EXOTICA SEARCHES AT THE CMS EXPERIMENT

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This paper presents the results of searches for various new physics phenomena in proton-proton collisions at $\sqrt{s} = 7$ TeV delivered by the LHC and collected with the CMS detector in 2010. While the sensitivity of these early searches varies, in many cases they set the most stringent limits on these new physics phenomena. These results demonstrate good understanding of the detector and backgrounds in a variety of channels, which is a fundamental component of successful searches in view of the much larger data sample expected to be delivered by LHC in 2011 and beyond.

1 Introduction

This paper presents the results of searches for various new physics phenomena beyond the standard model (SM) [a] in proton-proton collisions at $\sqrt{s} = 7$ TeV delivered by the LHC and collected with the Compact Muon Solenoid (CMS) [1] detector in 2010. For the majority of these searches the full dataset has been used, corresponding to an integrated luminosity of almost 40 pb^{-1}.

2 New Heavy Resonances

2.1 Dilepton and Diphoton Resonances

Many models of new physics beyond the SM predict the existence of narrow resonances, possibly at the TeV mass scale, that decay to a pair of charged leptons (such as Z' bosons) or to lepton and neutrino (such as W' bosons). Also the Randall-Sundrum (RS) model of extra dimensions foresees the existence of Kaluza–Klein graviton excitations ($\mathrm{G_{KK}}$) decaying to a pair of charged leptons or pair of photons. The CMS collaboration has searched for such narrow resonances in the invariant mass spectrum of dimuon/dielectron [2] and diphoton [3] final states, as well as in the transverse mass spectrum of electron+neutrino [4] and muon+neutrino [5] final states. The spectra are consistent with standard model expectations in both the bulk and the tails of the aforementioned distributions. Figure 1 shows the 95% confidence level (CL) upper limits on the cross section of $\mathrm{Z}'/\mathrm{G_{KK}}$ (W') production, obtained combining the dielectron (electron+neutrino) and dimuon (muon+neutrino) channels. A Z' (W') with SM-like coupling can be excluded below 1.14 (1.58) TeV. Model-independent lower limits on the Z' mass have also been reported in Ref. [2] as a function of the couplings of the Z' to fermions in the annihilation of charge 2/3 and charge

[a] Searches for Supersymmetry at CMS are not discussed in this paper. These results can be found in other proceedings of this conference.

-1/3 quarks. In the diphoton channel, limits are derived on the cross section for the production of RS gravitons, and hence on the parameters of the warped extra dimension model. For values of the coupling parameter ranging from 0.01 to 0.1, graviton masses below 371 to 945 GeV are excluded at the 95% CL.

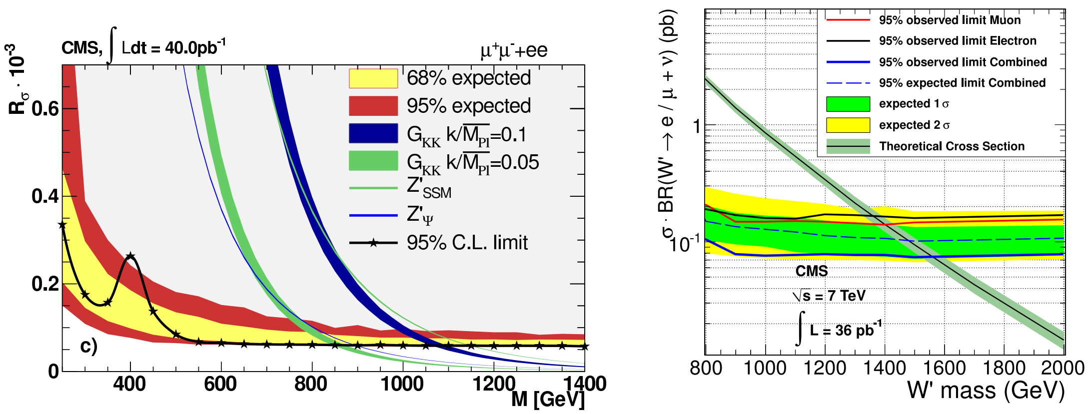

Figure 1: (Left) Upper limits as a function of resonance mass on the Z′ cross section relative to standard model Z boson production, obtained combining dielectron and dimuon final states. The distortion of the observed limits at ∼400 GeV is the result of a clustering of several dimuon and dielectron events around this mass. An excess of 1.1σ is quantified in the combined sample, after taking into account the "look-elsewhere" effect. (Right) Upper limits as a function of the resonance mass on the W′ cross section for the individual electron+neutrino and muon+neutrino channels, and their combination.

2.2 Leptoquarks

The standard model has an intriguing but ad hoc symmetry between quarks and leptons. In some theories beyond the SM, such as SU(5) gran unification, Pati–Salam SU(4), and others, the existence of a new symmetry relates the quarks and leptons in a fundamental way. These models predict the existence of new bosons, called leptoquarks. The leptoquark (LQ) is coloured, has fractional electric charge, and decays to a charged lepton and a quark with unknown branching fraction β, or a neutrino and a quark with branching fraction $(1-\beta)$. Constraints from experiments sensitive to flavour-changing neutral currents, lepton-family-number violation, and other rare processes favour LQs that couple to quarks and leptons within the same SM generation, for LQ masses accessible to current colliders. Searches for pair-production of first and second generation scalar LQs have been performed in the eejj [6], eνjj [7], and $\mu\mu$jj [8] channels. The dominant backgrounds for these searches arise from the SM production of Z/γ+jets, W+jets and $t\bar{t}$ events. The reconstructed variable S_T, defined below [b], has a large signal-to-background discrimination power, and it is used to select LQ candidate events. Figure 2 (left) shows the exclusion limits at 95% CL on the first generation leptoquark hypothesis in the β versus LQ mass plane for the eejj and eνjj channels, and their combination. First generation scalar LQ masses below 384 GeV (340 GeV) are excluded at 95% CL for $\beta = 1$ ($\beta = 0.5$). In the $\mu\mu$jj channel, a 95% CL lower limit on the second generation scalar LQ mass is set at 394 GeV assuming $\beta = 1$.

2.3 Dijet Searches

In the standard model, point like parton-parton scatterings in high energy proton-proton collisions can give rise to final states with energetic jets. At large momentum transfers, events

[b] In the eejj and $\mu\mu$jj channels, S_T is defined as the scalar sum of the transverse momenta of the two leading (in p_T) charged leptons and jets. In the eνjj channel, S_T is defined as the scalar sum of the transverse momentum of the electron, the missing transverse energy, and the two leading jets.

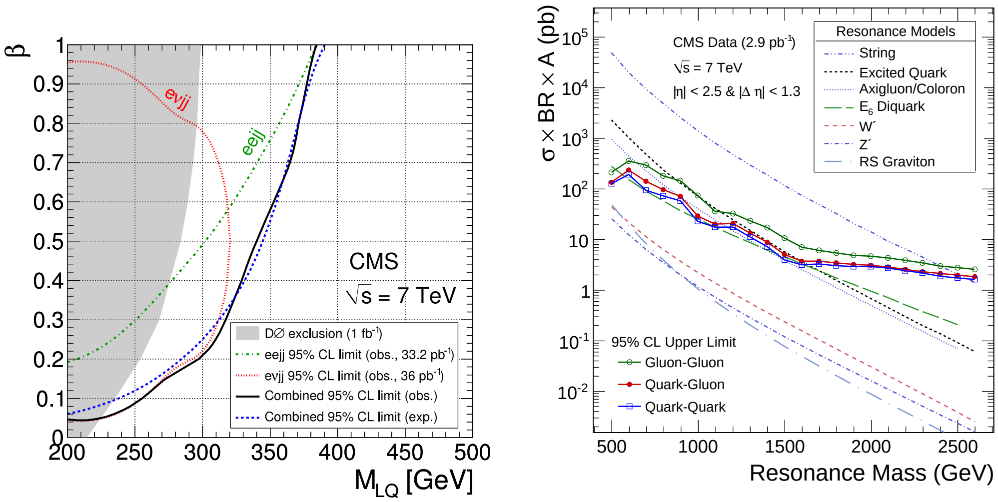

Figure 2: (Left) Exclusion limits at 95% CL on the first generation LQ hypothesis in the β versus LQ mass plane. The shaded region is excluded by the current D0 limits, which combine results of eejj, eνjj, and $\nu\nu$jj decay modes. (Right) 95% CL upper limits on signal cross section for dijet resonances of type gluon-gluon, quark-gluon, or quark-quark, versus dijet resonance mass, compared to theoretical predictions for various new physics models.

with at least two energetic jets (dijets) may be used to confront the predictions of perturbative Quantum Chromodynamics (QCD) and to search for signatures of new physics. The new physics could manifest itself via the direct production of a new massive particle that then decays into a dijet final state (quark-quark, quark-gluon, or gluon-gluon resonances), and/or the rate of dijet events could be enhanced through a new force that only manifests itself at very large CM energies (contact interactions). Complementary search strategies have been pursued by the CMS experiment in the dijet channel: search for narrow resonances in the dijet mass spectrum [9], search for narrow resonances and contact interactions using the dijet centrality ratio variable [10], and search for contact interactions using dijet angular distributions [11]. The first two analyses were performed with the early 3 pb^{-1} of proton-proton collisions at $\sqrt{s} = 7$ TeV, and they are now being updated with more data. Figure 2 (right) shows the 95% CL upper limits on signal cross section versus dijet resonance mass, compared to theoretical predictions for various new physics models. String resonances, with mass less than 2.50 TeV, excited quarks, with mass less than 1.58 TeV, and axigluons, colorons, and E_6 diquarks, in specific mass intervals, have been excluded at 95% CL. Using measurements of dijet angular distributions over a wide range of dijet invariant masses, a lower limit on the contact interaction scale for left-handed quarks of $\Lambda^+ = 5.6$ TeV ($\Lambda^- = 5.6$ TeV) for constructive (destructive) interference is obtained at the 95% CL.

2.4 Fourth Generation of Fermions and $\mathrm{t\bar{t}}$ *Resonances*

Recently, there has been renewed interest in extensions of the SM predicting a fourth generation of massive fermions. Theoretical studies have shown that indirect bounds on the Higgs boson mass can be relaxed, and an additional generation of quarks may possess enough intrinsic matter and anti-matter asymmetry to be relevant for the baryon asymmetry of the Universe. Driven by this motivation, a search for pair production of heavy bottom-like quarks (b$'$) in trileptons and same-sign dilepton final states [12], arising from the decay chain $\mathrm{b'\bar{b}'} \to \mathrm{tW^-\bar{t}W^+} \to \mathrm{bW^+W^-\bar{b}W^-W^+}$, has been performed at CMS. The total branching ratio for these channels is 7.3% and the very small expected SM background comes mainly from $\mathrm{t\bar{t}}$ events. No events are found in the signal region defined in the analysis, and the b$'$ mass range from 255 to 361 GeV has been excluded at the 95% CL.

The CMS experiment has also performed a model-independent search for new massive neutral bosons (such as Z′) decaying via a top-antitop quark pair [13]. The event reconstruction and selection is optimized for the production of top quarks close to rest, with well separated decay products. The analysis focuses on decay channels of the $\mathrm{t\bar{t}}$ system that include a single isolated electron or muon. No significant deviation from SM expectations is found in the $\mathrm{t\bar{t}}$ mass spectra obtained from eight independent data samples, categorized by lepton type, multiplicity of jets and number of b-tagged jets. Upper limits on the production cross section times branching fraction, $\sigma_{Z'} \times \mathrm{BR}(Z' \to \mathrm{t\bar{t}})$, of the order of 25, 7, and 4 pb^{-1} for invariant masses in the region $m_{Z'} = 0.5$, 1, and 1.5 TeV, respectively, are set. These results are competitive with the current limits from the Tevatron, particularly at high mass values.

3 Compositeness Models

A fundamental question in the standard model of particle physics is the source of the mass hierarchy of the quarks and leptons. A commonly proposed explanation for the three generations is a compositeness model in which the known leptons and quarks are bound states of either three fermions, or a fermion-boson pair. The underlying substructure of these new bound states implies a large spectrum of excited states. Novel strong contact interactions (CI) couple excited fermions (f^*) to ordinary quarks and leptons (f) and can be described with the effective lagrangian $\mathcal{L}_{\mathrm{CI}} \propto (\jmath^\mu \jmath_\mu)/\Lambda^2$, where Λ is the compositeness scale, and $\jmath_\mu$ is the fermion current.

3.1 Excited Leptons

A search for the associated production of a lepton (ℓ) and an oppositely charged excited lepton (ℓ^*) is performed [14]. The final state contains two leptons and a photon, $\ell\ell\gamma$, arising from the decay $\ell^* \to \ell\gamma$, where ℓ is either an electron or a muon. The SM backgrounds containing misidentified electrons or photons are estimated using data-driven methods. The maximum reconstructed invariant mass among the two possible lepton-photon combination, $\mathrm{M}_{\ell\gamma}^{\mathrm{max}}$, is used to discriminate between signal and SM backgrounds. No excess of events is found in the $\mathrm{M}_{\ell\gamma}^{\mathrm{max}}$ spectra above the SM expectation in the electron or muon channel. Figure 3 (left) shows the region excluded at 95% CL in the $\Lambda - \mathrm{M}_{\ell^*}$ parameter space for the $\mu\mu\gamma$ channel, where M_{ℓ^*} is the excited lepton mass. A similar exclusion is obtained in the $\mathrm{ee}\gamma$ channel.

3.2 Excited Quarks

The CMS experiment has performed a search for anomalous production of highly boosted Z bosons in the dimuon decay channel arising from the decays of new heavy particles [15]. The search is optimized for the detection of excited quark production and decay via $\mathrm{q}^* \to \mathrm{qZ} \to \mathrm{q}\mu\mu$, with no explicit requirement on the jet recoiling against a high transverse momentum Z. Figure 3 shows the dimuon p_{T} spectrum from data compared to the simulation of excited quark signals. The results are consistent with background-only expectations. Limits are derived on excited quark production in the plane of compositeness scale Λ versus mass for two scenarios of production and decay: one assuming excited quark transitions via SM gauge bosons only, and one including also novel contact interaction transitions from new strong dynamics. The q^* mass limits at 95% CL with contact interactions are more sensitive than previous searches in scenarios where the coupling to gluons is suppressed relative to the electroweak gauge bosons, ruling out masses below 1.17 TeV in the extreme case when this coupling is zero.

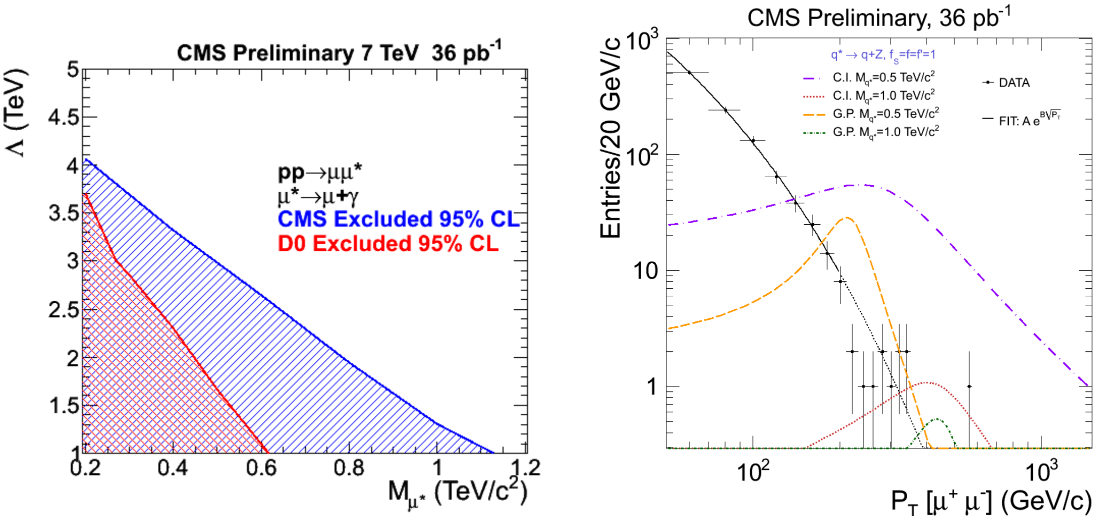

Figure 3: (Left) Exclusion at 95% CL in the $\Lambda - \mathrm{M}_{\ell^*}$ parameter space for the $\mu\mu\gamma$ channel. (Right) The dimuon p_{T} spectrum distribution from data with a background parametrization overlaid. Various excited quark signals are shown, corresponding to different production mechanisms (gauge interaction and contact interaction) and different q* masses.

4 Extra Dimensions

Compact large extra dimensions (ED) are an intriguing proposed solution to the hierarchy problem of the SM, which refers to the puzzling fact that the fundamental scale of gravity $\mathrm{M}_{\mathrm{Planck}} \sim 10^{19}$ GeV is so much higher than the electroweak symmetry breaking scale $\sim 10^3$ GeV. In the ADD model [c], the SM is constrained to the common 3+1 space-time dimensions, while gravity is free to propagate through the entire multidimensional space. The gravitational flux in 3+1 dimensions is effectively diluted by virtue of the multidimensional Gauss's Law. In this framework, the fundamental Planck scale can be lowered to the electroweak scale, thus making production of gravitons possible at the LHC. Some of the experimental signatures of the existence of such extra dimensions are discussed below.

4.1 Diphoton and Dimuon Channels

Searches for virtual-graviton contributions in the diphoton [16] and dimuon [17] final states have been performed. Figure 4 displays the diphoton (left) and dimuon (right) invariant mass distribution for the observed data, the backgrounds, and the ADD signal. The ADD signal, differently from the searches discussed in Section 2.1, would not appear as a narrow peak but as an overall excess of events at high values of invariant mass. In both $\gamma\gamma$ and $\mu\mu$ channels, the data is found to be consistent with SM expectations. Lower limits at the 95% CL are set on the fundamental Planck scale in the approximate range of 1.4–2.3 TeV, depending on the final state considered, the number of extra dimensions, and the theoretical conventions used to describe the virtual-graviton production.

4.2 Mono-jet Final State

A search for production of a real graviton G balanced by an energetic hadronic jet via the processes $q\bar{q} \to gG$, $qg \to qG$, and $gg \to gG$ has been performed [18]. Since gravitons are free

[c] The original proposal to use extra dimensions to solve the hierarchy problem was presented by Arkani-Hamed, Dimopoulos, and Dvali (ADD).

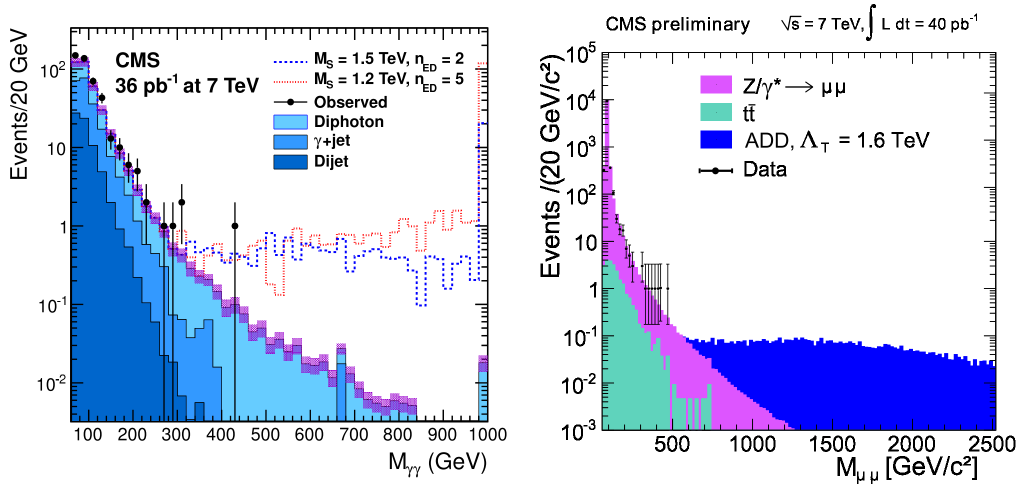

Figure 4: Diphoton (left) and dimuon (right) invariant mass spectra compared with the SM prediction and simulated ADD signals.

to propagate in the extra dimensions, they escape the detector and can only be inferred from the amount of missing transverse energy ($\not{E}_{\mathrm{T}}$). The offline event selection requires large $\not{E}_{\mathrm{T}}$, one high p_{T} jet, a veto on the presence of well-identified leptons and isolated tracks, and additional requirements to suppress the cosmics, beam halo, and instrumental backgrounds that can fake the mono-jet+$\not{E}_{\mathrm{T}}$ signature. Figure 5 (left) shows the p_{T} distribution of the leading jet after the full selection. A measurement of the electroweak background from $\mathrm{W} \rightarrow \mu\nu$ enriched data is used to derive a data-driven background estimate for the Z/γ+jets and W+jets contributions remaining in the signal region. The number of observed events in data is in good agreement with the SM prediction, and significant improvements are made to the current limits on the fundamental parameters of the model describing real-graviton emission.

4.3 Microscopic Black Holes

One of the exciting predictions of theoretical models with extra dimensions and low-scale quantum gravity is the possibility of copious production of microscopic black holes in particle collisions at the LHC. Events with large total transverse energy are analyzed for the presence of multiple high-energy jets, leptons, and photons, typical of a signal expected from a microscopic black hole [19]. Figure 5 (right) shows the distribution of the total transverse energy for data, background prediction and various signal samples. Good agreement with the standard model backgrounds, dominated by QCD multijet production, is observed for various final-state multiplicities and model-independent limits on new physics in these final states are set. Using simple semi-classical approximation, limits on the minimum black hole mass are derived as well, in the range 3.5–4.5 TeV.

5 Long-Lived Particles and Other Exotic Signatures

5.1 Massive Long-Lived Particles

Heavy stable (or quasi-stable) charged particles appear in various extensions of the SM. Heavy long-lived particles with hadronic nature, such as gluinos or stops, hadronize in flight, forming meta-stable bound states with quarks and gluons (so called R-Hadrons). If the lifetime of R-Hadrons produced at LHC is longer than a few nanoseconds, these particles will travel over distances that are comparable or larger than the size of a typical particle detector, and hence

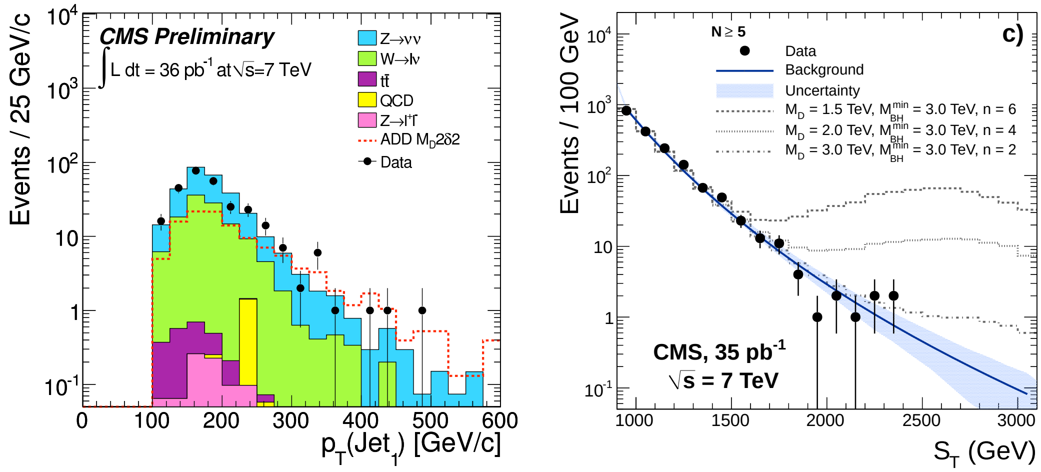

Figure 5: (Left) $p_{\rm T}$ distribution of the leading jet after the full mono-jet+$\not\!\!E_{\rm T}$ selection. The distribution for an ADD signal (shown in red) is overlaid. (Right) Total transverse energy (including the $\not\!\!E_{\rm T}$ in the sum) for events with more than 5 objects (jets, leptons, and photons) for data, background prediction, and black hole signals for three different parameter sets.

might be detected directly. The CMS experiment uses two complementary strategies to identify such long-lived particles.

A significant fraction of these massive particles (assuming masses greater than 100 GeV) will have a velocity $\beta = v/c$, smaller than 0.9. A search has been performed to identify R-Hadrons through the distinctive signature of a high momentum track with an anomalously large rate of energy loss through ionization in the silicon tracker, using the first 3 pb^{-1} of data collected in 2010 [20]. Lower limits at the 95% CL on the mass of a stable gluino are set i) at 398 GeV, using a conventional model of nuclear interactions that allows charged hadrons containing this particle to reach the muon detectors, ii) at 311 GeV, in a conservative scenario where any hadron containing this particle becomes neutral before reaching the muon detectors.

Searches have been also performed for very slow ($\beta \leq 0.4$) R-hadrons containing a gluino, for which the electromagnetic and nuclear energy loss is sufficient to bring a significant fraction of the produced particles to rest inside the CMS detector volume [21]. These stopped R-hadrons will decay into an hadronic jet and a neutralino only seconds, days, or weeks later (accordingly to their unknown lifetime), and out-of-time with respect to the LHC collisions. The online selection of events requires the firing of a single jet trigger with an explicit veto on the beam presence. In a dataset with a peak instantaneous luminosity of 1×10^{32}cm^{-2}s^{-1}, an integrated luminosity of 10 pb^{-1}, and a search interval corresponding to 62 hours of LHC operation, no significant excess above background (mainly instrumental noise) was observed. Limits at the 95% confidence level on gluino pair production over 13 orders of magnitude of gluino lifetime are set. For a mass difference $\mathrm{m}_{\tilde{\mathrm{g}}} - \mathrm{m}_{\tilde{\chi}^0_1} > 100$ GeV, and assuming $\mathrm{BR}(\tilde{\mathrm{g}} \to \mathrm{g}\tilde{\chi}^0_1) = 100\%$, $\mathrm{m}_{\tilde{\mathrm{g}}} < 370$ GeV are excluded for lifetimes from 10 μs to 1000 s.

5.2 New Light Resonances Decaying into Pairs of Muons

Recent astrophysical observations of an excess of high-energy positrons in the cosmic ray spectrum have motivated the rise of new physics scenarios suggesting that this excess may be associated with annihilation of dark matter particles in the galactic halo. One realization of such models assumes an extra U(1) gauge symmetry with weak coupling to the standard model. The U(1) symmetry is broken, leading to a light massive vector boson (m $\sim$ O(1GeV)), a "hidden sector" (or "dark") photon $\gamma_{\rm dark}$, which decays into leptons and, if kinematically allowed, hadrons. More complex models can lead to a whole hierarchy of the dark sector states or can have dark photons preferentially couple to leptons. Hidden sectors can be realized naturally in supersymmetric (SUSY) models where coupling of the dark sector to the SUSY sector can be enhanced. Depending on the complexity of the light dark sector, at the LHC one may expect either a single dark photon at the end of each SUSY cascade or a whole cascade of hidden state decays with emission of multiple dark photons. Subsequent decays of the new states into leptons leads to appearance of the energetic collimated groups of leptons (leptonic jets).

A signature-based search for groups of collimated muons has been performed at CMS [22]. The analysis searches for production of new low-mass states (m $\sim$ 0.5–5 GeV) decaying into pairs of muons and is designed to achieve high sensitivity to a broad range of models predicting leptonic jet signatures. With no excess observed in the data over the background expectation, model-independent upper limits on the production cross section times branching fraction times acceptance are derived for several event topologies, and range from 0.1 to 0.5 pb^{-1} at the 95% CL. In addition, the results are interpreted in several benchmark models in the context of supersymmetry with a new light dark sector exploring previously inaccessible parameter space.

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