95% CL upper limits for the mixing angle (θ_L) of a singlet T with the top quark.

CMS searched [201] for single production of T quarks decaying into tZ with the Z boson decaying to pairs of charged leptons (electrons and muons) and the top quark decaying hadronically using 35.9 fb^{-1} of data. Limits were placed on T quarks with masses between 0.7 and 1.7 TeV excluding the product of cross section and branching fraction above values of 0.27 to 0.04 pb. Additionally, limits on the product of cross section and branching fractions for a Z' boson decaying into tZ were set between 0.13 and 0.06 pb for Z' boson masses in the range from 1.5 to 2.5 TeV.

Similar searches by ATLAS for singly produced T decaying to Zt have been performed in final state signatures with two or three charged leptons [202]. The analysis relies on tagging b-jets and high p_T large-radius jets originating from top-quarks. Additional selections are devised to reduce the contributions from pair production of T quarks. For events with dilepton analysis, the discriminating variable is the mass of the T quark formed using the invariant mass of the Z boson candidate and the highest p_T top-tagged jet, while for the trilepton analysis, the variable S_T is used to search for an excess of data over the expected SM background. No excess above the SM expectations is observed. The two final states (dilepton and trileptons) are combined to obtain the final results. For the coupling parameter κ_T between 0.1–1.6, the 95% CL upper limits on the production cross section times branching fraction into Zt is between 0.16–0.18 (0.03–0.05) pb at T quark mass of 0.7 (2) TeV.

The search by the ATLAS experiment for VLQ pair production optimized to search for $T \to tZ$ decays [203] in a dataset with $139\,\mathrm{fb}^{-1}$ of luminosity has been performed in final states with either two leptons or three or more leptons. A multi-class boosted object tagger based on DNN techniques for large-radius jets is used to categorize events according to the number of high p_T boosted H^0, Z/W, and top quark jets. The discriminant in the signal to evaluate the sensitivity depends on the number of leptons in the event. For the two lepton analysis, the discriminant is the mass of the T quark which is constructed from b and Z candidates, while for the three or more lepton analysis, H_T computed using the p_T of the jets and leptons is used as the discriminant. This analysis excludes T quark masses up to 1.27 GeV (1.46 GeV), for the singlet (doublet) configuration [203].

Combination of $T \to tZ/tH^0$:

The search performed by the ATLAS experiment for electroweak single production of T quark decaying to tH^0 and tZ uses a dataset corresponding to 139 fb^{-1} of integrated luminosity, and events with a single lepton with multiple jets and b-jets in the final state [204]. The single production channel for VLQs probes κ, the universal coupling constant, which also controls the production cross section and the resonance width of the VLQ. The analysis uses techniques to tag boosted jets, and categorizes events by numbers of jets and b-jets. The event discriminant is the "effective mass" (meff) observable, defined as the scalar sum of the p_T of all central jets, p_T of leptons and the missing p_T in the event. No significant excess is observed. Limits on the mass of T quark and universal coupling strength (κ) are obtained. For singlet T quarks, values of κ above 0.5 are excluded for all masses below 1.8 TeV. For T quark mass of 1.6 TeV, κ above 0.41 is excluded [204].

A CMS search published in 2020 concentrates on the electroweak production of the T quark with $T \to tH^0$, and $T \to tZ$ decays, where subsequently both H^0 and Z Bosons decay hadronically, leading to fully hadronic final states [205]. The search focuses on evidence of T quarks produced in association with a b quark ($qg \to T\bar{b}q'$) or a top quark ($qg \to T\bar{t}q$). The production cross sections are model dependent, as the electroweak production depends on the strength of the T quark coupling, TbW (TtZ), for the charged-current (neutral-current) process, at the production vertex. The searches are split into two domains depending on the mass of the T quark and consider a wide range of widths of the T quark from a few percent to about 30% of the T quark mass. The event selection relies primarily on the large number of jets and on efficient identification of jets from b-quarks, in addition to double-b jet decays of the H^0 and Z bosons. The final sensitivity is derived by the search for a resonant peak in the tH^0/Z invariant mass spectrum. For low mass T quark searches, three independent regions based on the b-tagged jet requirements are examined. For T quark masses above 1 TeV, which result in highly Lorentz-boosted top quarks and H^0 or Z boson, large-area jets are used to form the T quark. This search reports upper limits at 95% confidence level on $\sigma B(T \to tH)$ and $\sigma B(T \to tZ)$ between 2 pb and 20 fb for T masses between 0.6 to 2.6 TeV in the Tbq and Ttq production channels. The analysis also reports combined results for $T \to tH$ and $T \to tZ$ associated production with a bottom quark and provides constraints on T quarks in the T singlet model for masses below 1.00 TeV. For an expected fractional width of 30%, the expected sensitivity extends to 1.28 TeV, comparable to the most stringent results.

Another inclusive search for pair produced T in the all-hadronic final state [178] has been performed by CMS using the boosted event shape tagger (BEST NN) neural network technique to classify jets in six categories W, Z, H^0, t, b, and light. This search does not focus on a given VLQ mode, but on various combinations of the boson and quark jets in the final state. Anti-k_T jets with a distance parameter of 0.8 are used. The BEST NN algorithm simultaneously classifies jets according to heavy object type. For each of the six particle hypotheses, it boosts each jet constituent into corresponding frame along the jet momentum direction, and calculates event shape and angular variables in the boosted frame, with the expectation that when boosting to the correct rest frame, jet constituents will be isotropic and show the expected N-prong structure of the decaying object in its rest frame. A neural network is trained using the event shape and angular variables in the boosted frame to classify jets according to one of those six possibilities (W, Z, H, t, b, or light).

The analysis bins the events into 126 categories depending on the number of W, Z, H, t, b, or light jets in the final state with a maximum of four such objects. For each category H_T^{AK8}, the scalar sum of p_T of all AK8 jets, is used as the signal discriminator. A scan over a combination of various branching fractions is also performed. This search excludes T quark masses in the range 0.74–1.37 TeV for the tH decay mode in the NN analysis.

An inclusive search for VLQs has been carried out by CMS targeted at heavy T quarks decaying to any combination of bW, tZ, or tH^0 as described in [186]. Selected events have at least one isolated charged lepton. Events were categorized according to number and flavor of the leptons, the number of jets, and the presence of hadronic vector boson and top quark decays that are merged into a single jet. The use of jet substructure to identify hadronic decays significantly increases the acceptance for high T quark masses. No excess above standard model backgrounds was observed. Limits on the pair production cross section of the new quarks are set, combining all event categories, for all combinations of branching fractions into the three final states. For T quarks that exclusively decay to $bW/tZ/tH^0$, masses below 0.70/0.78/0.71 TeV are excluded.

91.2.3.2 *Searches for $\boldsymbol{B}$ quarks that decay to $\boldsymbol{W}$, $\boldsymbol{Z}$ and $\boldsymbol{H^0}$ bosons*

ATLAS and CMS have performed searches for pair production of heavy B quarks which subsequently decay to Wt, bZ or bH^0. The searches have been carried out in final states with single leptons, dileptons (with same charge or opposite charge), multileptons, as well as in fully hadronic final states.

$B \to bH^0$:

A search for B pair-produced events has been performed by the CMS experiment [179] using $137\,\mathrm{fb}^{-1}$ of data where the B decays into a $b/\bar{b}$ quark and either a H^0 or a Z boson. This search concentrates on final states with fully hadronic signatures, and utilizes different jet multiplicity categories to account for two resolved jets or merged single jets from H^0 or Z boson to $b\bar{b}$ decays, depending on the p_T of the H^0 or Z bosons. Nine final state categories are used, depending on the number of observed jets and the reconstructed event mode. No significant excess over expected background is observed. For the case $\mathcal{B}(B \to bH) =$ 100%(50%), VLQs with masses below 1.57 (1.45) TeV are ruled out.

Using $36.1\,\mathrm{fb}^{-1}$ of data, ATLAS has performed a search for pair produced VLQs with all-hadronic final state signature [206]. While this analysis provides exclusion limits for all third generation VLQs, it provides the strongest results for the $B \to bH^0$ decay mode and excludes decays with $\mathcal{B}(\mathcal{B} \to \lfloor\mathcal{H}') = \infty.\prime$ scenario for B masses upto 1.01 TeV. The limits are also cast in a two-dimensional plane of branching ratio values of $B \to bH^0$ vs. $B \to Wb$. This analysis required the presence of high p_T jets and multiple b tags. It used a multi-class DNN to classify jets arising from W, Z, H^0 bosons and top-quarks. In addition, the matrix element method was used to compute the likelihood for the event to arise from a particular VLQ final state and to construct the final discriminator. To increase the sensitivity of the analysis, processes with the same number of top quarks, W/Z bosons, and H^0 Higgs bosons are combined into a single hypothesis.

ATLAS has performed a search for single production of a vector-like B quark decaying to a b-quark and a H^0 boson, with $H^0 \to b\bar{b}$ decay, using a dataset corresponding to an integrated luminosity of $139\,\mathrm{fb}^{-1}$ [207]. The all hadronic final state signature relies on identification of at least 3 b-jets, with an additional soft forward jet from the spectator quark. Large area jets are used to identify boosted H^0 decays. This analysis results in excluding the single production of a VLQ (B, Y) doublet with relative width larger than 5% between masses of 1.0 TeV and 2.0 TeV [208]. The CMS experiment has searched for a single vector-like quark decaying into tH or tZ in the all hadronic final state with $138\,\mathrm{fb}^{-1}$ of data in the all hadronic channel reconstructing both the boson invariant mass and the tH or tZ invariant mass and searching for a resonance. No significant excess is found and cross-section limits are placed between 600 GeV and 1200 GeV between 600 and 68 fb [209].

<u>$B \to Wt$:</u>

A search for $B \to tW$ in B pair produced events has been performed by ATLAS [179] using lepton+jets events with one hadronically decaying W and one leptonically decaying W utilizing 36.1 fb^{-1} of data at $\sqrt{s} = 13$ TeV. The search was optimized for T production decaying into Wb. Since the analysis was optimized for $T \to Wb$ rather than Wt decays the analysis does not reconstruct the full B mass. As discussed earlier, the hadronically and leptonically decaying heavy quarks were required to have similar reconstructed masses (within 300 GeV). The interpretation of the $T \to Wb$ in the context of $B \to tW$ production led to the exclusion of heavy B like VLQs for masses less than 1.25 TeV and 1.08 TeV, assuming a 100% branching fraction to tW or SU(2) singlet B scenario, respectively.

A similar search by CMS [210], using 19.8 fb^{-1} of $\sqrt{s} = 8$ TeV data, selected events with one lepton and four or more jets, with at least one b-tagged jet, significant missing p_T, and further categorized them based on the number of jets tagged as arising from the decay of boosted W, Z or H^0 bosons. The S_T distributions of the events in different categories showed no excess of events above the expected background and yielded a lower limit on the B quark mass of 0.73 TeV for $BR(B \to Wt) = 1$.

CMS [188] also searched for pair production of both TT and BB with collisions from 2.5 fb^{-1} of $\sqrt{s} = 13$ TeV data. The analysis searched for events with one high p_T lepton , multiple jets, and highly boosted W or Higgs bosons decaying hadronically. The analysis focused on pair production and selects events with either a boosted W or Higgs candidate and then proceeds to search for anomalous production in excess of standard model production. Seeing no significant excesses CMS then proceeded to set limits in many different interpretations. The strongest was from the $B \to Wt$ interpretation leading to excluding heavy vector-like B quarks with mass less than 0.73 TeV.

The all-hadronic inclusive analysis [178] performed by CMS using the BEST NN technique to classify $W/Z/H^0/t/b$/light jets also gives exclusion limits on B quark production for various combinations of branching fractions for decays to tW, bZ, bH^0. By considering categories based on various combinations of the boson and quark jets in the final state it excludes B quarks with masses up to 1230 GeV, for B decays to tW with a 100% branching fraction.

Electroweak production of single heavy B+b production has been studied by CMS in the decay to tW with the lepton+jets final state [211]. Single lepton events with hadronic jets, including a forward jet, and missing p_T are selected and divided into 10 different categories based on lepton flavor (e/μ), top-tagged, W-tagged, and 0/1/2 b-tagged jets. The B quark mass m_{reco} is fully reconstructed from lepton, jets, and missing p_T, where the neutrino four-momentum is computed using the missing p_T and the W mass constraint. For events within the top-tagged category, the high p_T top-tagged hadronic jet and the leptonically decaying W boson are used to compute m_{reco}. The m_{reco} distribution are used as the signal discriminator. In the absence of an excess over the expected SM background, the exclusion limits on the production cross section for B quark masses between 0.7-2 TeV varies between 0.3 to 0.03 pb. In addition, B quarks with left-handed couplings and a relative width of 10, 20, and 30% are excluded for masses below 1.49, 1.59, and 1.66 TeV respectively.

<u>$B \to bZ$:</u>

As mentioned above, a search for B pair produced events, with final states with fully hadronic signature, using 137 fb^{-1} of data, has been performed by the CMS experiment [179]. In this search, the B decays into a $b/\bar{b}$ quark and either a H^0 or a Z boson. For the case $\mathcal{B}(B \to bZ) = 100\%(50\%)$, VLQs with masses below 1.39 (1.45) TeV are ruled out by this analysis.

A search by CMS [212] for the pair-production of a heavy B quark and its antiparticle has been performed, where one of the heavy B quark decays to bZ. Events with a Z boson decaying to e^+e^- or $\mu^+\mu^-$ and at least one b jet are selected. The signal from $B \to bZ$ decays is expected to appear as a local enhancement in the bZ mass distribution. No such enhancement was found and B quarks that decay 100% into bZ are excluded below 0.70 TeV. This analysis also set upper limits on the branching fraction for $B \to bZ$ decays of 30-100% in the B quark mass range 0.45-0.70 TeV. A complementary search has been carried out by ATLAS for new heavy quarks decaying into a Z boson and a b-quark [213]. Selected dilepton events contain a high transverse momentum Z boson that decays leptonically, together with two b-jets. If the dilepton events have an extra lepton in addition to those from the Z boson, then only one b-jet is required. No significant excess of events above the standard model expectation was observed, and mass limits were set depending on the assumed branching ratios. In a weak-isospin singlet scenario, a B quark with mass lower than 0.65 TeV was excluded, while for a particular weak-isospin doublet scenario, a B quark with mass lower than 0.73 TeV was ruled out.

The search by ATLAS for $B \to bZ$ decays [203] in final states with either two leptons or three or more leptons using a multi-class boosted object tagger to categorize events according to the number of high p_T boosted H^0, Z/W, and top quark jets excludes B quark masses up to 1.20 GeV (1.32 GeV), for the singlet (doublet) configuration [203].

In addition to pair production, ATLAS has also searched for the electroweak production of single B quarks, which is accompanied by a b-jet and a light jet [213]. The dilepton selection for double B production was modified for the single B production study by requiring the presence of an additional energetic jet in the forward region. An upper limit of 200 fb was obtained for the process $\sigma(pp \to B\bar{b}q) \times B(B \to Zb)$ with a heavy B quark mass at 0.70 TeV. This search indicated that the electroweak mixing parameter X_{Bb} below 0.5 is neither expected nor observed to be excluded for any values of B quark mass.

91.2.3.3 *Searches for top-partner quark* $\boldsymbol{X_{5/3}}$

Searches for a heavy top vector-like quark $X_{5/3}$, with exotic charge $\pm 5/3$, such as that proposed in Refs. [215, 216], have been performed by both ATLAS and CMS [179, 217].

The analyses assumed pair-production or single production of $X_{5/3}$ with $X_{5/3}$ decaying with 100% branching fraction to tW. Searches for $X_{5/3}$ have been performed using two final state signatures: same-sign leptons and lepton+jets.

The analysis based on searching for same-sign leptons, from the two W bosons from one of the $X_{5/3}$, has smaller backgrounds compared to the lepton+jets signature. Requiring same-sign leptons eliminates most of the standard model background processes, leaving those with smaller cross sections: $t\bar{t}W$, $t\bar{t}Z$, WWW, and same-sign WW. In addition, backgrounds from instrumental effects due to charge misidentification were considered. Assuming pair production of $X_{5/3}$, the analysis by CMS using H_T as the discriminating variable restrict the $X_{5/3}$ mass to be higher than 1.16 (1.10) TeV for a right (left) handed chirality particle [217–219]. The limits obtained by ATLAS, by classifying the signal region by number of b-jets, H_T, and missing p_T in the event, led to a lower mass limit on $X_{5/3}$ of 1.19 TeV [220, 221].

Searches for $X_{5/3}$ using leptons+jets final state signatures are based on either full or partial reconstruction of the T mass from the lepton, jets (including b-jets) and missing p_T. The CMS search [217, 222] also utilized jet substructure techniques to identify boosted $X_{5/3}$ topologies. The discriminating variable used was the mass constructed from the lepton and b-tagged jet, $M_{(\ell,b)}$, which corresponds to the visible mass of the leptonically decaying top quark. To optimize the search sensitivity, the events were further separated into categories based on lepton flavor (e, μ), the number of b-tagged jets, the number of W-tagged jets, and the number of t-tagged jets. In

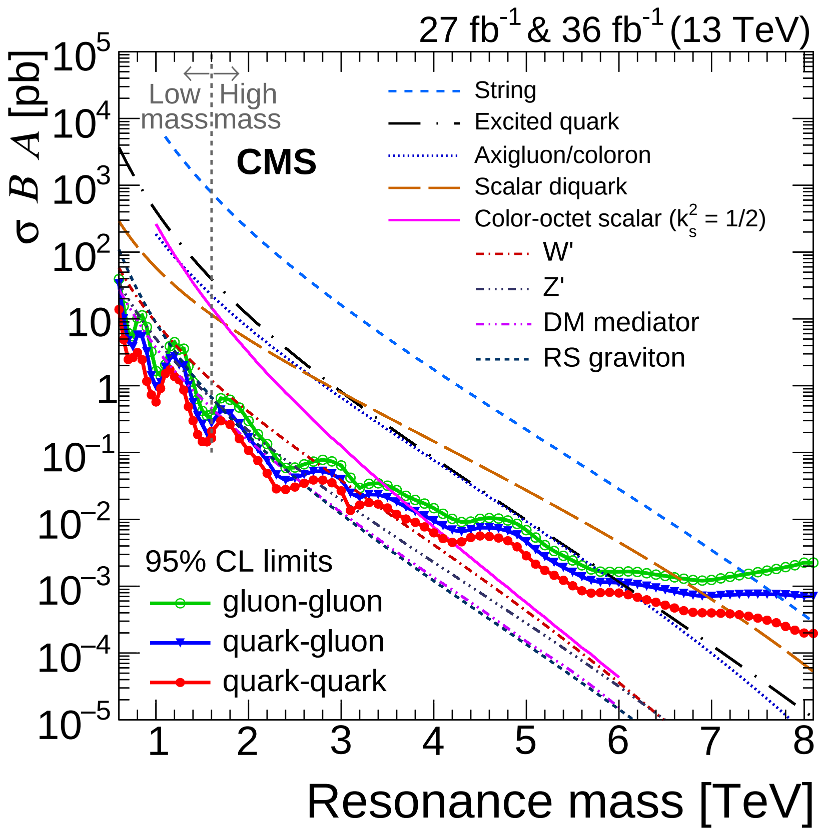

Figure 91.3: Observed 95% C.L. limits on $\sigma \times B \times A$ for string resonances, excited quarks, axigluons, colorons, E6 diquarks, s8 resonances, W' and Z' bosons, and Randall–Sundrum Gravitons g_{KK} from [214].

the absence of a signal, the CMS analysis excluded $X_{5/3}$ quark masses with right-handed (left-handed) couplings below 1.32 (1.30) TeV [222]. Combining the lepton+jets with the same-sign leptons analyses leads to a slight improvement and excludes $X_{5/3}$ quark masses with right-handed (left-handed) couplings below 1.33 (1.30) TeV.

The ATLAS lepton+jets search for $X_{5/3}$ utilized events with high p_T W bosons and b-jets. The search described earlier for T pair production, with $T \to Wb$ decays, can be reinterpreted as a search for $X \to tW$. This analysis excluded $X_{5/3}$ with masses below 1.25 TeV [179].

The single $X_{5/3}$ production cross section depends on the coupling constant λ of the tWX vertex. ATLAS has performed an analysis of same-sign dileptons which includes both the single and pair production. This analysis led to a lower limit on the mass of the $X_{5/3}$ of 0.75 TeV for both values of $\lambda = 0.5$ and 1.0 [223].

Single heavy $X_{5/3}$+t production has been studied by CMS in the decay to tW with the lepton+jets final state [211]. The description of the analysis is provided earlier in the discussion of $B \to WtX$ decays, where the reconstructed mass of $X_{5/3}$, m_{reco} distribution is used as the signal discriminator. In the absence of an excess over the expected SM background, the exclusion limits on the production cross section for $X_{5/3}$ quark masses between 0.7–2 TeV varies between 0.3 to 0.03 pb, depending on the width of $X_{5/3}$ between 1–10%. In addition, $X_{5/3}$ quarks with left-handed couplings and a relative width of 10, 20, and 30% are excluded for masses below 0.92, 1.3, and 1.45 TeV respectively.

91.2.4 *Heavy resonances decaying to VLQ*

CMS has performed search for VLQ production in the decay of massive resonances such as Z' and W' bosons.

$\underline{Z' \to tT}$: Specifically searches are presented by CMS in Refs. [224] and [225] for massive spin-1 Z' resonances decaying to a top quark and a heavy VLQ top quark partner T. The results of this search for a heavy spin-1 resonance are interpreted in the context of two different models. In the $G^\star$ model which predicts ten VLQs ($T,\ B, \tilde{T}, \tilde{B}, T_{5/3}, T_{2/3}, T', B', B_{-1/3}, B_{-4/3}$) with the mass relationship $M(T_{5/3}) = M(T_{2/3}) = M(T)\cos(\phi_L)$. For the benchmark scenario [226], $\cos(\phi_L)$=0.84 and the branching fractions $T \to tH^0, tZ, Wb$ are 0.25, 0.25 and 0.5 respectively. The ρ^0 model predicts a multiplet of four new VLQs $T, B, X_{2/3}, X_{5/3}$, and in the benchmark scenario [227], the branching fractions $T \to tH^0, tZ, Wb$ are 0.5, 0.5 and 0 respectively.

Two of the three decays of the $Z' \to tT$ with $T \to tH^0, tZ, Wb$ are characterized by the presence of two top quark decays and a boson (H^0/Z). A search [225] by CMS, optimized for $T \to tH/Zt$ decays was carried out in the lepton+jets final state using a dataset corresponding to an integrated luminosity of 35.9 fb^{-1}. Jet substructure techniques are used to identify (or tag) the high p_T large-radius jets originating from H^0, Z bosons and merged top quarks. The mass of the Z' boson is used as the signal discriminator and constructed using H^0 or Z-tagged dijet, the hadronic and leptonic top quark four vectors. For the leptonic top quark reconstruction ($t \to b\ell\nu_\ell$), the neutrino four vector is obtained from the event missing p_T using the W boson mass constraint. While the high p_T hadronic top quark jets from decays of massive Z' bosons are mostly merged and identified by top tagging techniques, those from T decays maybe resolved. The reconstructed Z' candidate events are classified into six different categories requiring the presence of either a H^0-tagged jet with 2 b-tagged subjets or one b-tagged subjet or a Z-tagged boson, each with either zero or one top-tagged jet. This search does not observe any significant deviation in data over the expectation from standard model backgrounds. Within the context of the $G^\star$ model, for a T mass of 1.2 (1.5) TeV, this search excludes $G^\star$ [226] resonances with masses between 1.5–2.3 (2.0–2.4) TeV.

The search in the all-hadronic final state is based on a 2.6 fb^{-1} dataset [224], and optimized for $T \to Wb$ decays. Jet substructure techniques are deployed for tagging jets from high p_T W boson and top quarks. Events are categorized into two groups based on the presence of b-tagged subjets in the top-tagged jet. The multijet background estimation is challenging and determined using side-bands defined by inverting the b-tagging requirement. Upper limits on the cross section for $Z' \to tT$ are obtained in the range of 0.13–10 pb.

$\underline{W' \to Tb/Bt}$: W' bosons are predicted to decay to VLQ third generation partners $T,\ B$ quarks within composite Higgs and warped extra dimensional models [228]. In the benchmark scenarios of this framework, W' decays to Tb or Bt are equally distributed and the subsequent VLQ decays $T \to tH$ and $B \to bH^0$ each are assumed to have a branching fraction of 0.5. The search for $W' \to Tb/bH^0 \to tbH^0$ is performed using a sample of 35.9 fb^{-1} by CMS [229] in the final state with all-hadronic decays of both the Higgs boson ($H^0 \to b\bar{b}$) and the top quark. Both the H^0 boson and the top quark are expected to be boosted in the decay of a heavy W', and hence jet substructure techniques, including subjet b-tagging and double b-tagging are deployed to identify the H^0-tagged and the top-tagged jets. The three particle mass m_{tbH^0}, is used as the signal discriminant to observe the W' resonance. There is no excess observed in data above the expected SM background. This search excludes W' production cross section above 0.01–0.43 pb for masses between 1.5–4.0 TeV.

91.2.5 *Colorons and Colored Scalars*

These particles are associated with top-condensate and top-seesaw models, which involve an enlarged color gauge group. The new particles decay to dijets, $t\bar{t}$, and $b\bar{b}$.

Direct searches for colorons, color-octet scalars and other heavy objects decaying to $q\bar{q}$, qg, qq, or gg have been performed using LHC data from pp collisions at $\sqrt{s}$ =7, 8 and 13 TeV. Based on the analysis of dijet events from a data sample corresponding to a luminosity of 19.6 fb^{-1}, at $\sqrt{s}$ = 8 TeV, the CMS experiment excluded pair production of colorons with mass between $1.20-3.60$ and $3.90-4.08$ TeV [230]. Analyses of inclusive 8- and 10-jet final states with low missing transverse momentum by CMS [231], set limits in several benchmark models. Colorons (axigluons) with masses between 0.6 and 0.75 (up to 1.15) TeV were excluded, and gluinos in R-parity violating supersymmetric scenarios were ruled out from 0.6 up to 1.1 TeV.

A search for pair-produced colorons based on an integrated luminosity of 5.0 fb^{-1} at $\sqrt{s}$ = 7 TeV by CMS excluded colorons with masses between 0.25 TeV and 0.74 TeV, assuming colorons decay 100% into $q\bar{q}$ [232]. This analysis was based on events with at least four jets and two dijet combinations with similar dijet mass. Color-octet scalars (s8) with masses between $1.20-2.79$ TeV were excluded by CMS [230], and below 2.7 TeV by ATLAS [233].

These studies have now been extended to take advantage of the increased center-of-mass energy during Run 2 of the LHC. Using $35.9\,\text{fb}^{-1}$ of data collected at $\sqrt{s}$ =13 TeV, searches for narrow resonances have been performed by CMS. An analysis of the dijet invariant mass spectrum formed using wide jets [214, 234, 235], separated by $\Delta\eta_{jj} \leq 1.3$, led to limits on new particles decaying to parton pairs (qq, qg, gg). Specific exclusions on the masses of colorons and color-octet scalars were obtained and are shown in Fig. 91.3. Exclusions have been obtained for axigluons and colorons below 6.1 TeV, and color-octet scalars below 3.4 TeV.

Additional searches for dijet resonances have been performed by both ATLAS [236–238] and CMS [239, 240], though they have not been interpreted in the context of coloron production.

91.3 Conclusions

As the above analyses have demonstrated, there is already substantial sensitivity to possible new particles predicted to accompany the H^0 in dynamical frameworks of electroweak symmetry breaking. No significant hints of any deviations from the standard model have been observed, and limits typically at the scale of a few hundred GeV to a few TeV are set.

Given the need to better understand the H^0 and to determine in detail how it behaves, such analyses continue to be a major theme of Run 3 of the LHC, and we look forward to increased sensitivity as a result of the higher luminosity at the increased center of mass energy of collisions.

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