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The Compact Muon Solenoid Experiment

Conference Report

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

18 September 2024 (v2, 25 September 2024)

Searches for New Resonances in CMS

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Abstract

The quest for new physics is a major aspect of the CMS experimental program. This includes a myriad of theoretical models involving resonances that can decay to massive bosons, photons, leptons or jets. This talk presents an overview of such analyses with an emphasis on new results and the novel techniques developed by the CMS collaboration to boost the search sensitivity. The searches are carried out with the full luminosity of the Run-II of the LHC in proton-proton collisions at $\sqrt{s}$ = 13 TeV with the CMS detector.

Presented at *ICHEP2024 42nd International Conference on High Energy Physics*

PROCEEDINGS OF SCIENCE

Searches for New Resonances in CMS

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The quest for new physics is a major aspect of the CMS experimental program. This includes a myriad of theoretical models involving resonances that can decay to massive bosons, photons, leptons or jets. This talk presents an overview of such analyses with an emphasis on new results and the novel techniques developed by the CMS collaboration to boost the search sensitivity. The searches are carried out with the full luminosity of the Run-II of the LHC in proton-proton collisions at $\sqrt{s}$ = 13 TeV with the CMS detector.

42nd International Conference on High Energy Physics (ICHEP2024)
18-24 July 2024
Prague, Czech Republic

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1. Introduction

The Standard Model (SM) may be the most successful theory of particle physics so far, but it is incomplete. A plethora of models involve new resonances beyond the SM that decay to massive bosons, photons, leptons or jets. The analyses presented in this report, that hunt for such resonances, use proton-proton collision data collected at $\sqrt{s}$ = 13 TeV by the CMS experiment [1] at the CERN LHC Run-II period, corresponding to an integrated luminosity of 138 fb^{-1}.

It is also worth mentioning that a rich program of CMS exotic analyses that are not mentioned here, including searches for low and high mass resonances, is part of a review paper on dark sector searches [2]. There, the impact of nearly 40 CMS analyses on the search of dark matter is reviewed, including new results, combination of existing ones and re-interpretations.

2. Search for a neutral gauge boson with non-universal fermion couplings in vector boson fusion processes

This is the first analysis at the LHC that is searching for a heavy neutral spin−1 gauge boson (Z') produced via vector boson fusion (VBF) processes. Scenarios in which the Z' boson has non−universal fermion couplings, favoring higher generation fermions, are considered, offering a new physics phase space not fully explored yet. The Z' boson in this analysis can decay to either a pair of τ leptons or a pair of W bosons, leading to four different final states; $\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$ and $e\mu$.

The analysis performs a bump hunt in the invariant mass of the final state leptons and missing energy ($m(\ell_1, \ell_2, p_T^{miss})$), and sets mass exclusion limits on the Z' mass as a function of the branching fraction to $\tau\tau$ and WW, depending on the Z' coupling to SM weak bosons (κ_V), as can be seen in Fig. 1. The Z' coupling to first and second generation fermions (g_ℓ) is set to 0 or 1, thus examining both non−universal and universal fermion coupling scenarios respectively.

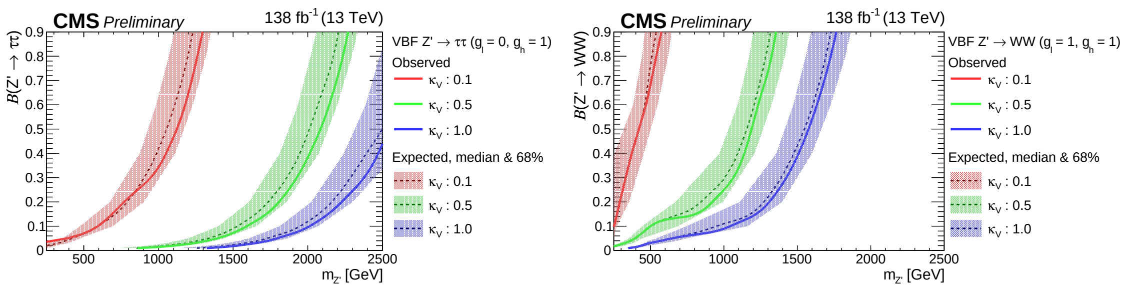

Figure 1: Combined 95% CL upper limits on Z' mass as a function of Z' branching fraction to $\tau^+\tau^-$ for the $g_\ell = 0$ scenario (left) and to W^+W^- for the $g_\ell = 1$ scenario (right) [3].

3. Search for heavy neutral resonances decaying to τ lepton pairs

This analysis is also searching for a Z' boson, with a different production mode, as s−channel annihilation of quark−antiquark pairs is considered. The Z' boson consequently decays to a pair of τ leptons, leading to 3 main channels in which this analysis is sensitive to, depending on the τ decays; $\tau_h\tau_h$, $\tau_e\tau_h$ and $\tau_\mu\tau_h$. The analysis is both orthogonal and complementary to the one presented in the preceding chapter, as events from VBF processes are rejected.

Given that in the considered topology the τ leptons of the Z' decay are produced back–to–back, an estimate of the Z' candidate mass is reconstructed ($m_{\text{rec}}(Z')$), making use of the transverse momentum imbalance between the visible components of the τ decays. The $m_{\text{rec}}(Z')$ distribution is then used as the fit discriminant to determine the likelihood of observing signal in the presence of the predicted background rate.

The analysis sets upper limits at 95% confidence level (CL) on the production cross section times branching fraction as a function of the Z' mass, as seen in Fig. 2. Mass exclusion limits are also derived for scenarios where the branching fraction is 1%, 3.37% (Sequential Standard Model scenario) and 10%, and found to be the most stringent to date for $Z' \to \tau^+\tau^-$.

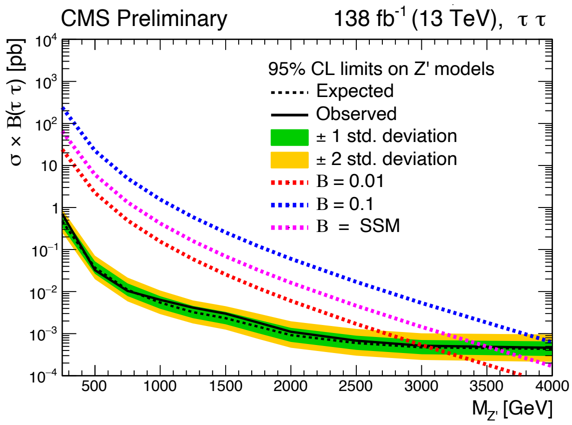

Figure 2: Upper limits at the 95% CL on the production cross section times $Z' \to \tau^+\tau^-$ branching fraction. The red, pink, and blue dashed lines represent the theoretical predictions for values of $B(Z' \to \tau^+\tau^-) = 1$, 3.37, and 10%, respectively [4].

4. Search for lepton flavour universality violation via production of a new neutral gauge boson decaying to two muons with one or two b–jets

This analysis focuses on a scenario with non–democratic flavour production via bottom quark (g_b) and bottom–strange quark ($g_b\delta_{bs}$) couplings of a hypothetical spin–1 narrow resonance Z' decaying into a dimuon pair only, as decays to electrons and taus are forbidden. This search is sensitive to resonance masses between 125 and 350 GeV, thus extending a previous CMS result on higher mass dimuon resonances above 350 GeV [5].

The experimental signature is a dimuon pair associated with one b–jet ($SR_b^{\mu\mu}$) or two jets where at least one is a b–jet ($SR_{b+j/b}^{\mu\mu}$). The dilepton distribution for the former signal region can be found in Fig. 3. The background estimation relies entirely on data, utilizing the ABCD method to construct control regions with dielectron and non b–jet final states, which are fitted to smoothen the prediction. Mass dependent selections are also deployed in order to boost the sensitivity.

Model independent limits, seen for $SR_b^{\mu\mu}$ in Fig. 3, are set at 95% CL via a simultaneous maximum likelihood fit across data–taking years, since no significant excess was observed. The limits between 125 and 200 GeV are the only ones available in Run-II, while between 200 and 350 GeV are the most stringent for this set of production modes.

5. Search for low mass vector and scalar resonances decaying into quark–antiquark pairs

This analysis is searching for narrow, boosted dijet resonances in the mass range of 50 to 300 GeV, that are associated with large initial state radiation (ISR). The benchmark models that are considered are a spin–1, vector boson, Z', that couples equally to all quark flavors with a coupling

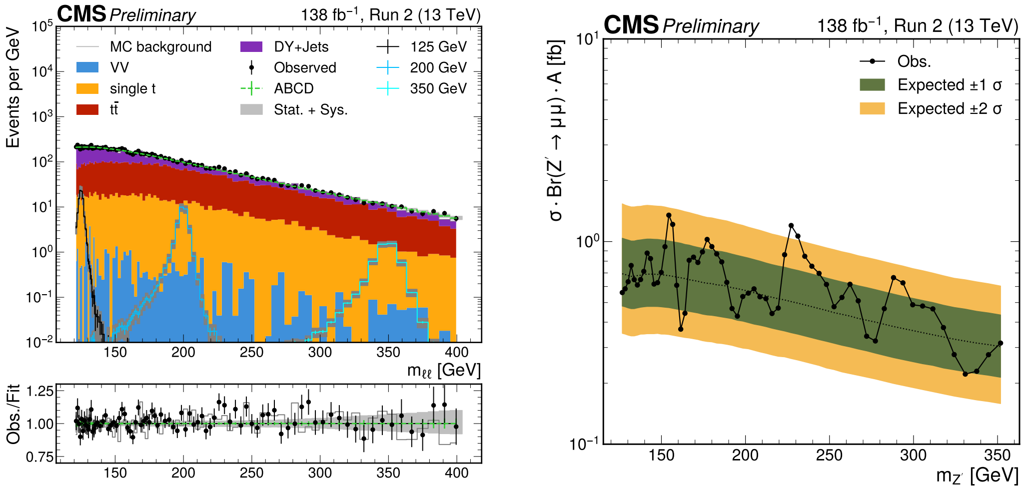

Figure 3: Left: Distributions of $m_{\ell\ell}$ in the $SR_b^{\mu\mu}$ signal region. Right: Limits at the 95% CL on acceptance times cross section times branching fraction to dimuon decays, for the $SR_b^{\mu\mu}$ signal region [6].

constant g_q, and a spin−0 scalar boson ϕ (or pseudo−scalar A) with quark couplings equal to the SM Yukawa couplings times a flavor−universal scaling factor $g_{q\phi}$ (or g_{qA}). In the latter model, the scalar resonance decays dominantly to bottom quark−antiquark pairs ($b\bar{b}$).

Due to the large ISR, such dijet resonances are produced with large transverse momentum ($p_T > 500$ GeV) and are reconstructed as a single large−radius jet with a two−pronged substructure. The ParticleNET algorithm [7], which is the leading graph−based jet tagger in CMS, not only discriminates this two−pronged substructure from the common QCD background, but also categorizes the events into two separate signal regions; one targeting light quark (u, d, s, c) decays (low−p_{bvl} SR) and one targeting heavy quark (b) decays (high−p_{bvl} SR).

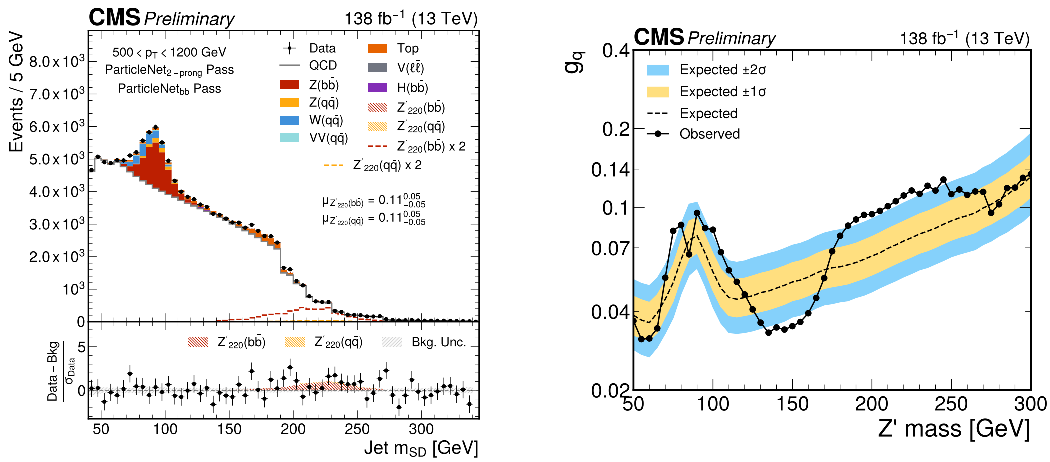

Figure 4: Left: The jet m_{SD} distribution in the high-p_{bvl} signal region, fitted with a signal plus background hypothesis corresponding to a Z' boson with a mass of 220 GeV. Right: Upper limits at 95% CL on the coupling g_q between the Z' boson and quarks [8].

The jet soft−drop mass (m_{SD}), shown in Fig. 4 for the high−p_{bvl} SR, is the main analysis observable and is fitted simultaneously across 5 p_T bins, data−taking years and the two quark flavor categories. Limits are set on the couplings of new vector and scalar resonances to quarks, as seen in Fig. 4 for Z', since no significant deviations from SM were found. Due to the luminosity scaling, integration of ParticleNET and the simultaneous sensitivity to light and heavy decays, these limits provide a large improvement compared to previous CMS results [9, 10].

6. Search for resonant production of paired dijet resonances

This analysis is searching for the pair production of identical mass particles, X, through a new intermediate heavier particle, Y. Each of the particles X decays to two jets, resulting in a four−jet final state. In the benchmark model that is utilized [12], a massive diquark S_{uu} decays to a pair of vector−like quarks χ, which in turn decay to a pair of up quark and gluon.

This signature probes resonant production in the four-jet and dijet mass distributions. As can been seen in the two dimensional distribution of these variables in Fig. 5, the CMS experiment has recorded two high mass events with a four−jet mass of ∼ 8 TeV, that are entirely isolated from the rest of the QCD multijet events and are nicely described by a possible new−physics signal; a diquark decaying to vector−like quarks with a four−jet mass of 8.4 TeV and a dijet mass of 2.1 TeV. The three dimensional display of these candidate events can be seen in Fig. 6.

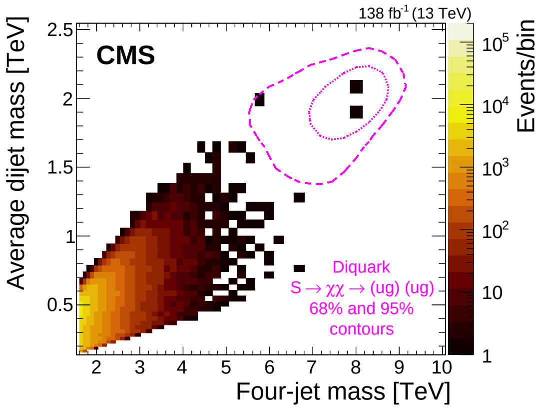

Figure 5: Observed number of events (color scale) within bins of the four-jet mass and the average mass of the two dijets, and the probability contours (magenta curves) of a signal simulation with diquark mass of 8.4 TeV and vector-like quark mass of 2.1 TeV [11].

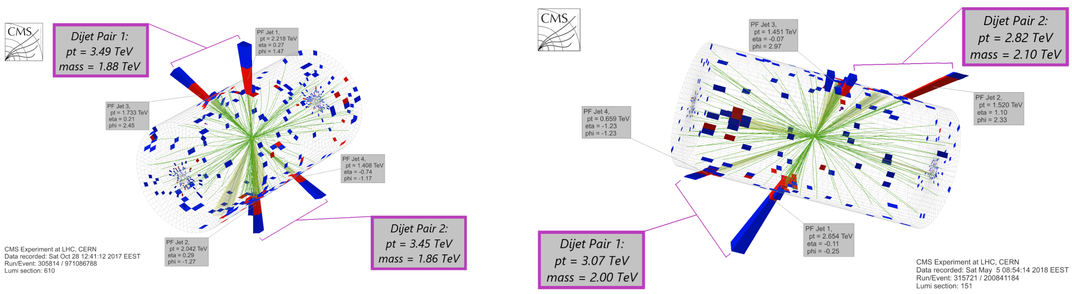

Figure 6: 3D displays of the events with the highest four-jet mass of 8.0 (left) and 7.9 (right) TeV [11].

The analysis strategy involves simultaneous fits to the four−jet mass distribution, in bins of the average dijet mass over the four−jet mass, with multiple parametric functions, using the discrete profiling method [13]. The probability of the two candidate events originating from SM processes is small, yielding a local (global) significance of 3.9σ (1.6σ). This very interesting excess is currently being followed up with Run-III data in order to ascertain whether these events are statistical fluctuations of the SM expectation, or the first signs of a new discovery.

7. Summary

The main aspects of selected analyses that make use of the full Run-II dataset collected with the CMS detector at the CERN LHC are discussed. These searches are actively probing previously unexplored regions, new final states and production modes, as well as improve the sensitivity over previous results or report interesting deviations from the SM. With the increased center of mass energy and luminosity of Run-III and HL−LHC, together with more advanced techniques and methods, there is growing expectation of fully exploiting the discovery potential.

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