Abstract. New heavy resonances are predicted by many extensions of the standard model of particle physics. Recent results for high mass resonance searches with the Compact Muon Solenoid detector, in the diphoton, dilepton, dijet and $t\bar{t}$ channels, are discussed. Limits for numerous benchmark models are presented.

1 Introduction

We present recent results for high mass resonance searches with the Compact Muon Solenoid (CMS) detector. The searches are conducted in a model independent manner, looking for excesses in the diphoton, dilepton, dijet, and $t\bar{t}$ invariant mass spectra. As no excesses above standard model (SM) expectations are observed, limits are computed, probing a variety of benchmark models, such as those predicting Randall-Sundrum (RS) gravitons [1], extra heavy gauge bosons ($Z'$, $W'$) [2], and other exotic phenomena.

2 The CMS Detector

The central feature of the CMS apparatus is a superconducting solenoid, of 6m internal diameter, providing a field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL) and the brass and scintillator hadron calorimeter (HCAL). Muons are measured in gas-ionization detectors embedded in the steel return yoke. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry. A more detailed description can be found in Ref. [3].

3 Diphoton Resonances

Kaluza-Klein (KK) gravitons predicted by RS warped extra dimensions may manifest themselves as high mass resonances in the diphoton invariant mass spectrum. The diphoton channel has the advantage that the branching ratio for spin-2 gravitons is twice that to leptons. Two isolated photons are selected with $E_T > 70$ GeV and $|\eta| < 1.44$. The resulting diphoton invariant mass distribution with $2.2$ fb$^{-1}$ of data is shown in Fig. 1. The expected background arises from irreducible SM diphoton production is estimated using simulation, scaled by a next-to-leading order mass dependent $K$ factor. Instrumental backgrounds, arising from $\gamma$+jet and dijet processes, in which the jets are misidentified as photons, are estimated using a data-driven fake rate method. Observing no excess in the diphoton invariant mass distribution above SM expectations, upper limits are set on the production cross section for RS gravitons, using the CL$_S$ technique [5,6]. The limits on the cross section are translated into lower limits on the model parameters (Fig. 2), where $M_1$ is the mass of the first graviton excitation, and $\tilde{k}$ is a dimensionless parameter which quantifies the strength of the graviton coupling to SM fields. We exclude at the 95% confidence level (CL) resonant graviton production in the RS1 model with values of $M_1 < 0.86 - 1.84$ TeV, depending on $\tilde{k}$.

4 Dilepton Resonances

High mass dilepton resonances may arise in models with extra heavy gauge bosons, as well as in the RS warped extra dimension scenario. In this search, two isolated leptons with $p_T > 35$ GeV (40 GeV for endcap electrons) are required, in addition to further quality criteria. In the case of dimuons, opposite-sign is required. The resulting dielec-
5 Dijet Resonances

Dijets can be used to probe a variety of beyond-the-SM signatures, including string resonances \( \Psi \), \( F_6 \) diquarks \( \Psi ' \), excited quarks \( \Omega \), axigluons \( \Omega ' \), colorons \( \Omega '' \), \( W' \) and \( Z' \), and RS gravitons. We perform a general model-independent shape-based search for three types of resonances (q\( q \), q\( g \), gg), the differences arising from final state radiation (FSR).

We require the two leading jets have \(|\eta| < 2.5 \) and \( |\Delta \eta| < 1.3 \) and dijet invariant mass \( > 838 \) GeV. To recover radiation lost through FSR and to improve the dijet mass resolution, we combine particle flow jets with the anti-\( k_T \) algorithm \( (R = 0.5) \) into “wide jets”. QCD multijets comprise the main background, following a smoothly falling dijet mass distribution predicted by the SM. Fig. 5 shows the dijet invariant mass spectrum with \( 1.0 \) fb\(^{-1} \), where the expected background from QCD multijets is described with a functional fit \([14]\). The systematic uncertainties from the 

![Graph](image-url)
The 95% CL upper limits on cross section \( \sigma(pp \to Z' \to t\bar{t}) \) for narrow resonances \( Z' \), as a function of invariant mass. The topcolor \( Z' \) cross section is from [17], updated to \( \sqrt{s} = 7 \) TeV via private communication.

### 6 \( t\bar{t} \) Resonances: Semileptonic Decay

New bosons with enhanced coupling to the top quark appear in many SM extensions, such as those predicting axigluons and KK gluons [15]. We present a search for heavy \( t\bar{t} \) resonances in the semileptonic \((qqb)(\nu\bar{\nu})\) final state, focusing on highly boosted top pairs with decay products narrowly collimated along the direction of the top. Backgrounds arise from SM \( t\bar{t} \), \( W/Z+jets \), single top, and QCD multijets.

For high mass \( t\bar{t} \), the decay products of the hadronic-decaying top can have small opening angles in the detector frame. Thus, instead of requiring four jets, we require two particle flow jets with \( p_T > 50 \) GeV and \( |\eta|<2.4 \), with the leading jet \( p_T > 250 \) GeV; jets are reconstructed with the anti-\( k_T \) algorithm (\( R = 0.5 \)). The high top \( p_T \) also results in low \( dR = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \) between the \( t \) and \( \bar{t} \), making it difficult to require the muon be well-isolated. To suppress QCD multijet backgrounds, we thus apply a two-dimensional requirement, \( dR > 0.5 \text{ or } p_{T,\text{rel}} > 25 \) GeV, where \( p_{T,\text{rel}} \) is the magnitude of the \( p_T \) component orthogonal to the jet axis. In addition, muons are required to have \( p_T > 35 \) GeV and \( |\eta|<2.1 \). Events with additional muons or electrons (from \( \ell \) and \( Z' \) decays) are vetoed. Lastly, \( H_{T,\text{lep}} \), the scalar sum of the jet and missing transverse energy (MET), is required to be \( > 150 \) GeV.

Fig. 7 shows the resulting 95% CL upper limits on the cross section for a benchmark topcolor \( Z' \) [16], computing using a Bayesian method. The largest uncertainties come from the jet energy resolution (10–20%) and the jet energy scale (2–3%). With 1.1 fb\(^{-1}\), we exclude a topcolor \( Z' \) of width 3% in the mass regions 805 \( < m_{Z'} < 935 \) GeV and 960 \( < m_{Z'} < 1060 \) GeV.

### 7 \( t\bar{t} \) Resonances: All-Hadronic Decay

The motivations for studying the fully hadronic decay of \( t\bar{t} \) are similar to those for the semileptonic search. Likewise, the all-hadronic search exploits the highly boosted nature of the top quarks from high mass resonances. Moreover,
the all-hadronic decay benefits from a higher branching ratio than the semileptonic decay. In this analysis, each event is divided into hemispheres, such that each hemisphere contains the final products of each top. Then, the top decays are classified into categories, depending on how boosted the top is: (1) “high boost” tops are those in which all three jets are merged into one top jet and (2) “moderate boost” tops are those in which only two out of three of the jets are merged. We conduct the search in two categories: “type 1+1”, which have two highly boosted top jets, or “type 1+2”, which are three-jet events. Jets are reconstructed using particle flow and Cambridge-Aachen clustering algorithms. The dominant background comes from QCD multijets, which is estimated with a data-driven top-tagging mistag rate. The small continuum $t\bar{t}$ contribution is estimated with simulation. The limits are evaluated with a counting experiment, using a Bayesian procedure. Fig. 8 depicts the 95% CL upper limits on the product of the cross section of $Z'$ and the branching ratio for its decay into $t\bar{t}$ pairs [18]. With 886 pb$^{-1}$, we exclude the KK gluon masses between 1.0 – 1.5 TeV.

8 Conclusions

We present searches for high mass resonances with the CMS detector in the diphoton, dilepton, dijet, and $t\bar{t}$ channels. Observing no excess above standard model predictions, we set limits on a variety of benchmark models, including those predicting gravitons and $Z'$. 

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References

1. L. Randall and R. Sundrum, “An alternative to compactification,” Phys. Rev. Lett. 83 (1999) 4690.
2. E. Eichten, I. Hinckhiffe, K. D. Lane and C. Quigg, “Super Collider Physics,” Rev. Mod. Phys. 56 (1984) 579.
3. CMS Collaboration, “The CMS experiment at the CERN LHC,” JINST 3 (2008) S08004.
4. CMS Collaboration, “Search for signatures of extra dimensions in the diphoton mass spectrum at the Large Hadron Collider,” [arXiv:1112.0688 [hep-ex]]
5. A. L. Read, “Presentation of search results: The CL(s) technique,” J. Phys. G 28, 2693 (2002).
6. T. Junk, “Confidence Level Computation for Combining Searches with Small Statistics,” Nucl. Instrum. Meth. A 343, 435 (1999).
7. CMS Collaboration, “Search for Resonances in the Dilepton Mass Distribution in pp Collisions at $\sqrt{s} = 7$ TeV,” CDS Record 1369192 (2011).
8. L. A. Anchordoqui et al., “Dijet signals for low mass stringy LHC,” Phys. Rev. Lett. 101 (2008) 241803.
9. J. L. Hewett and T. G. Rizzo, “Low-Energy Phenomenology of Superstring Inspired E(6) Models,” Phys. Rept. 183 (1989) 193.
10. U. Baur, I. Hinckhiffe and D. Zeppenfeld, “Excited Quark Production At Hadron Colliders,” Int. J. Mod. Phys. A 2 (1987) 1285.
11. P. H. Frampton and S. L. Glashow, “Chiral Color: An Alternative to the Standard Model,” Phys. Lett. B 190 (1987) 157.
12. E. H. Simmons, “Coloron phenomenology,” Phys. Rev. D 55 (1997) 1678.
13. CMS Collaboration, “Commissioning of the Particle-Flow reconstruction in Minimum-Bias and Jet Events from pp Collisions at 7 TeV,” CDS Record 1279341 (2010).
14. CMS Collaboration, “Search for Resonances in the Dijet Mass Spectrum from 7 TeV pp Collisions at CMS,” Phys. Lett. B 704 (2011) 123.
15. K. Agashe et al., “LHC signals from warped extra dimensions,” Phys. Rev. D 77, 015003 (2008).
16. CMS Collaboration, “Search for heavy narrow resonances decaying to ttbar in the muon+jets channel,” CDS Record 1376673 (2011).
17. R. M. Harris, C. T. Hill and S. J. Parke, “Cross section for topcolor Z’(t) decaying to $t\bar{t}$,” [arXiv:hep-ph/9911288]
18. CMS Collaboration, “Search for BSM $t\bar{t}$ Production in the Boosted All-Hadronic Final State,” CDS Record 1370237 (2011).