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Search for new resonances involving Higgs, W or Z bosons at CMS

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Beyond the standard model theories like composite Higgs models predict resonances with large branching fractions in a Higgs boson and a vector boson with negligible branching fractions to light fermions. We present an overview of searches for new physics containing a Higgs boson and a W or Z boson in the final state, using proton-proton collision data collected with the CMS detector at the CERN LHC. For high-mass resonances decaying to intermediate bosons, the large boost for hadronic decays gives rise to one single "merged" jet, which can be identified through a study of its substructure consistent with the presence of two quarks, enhancing the sensitivity due to the large branching ratios for hadronic decays. B-quark identification algorithms are used in addition to identify the hadronic H decays.

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1. Introduction

After the discovery of the Higgs boson by the ATLAS and CMS collaborations in 2012 [1, 2], the resolution of the problem of electroweak symmetry breaking has been definitively established. However, the resolution of this problem gives rise to the question of why the Higgs mass is much lower than naively expected from quantum mechanical calculations (the "hierarchy problem"). Guided by an ansatz of "naturalness", whereas solutions to the hierarchy problem should not introduce requirements of a high degree of coincidence, several classes of solutions to this outstanding question have been presented. One major class of solutions propose that there are extra spatial dimensions, reducing the effective strength of gravity but not other forces [3, 4]. This led to a great deal of opportunity for accessible phenomenological signatures of large extra dimensions (ED) at the LHC involving diboson signatures [5, 6, 7]. Other models have proposed more agnostic extensions of the gauge group for the electroweak sector, such as Heavy vector triplet (HVT) models [8].

The signatures of these models often involve new particles (such as Kaluza-Klein excitations of the graviton or heavy Higgses) that decay into W, Z, or H bosons. Due to the fact that these models are solutions to the hierarchy problem, the new particles would have very large masses. Since the mass of the new particle is so large, when it decays into two bosons (W,Z, or H), they acquire a large energy compared to their mass. This gives the bosons a large Lorentz boost. From the kinematics of the decay, the angular separation between the decay products of the bosons is $\Delta R\ 2/\gamma$, where γ is the Lorentz boost of the boson. At high Lorentz boosts, the angular separation decreases. This leads to the need for solutions to many technical challenges, since most "standard" particle physics techniques rely on the assumption of well-separated decay products. For "boosted" topologies, this is no longer true. New techniques must be developed to accomodate this regime, including new trigger strategies that rely on jet mass or non-isolated leptons [9], new kinematic reconstruction techniques, new bottom quark tagging techniques to handle overlapping bottom hadrons [10], new τ lepton reconstruction techniques [11], and new hadronic jet reconstruction algorithms to identify the "substructure" of hadronically decaying W,Z, and H bosons [12, 13, 14, 15].

The signatures of these models in the CMS detector [16] include resonances decaying to two electroweak vector bosons (WW, WZ, ZZ), Higgs bosons with one electroweak vector boson (HW, HZ), and two Higgs bosons (HH). Defining V_{had} as a hadronically decaying W or Z boson, W_{lep} as a leptonically decaying W boson, Z_{lep} as a leptonically decaying Z boson, H_{bb} as a hadronically decaying H boson, and $H_{\tau\tau}$ as a H boson decaying into τ lepton pairs, the search topologies are $V_{had}V_{had}$ (0 e/μ), $V_{had}W_{lep}$ (1 e/μ), $V_{had}Z_{lep}$ (2 e/μ), $H_{bb}W_{lep}$ (1 e/μ), $H_{bb}Z_{lep}$ (2 e/μ or 2 ν), $H_{bb}H_{bb}$ (0 e/μ), and $H_{bb}H_{\tau\tau}$ (0 e/μ, $\geq 2\,\tau$).

2. Background Strategies

The different analyses have different background strategies. However, all rely on one or more of the following tactics.

The first tactic is event categorization. In this strategy, events are not discarded by traditional selection criteria. Instead, events are separated into categories with varying signal-to-background ratios (purity). A relationship between the categories is established using predictions from MC simulation corrected with data-to-MC scale factors. The events are then simultaneously fit in a likelihood to extract the signal and background fractions. In particular, this is employed by searches with hadronic W and Z bosons in the final state, where events are categorized as W or Z enriched with a jet mass selection with the jet pruning algorithm [12, 13], and in high and low tagging purity with a selection on the substructure variable τ_{21} (the 2-subjettiness over 1-subjettiness ratio) [14, 15]. As an example, Fig. 1 shows the jet mass categories in the muon channel of the analysis in Ref. [17], and Fig. 2 shows the τ_{21} variable in the electron channel of the same analysis.

The second tactic is extrapolation from control regions. Typically this is used in all of the searches with a hadronically decaying W,Z, or H boson. The backgrounds are extrapolated inwards from the sidebands of the jet mass selection window using a kinematic model derived from simulation.

The third tactic is to employ a smoothness test on the diboson mass. This is a more traditional technique employed in other LHC searches, where a peak of signal events is compared to the smooth background shape, and a probability is assigned to the fluctuations observed.

These three tactics can be used separately or in conjunction with one another. They can also be used for cross checks. The applications are discussed specifically below.

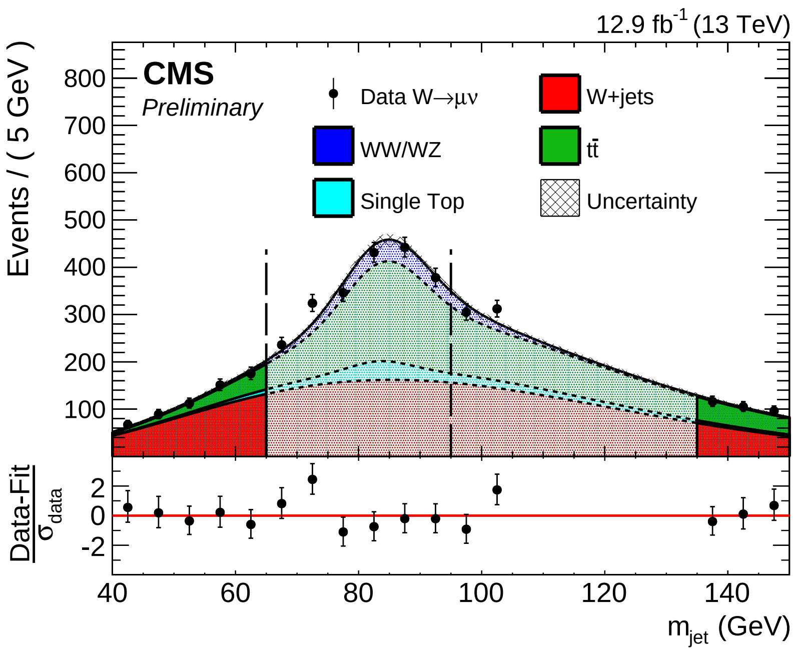

Figure 1: Distribution of the pruned jet mass in the muon channel from Ref. [17]. The shaded regions show the different jet mass categories corresponding to W and Z enriched regions. The blank area on the plot is the H channel not considered in that analysis.

3. Individual Results

The individual results are discussed separately below.

$V_{had}V_{had}$ [9] : This search focuses on pairs of boosted hadronically-decaying vector bosons. The events are collected with an H_T trigger with $H_T > 1000$ GeV. The jet pruning [12, 13] and n-

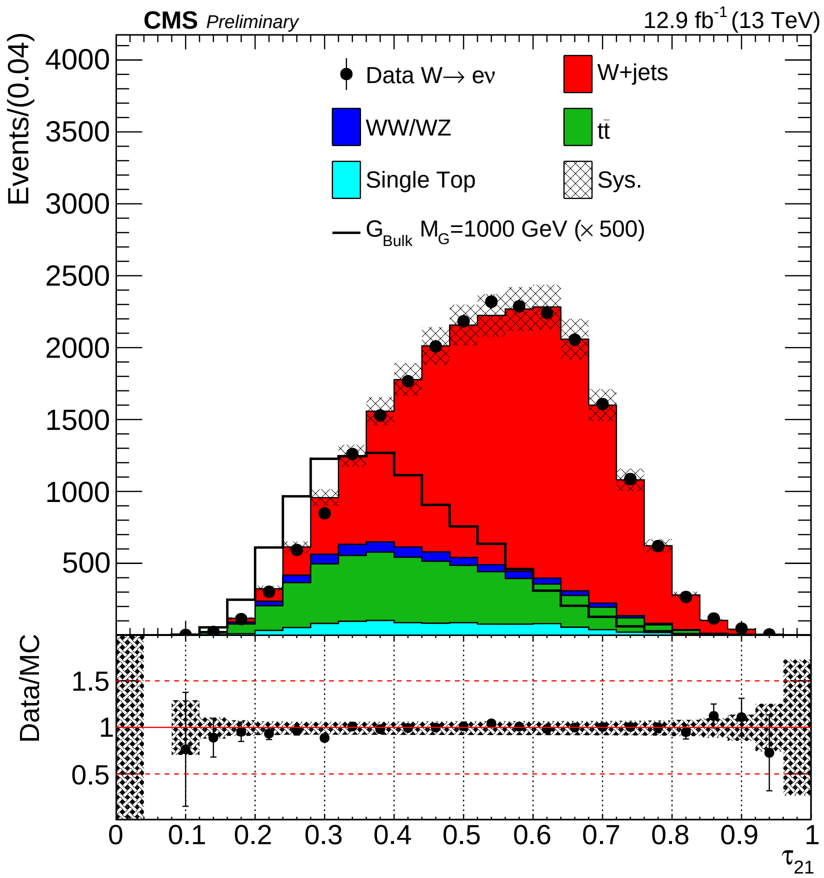

Figure 2: Distribution of the τ_{21} variable in the muon channel from Ref. [17]. This variable is used for event categorization based on the purity of the selection.

subjettiness [14, 15] techniques are used to identify massive jets with 2-prong structure. The events are categorized into WW, WZ, and ZZ jet mass categories (separated at a jet mass of 90 GeV), and high and low purity τ_{21} categories (0.45-0.8, and < 0.45, respectively). Coupled smoothness tests of the diboson invariant masses in the various categories is performed to test the signal+background versus background-only hypotheses.

$V_{had}W_{lep}$ [17] : The signature for this search is one leptonically-decaying W boson and one hadronically-decaying W or Z boson. The leptonic decay involves one electron or muon, plus significant missing transverse momentum. The data are collected with triggers requiring a single electron or muon. The transverse momentum of the W is estimated by the scalar sum of the transverse momenta of the lepton and missing transverse momentum. Events are again categorized into W and Z regions based on their jet mass, although they are not separated by τ_{21}. The lower diboson mass region extending below 1 TeV is analyzed with separate triggers and a slightly different selection optimization than for diboson masses above 1 TeV. The sideband regions of the jet mass are used to extract the signal and background fractions simultaneously in each event category.

$V_{had}Z_{lep}$ [18] : These events are reconstructed at high diboson mass (boosted), as well as at low diboson mass (both boosted and resolved topologies). The high mass diboson search uses the same fitting strategy as the $V_{had}W_{lep}$ search described above. The events are categorized into high and low purity categories of τ_{21} as in the $V_{had}V_{had}$ case, but do not separate into jet mass categories. The low mass diboson search uses Z+jets MC simulation to extrapolate from sideband regions in the jet mass (for the boosted topology) and the dijet mass (for the resolved category). Events are categorized by the number of bottom-quark tagged jets, and whether they are boosted or resolved.

HW_{lep}, HZ_{lep} [19] : This analysis utilizes bottom-quark tagging techniques developed specifically for the case of overlapping bottom quark subjets from a Higgs boson decay. The events are categorized into the number of leptons from the W or Z decay, and the number of bottom quark tags in the H candidate jet. The background is estimated by extrapolating the sidebands of the jet mass.

$H_{bb}H_{bb}$ [20] : There are two approaches to this analysis presented together. Both utilize the same bottom quark subjet tagging techniques as the HW_{lep} and HZ_{lep} analyses. In the first approach, the events passing and failing this criterion are also categorized into jet mass categories of the H boson, and the sidebands of these two categorizations are together used to extrapolate the background estimate in two dimensions. In the second approach, a similar smoothness test to the $V_{had}V_{had}$ case is used.

$H_{bb}H_{\tau\tau}$ [20] : The branching ratio of $H \to \tau\tau$ is very low, so this analysis has very few events. There are no categorizations in this case. The two τ leptons from the H decay are themselves boosted together, necessitating the application of new τ reconstruction algorithms inspired by the boosted jet algorithms described above. The backgrounds are again estimated using the jet mass sidebands. Only one event passes the final event selection, but this is a very pure channel with a distinct signal contribution. In the future, this will gain in sensitivity.

Combination [21] : A combination of the 8 TeV and 13 TeV data (from 2015 only) was also performed with all available channels. This did not yet include the HW_{lep}, HZ_{lep}, $V_{had}Z_{lep}$ channels, nor the $V_{had}W_{lep}$ channel with 2016 data. The combination tested a warped extra dimensional graviton model, a bulk graviton model, and a heavy vector triplet model. As an example, the HVT model excluded a massive W' boson below 2.1 TeV as shown in Fig. 3.

4. Conclusion

In conclusion, the searches for dibosons is a very mature field at the LHC. CMS has a very well-developed program, developing and deploying a plethora of cutting-edge techniques to handle this challenging final state. The excitement of the 750 GeV diphoton excess has subsided, and no heavy boson resonance confirmed the excess, but the territory for the diboson final state with heavy bosons is just now joining the forefront of the searches for new physics at the LHC. Now and in the years to come, these searches explore the mechanism for the hierarchy problem, with promising capability of discovering a new physical interaction to explain what we observe in nature.

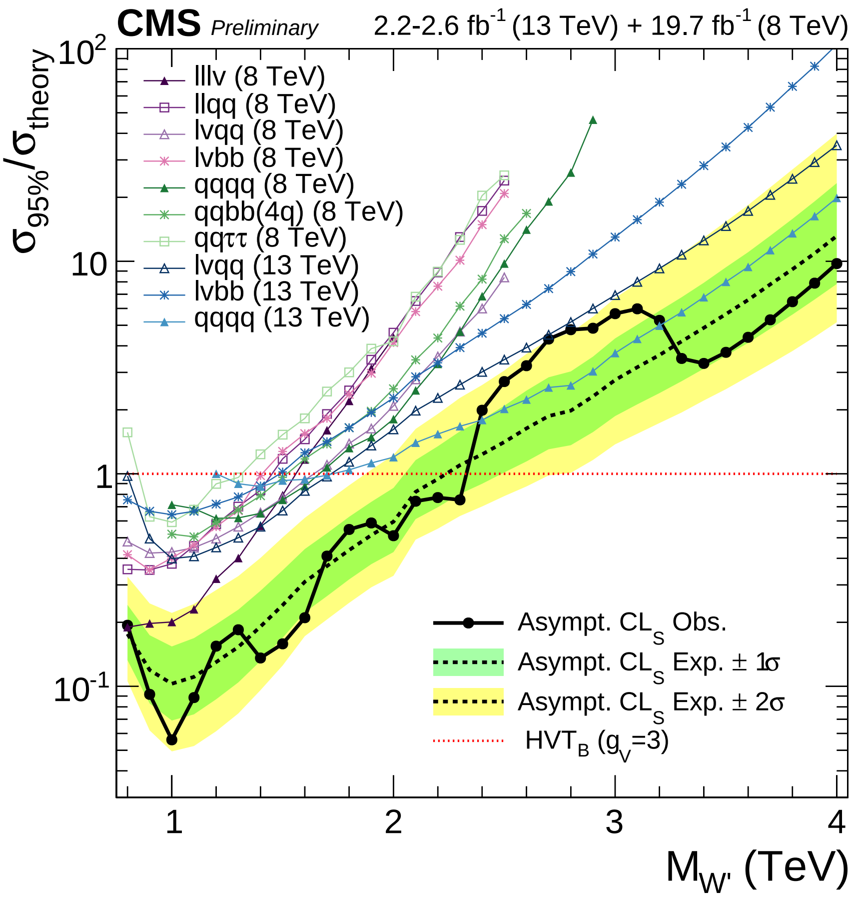

Figure 3: Oberved (black solid) and expected (black dashed) exclusion limits at 95% CL on $\sigma(pp \to W' \to WZ/WH$ as a function of the resonance mass by combining the 8 and 13 TeV diboson searches [21]. The curve corresponding to the cross sections predicted by the HVT model B is overlaid. The different colored lines correspond to the searches entering the combination.

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