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Beyond the Standard Model Searches with CMS

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Abstract

The results of several searches for physics beyond the Standard Model are presented here, using up to 5 fb⁻¹ of proton-proton collisions at a center-of-mass energy of 7 TeV recorded by the CMS detector. Among others, the latest searches for the production of heavy gauge bosons, heavy quarks, leptoquarks, heavy stable charged particles, and signatures of extra dimension and black holes are discussed.

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Beyond the Standard Model Searches at CMS

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Abstract. This paper describes recent searches for signatures of physics beyond the Standard Model (SM) performed by the CMS collaboration at the LHC using 5 fb^{-1} of 7 TeV proton-proton collisions, including signatures of the production of new heavy particles (Z' , W' , and Heavy Majorana neutrinos, etc.), extra dimensions, quarks/lepton compositeness, and mini-black holes.

Keywords: LHC, CMS, Standard Model, Supersymmetry, Leptoquarks, Exotic Mesons

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SEARCHES FOR NEW HEAVY PARTICLES

Several searches for heavy stable charged particles (HSCPs), leptoquarks, heavy Majorana neutrinos, 4^{th} generation heavy quarks, and heavy gauge bosons (Z' , W') have been undertaken by CMS [1] on 7 TeV pp collisions and are summarized in this report.

Heavy stable charged particles (HSCP) are predicted by SUSY models with pair produced gluinos or scalar top quark (with stable R-hadrons at hadronization), GMSB models with scalar τ 's, and pair-produced hyper-mesons from a vector-like confinement model. HSCPs are characterized by a long lifetime $1/\beta$, large energy loss (dE/dx), and high transverse momentum (p_T). The search uses $\sim 5 \text{ fb}^{-1}$ and two strategies: tracker-only, identified by large p_T and dE/dx , and tracker+TOF (time-of-flight), identified by large p_T and dE/dx , and large $1/\beta$ (computed from muon timing information). 95% confidence level (CL) limits are set for different scenarios. Among others, pair-produced gluinos hadronizing to R-gluonballs with 0.1 (0.5) probability are excluded for masses $< 1098(1046) \text{ GeV}$ (tracker-only) and $< 1082(1030) \text{ GeV}$ (tracker+TOF), as well as stop masses $< 714 \text{ GeV}$ (tracker-only) and $< 737 \text{ GeV}$ (tracker+TOF), and GMSB and pair produced scalar τ masses $< 314 \text{ GeV}$ and $< 223 \text{ GeV}$ (tracker+TOF).

Leptoquarks (LQ) are predicted by GUTs, technicolor, and composite models. LQs carry both baryon and lepton numbers. Pair production and decay are characterized by the mass M_{LQ} and the branching ratio $\beta \rightarrow \ell^+ q$. The analysis strategy for 1^{st} and 2^{nd} generation searches requires high p_T objects (≥ 2 isolated leptons and ≥ 2 jets, or one isolated lepton, ≥ 2 jets and E_T^{miss}). Optimized thresholds are placed on $M(\ell\ell)$, $M_T(\ell\nu)$, $M(\ell j)$, and the transverse scalar activity S_T . The analysis strategy for 3^{d} generation LQ searches uses the so-called "Razor" variables developed to search for pairs of heavy particles. The most recent LQ results are the search for pair-production of scalar 2^{nd} generation LQs in the $\mu\mu jj$ and $\mu\nu jj$ channels with 2 fb^{-1} , and 3^{d} generation LQs in the $\nu\bar{\nu} b\bar{b}$ channel with 1.8 fb^{-1} . At 95% CL pair-produced 2^{nd} generation scalar LQs with $M_{LQ} < 632(523) \text{ GeV}$ are excluded for $\beta = 1(0.5)$ [2], and pair-produced 3^{d} generation scalar LQs with $M_{LQ} < 350 \text{ GeV}$ are excluded for $\beta = 0$ [3].

FIGURE 1. The 95% CL exclusion region for the muon channel in (M_N, M_{W_R}) , assuming equal coupling in the left and right sectors and the $\mu\nu$ channel as the only available leptonic decay channel

Right-handed W_R bosons and heavy neutrinos N arise in Left-Right Symmetric extensions of the SM. Due to the production and decay chain: $pp \rightarrow W_R \rightarrow N\ell \rightarrow W_R^* \ell\ell \rightarrow \ell\ell jj$, the final state signature is characterized by mass resonances both in $\ell\ell jj$ and $\ell\nu jj$. This analysis [4] (5 fb^{-1}) uses final states with two muons and two jets, leading muon $p_T > 60 \text{ GeV}$, $M(\mu\mu) > 200 \text{ GeV}$, and $M(\mu\mu jj) > 600 \text{ GeV}$. At 95% CL, a region in the (M_N, M_{W_R}) space that extends to $M_{W_R} = 2.5 \text{ TeV}$ is excluded (as shown in Fig. 1).

CMS searches for pair produced heavy bottom-like in 5 fb^{-1} . Assuming $m_{b'} > m_t + m_W$, the final state contains two b -quarks and four W 's. Two same-sign leptons or three leptons (among which two of opposite-sign) are required, ≥ 1 b -tags, and $S_T = \Sigma p_T(\text{jets}) + \Sigma p_T(\ell) + E_T^{\text{miss}} > 500 \text{ GeV}$. At 95% CL, $m_{b'} < 611 \text{ GeV}$ are excluded [5].

Dilepton and/or dijet resonances are predicted by Z' models, gravitons, extra-dimensions, technicolor, axigluons, excited quarks models etc. Several searches for $Z' \rightarrow \ell\ell$ (e, μ , or τ 's) and for $Z' \rightarrow qq$ have been performed by CMS with 5 fb^{-1} . One notable example described here is the search for $Z' \rightarrow t\bar{t}$ in the all-jets final state. This analysis focuses on high masses ($> 1 \text{ TeV}$) where the decay products are highly boosted. The jet reconstruction makes use of novel jets substructure algorithms. The jets p_T , mass, and substructure scale are selected to be consistent with top and W merged jet topologies. 95% CL limits in the 1-2 TeV range are derived [6] on Topcolor Z' (small/large width), and Kaludza-Klein gluons. The analysis also yields constraints on enhancements to the SM $t\bar{t}$ cross-section for $m_{t\bar{t}} > 1 \text{ TeV}$. Heavy W' are also predicted by many extensions to the SM, with left-handed or right-handed couplings to fermions, or both. Couplings to third generation are enhanced in many models. A recent search for $W' \rightarrow t\bar{d}$ with 5 fb^{-1} looks for W' produced in association with a top quark. The final state contains a lepton (e or μ) plus jets. The hadronic activity is required to be large, $> 700 \text{ GeV}$, to suppress SM $t\bar{t}$ production. W' masses below 840 GeV are excluded at 95% CL [7]. Two other recent W' searches look at diboson final states. A search for $W' \text{ (or techni-}\rho\text{)} \rightarrow WZ$ (4.7 fb^{-1}) considers Z and W leptonic decays with a final state

of three high p_T leptons (e or μ) + E_T^{miss} (with two opposite sign same-flavor leptons consistent with the Z , and large H_T). 95% CL exclusion limits for a SSM $m_{W'}$ below 1141 GeV, or a ρ_{TC} between 180-935 GeV are set [8]. A second W' (or techni- ρ) $\rightarrow VZ$ search selects leptonic Z decays and hadronic V decays. The analysis (5 fb^{-1}) requires two high p_T same flavor, opposite sign leptons (e or μ), two overlapping jets (mono-jet) from $W' \rightarrow qq$ decay and mono-jet masses in the 65-120 GeV range. SSM W' masses between 700-929 GeV are excluded [9].

SIGNATURES OF EXTRA DIMENSIONS

Extra spatial dimensions are proposed as a solution to the hierarchy problem. Searches for Arkani-Hamed-Dimopolous-Dvali (ADD) or Randall-Sundrum (RS) extra dimensions look for enhanced $\ell\ell$, $\gamma\gamma$ production via virtual graviton exchange, or gravitons produced with a jet or a gluon.

The invariant $\gamma\gamma$ mass spectrum is used [10] to search for enhanced $\gamma\gamma$ production via virtual graviton exchange. The analysis (2.2 fb^{-1}) requires two high p_T photons, and focuses on the region $m_{\gamma\gamma} > 140 \text{ GeV}$. 95%CL limits on the RS1 model resonant graviton mass M_1 are set in the 0.86-1.84 TeV range depending on the value of the associated coupling parameter. Limits are also derived on M_S , the effective Planck scale in ADD models. A separate search looks at the ee and $\mu\mu$ invariant mass spectra (2.1 - 2.3 fb^{-1}) [11]. The analysis requires central high p_T , isolated electrons or muons. 95% CL limits on the value of M_S in ADD models are extracted from the combination of $ee + \mu\mu$, but it is the combination with the $\gamma\gamma$ search that yields the most stringent limits to date, in the 2.6-4.1 TeV range depending on the number of extra dimensions.

The RS graviton G^* , a spin-2 resonance, is the first resonance of the Kaludza-Klein modes. There are two parameters to the model: the graviton mass (M_G) and the ratio of the 5-D curvature of the warped geometry to the reduced Planck mass ($k/\bar{M}_{Pl}$). The analysis described in [12] (4.7 fb^{-1}) has the G^* decaying to $ZZ \rightarrow \nu\bar{\nu}q\bar{q}$ and a topology consisting of two very boosted Z 's decaying to two jets and neutrinos: one collimated qq jet ($m_{jet} > 70 \text{ GeV}$), large $E_T^{miss} (> 300 \text{ GeV})$, and $M_T^G > 900 \text{ GeV}$ are required. Cross-section 95%CL upper limits are in the range 0.047–0.021 pb for M_G between 1000 and 1500 GeV. A second search (5 fb^{-1}) focuses on the dilepton plus jets final state [13]. It requires di- e or di- μ consistent with a Z decay and discriminates against backgrounds using a jet-flavor analysis (b -tag bins and gluon/light quark separation) and spin information (a discriminant based on angular spin correlation of the decay products). 95% CL limits exclude RS1 Graviton masses $M_1 < 720 \text{ GeV}$ and $760 < M_1 < 850 \text{ GeV}$ ($< 945 \text{ GeV}$) for $k/\bar{M}_{Pl} = 0.05$ (0.10). These are the most stringent limits for the $G^* \rightarrow ZZ$ process in the range below 750 GeV.

A search for Dark Matter or for Graviton production in association with a γ is performed with 5 fb^{-1} [14] to study both Dark Matter processes ($qq \rightarrow \chi\chi\gamma \rightarrow \gamma + E_T^{miss}$) and ADD process ($qq \rightarrow G\gamma \rightarrow \gamma + E_T^{miss}$). The analysis uses central, isolated high p_T photons ($> 145 \text{ GeV}$) and large $E_T^{miss} (> 130 \text{ GeV})$. 95% CL limits are placed on the modified Planck scale, M_D , in ADD models between 1.65-1.71 TeV (for $n = 3$ -6), and 90% CL upper limits are derived for spin-(in)dependent χ -nucleon scattering.

FIGURE 2. Comparison of dimuon mass spectra for data and MC with the LLIM model predictions for $\Lambda = 4$ TeV and 5 TeV superimposed.

FIGURE 3. Data and simulation comparison of dimuon $1/p_T$ (final selection and $p_T(\mu\mu) > 125$ GeV). A hypothetical signal produced via contact interaction with $M_{q^*} = 1.5$ TeV is shown in red.

QUARK AND LEPTON COMPOSITENESS

The di-muon invariant mass spectrum shown in Fig. 2 was recently analyzed (5.3 fb^{-1}) [15] in the context of a left-left isoscalar contact interaction model of quark and muon compositeness, with an energy scale parameter Λ . 95% CL lower limits on the compositeness scale Λ were derived: 9.5 TeV for destructive interference and 13.0 TeV for constructive interference. These are the most stringent limits to date. Another search for quark compositeness through the anomalous production of highly boosted Z 's ($q^* \rightarrow qZ$) is reported in [16]. This 5 fb^{-1} analysis requires two isolated high p_T muons consistent with a Z decay and looks for distortions in $1/p_T(\mu\mu)$ spectrum (shown in Fig. 3) from the production and decay of a heavy new particle. 95% CL limits on excited quark (q^*) production with electroweak decay are extracted assuming a compositeness scale $\Lambda = M_{q^*}$: $M_{q^*} < 1.94(2.14)$ TeV via gauge boson (four-fermions) interactions and $M_{q^*} < 2.18$ TeV for fully suppressed strong interactions.

SEARCH FOR MICROSCOPIC BLACK HOLES

Mini black holes are a signature of TeV scale gravity: they are characterized by a democratic decay via Hawking radiation into high multiplicity, isotropic, energetic, final states of jets, electrons, photons, and muons. The CMS analysis [17] (4.7 fb^{-1}) looks for deviations in the total transverse energy distribution, in bins of N objects, and finds none. Model independent upper cross-section limits are thus placed, as well as 95% CL limits on the mass of quantum black holes predicted by ADD models (3.8-5.2 TeV range), String balls (4.6-4.8 TeV), and semi-classical black holes (3.9-5.3 TeV).

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