Recent results on searches for physics beyond the Standard Model at Large Hadron Collider are presented, based on early LHC data in proton-proton collisions at \(\sqrt{s} = 7\) TeV collected by the CMS experiment. Prospects of early SUSY searches at CMS are also outlined.

1. INTRODUCTION

The Standard Model (SM) has been enormously successful, but it leaves many important questions unanswered. It is also widely acknowledged that, from the theoretical standpoint, the SM must be part of a larger theory, “beyond” the SM (BSM), which is yet to be experimentally confirmed.

One of the most popular suggestions for the BSM theory is Supersymmetry (SUSY) which introduces a new symmetry between fundamental particles. SUSY signals are of particular interest, as they provide a natural explanation for the Dark Matter, known to pervade our universe, and help us to understand the fundamental connection between particle physics and cosmology. Furthermore there are a large number of important and well thought out theoretical models that make strong cases for looking for new physics at the LHC. These theories include Extra Dimensions, Black Hole, Grand Unified Theories, Composite models, Anomalous couplings and non-SM Higgs models. None of the rich new spectrum of particles predicted by these models have yet been found within the kinematic regime reachable at the present experiments. The LHC will increase this range dramatically after several years of running at the highest energy and luminosity.

One of the primary objectives of CMS experiments is to find incontrovertible evidence for new physics beyond SM using a signature of high-energy objects in the final state, and the ‘signatures’ expected for new physics have been taken into consideration extensively in the design of the experiment [1]. In this article we summarize the current experimental results of searches for physics beyond the SM from the CMS experiment at the Large Hadron Collider (LHC).

2. SEARCHES FOR DIJET RESONANCES

The signatures of new physics at the LHC involve high-\(p_T\) final-state jets. The dijet mass spectrum predicted by Quantum Chromodynamics (QCD) falls smoothly and steeply with increasing dijet mass. As an example of the new physics, many extensions of the SM predict the existence of new massive objects that couple to quarks and gluons, and result in resonant structures in the dijet mass spectrum. CMS has performed a search for narrow resonances in the dijet mass spectrum using 2.9 \(\text{pb}^{-1}\) of early LHC data, at a proton-proton collision energy of \(\sqrt{s} = 7\) TeV [2].

The dijet system is composed of the two jets with the highest \(p_T\) in an event (leading jets). CMS requires that the pseudorapidity separation of the two leading jets, \(\Delta \eta = \eta_1 - \eta_2\), satisfies \(|\Delta \eta| < 1.3\), and that both jets be in the region \(|\eta| < 2.5\). These \(\eta\) cuts maximize the search sensitivity for isotropic decays of dijet resonances in the presence of QCD background. The dijet mass is given by \(m = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}\). CMS selects events with \(m > 220\) GeV without any requirements on jet \(p_T\).

Figure 1 (left) presents the inclusive dijet mass distribution for \(pp \rightarrow 2\) leading jets + \(X\), where \(X\) can be anything, including additional jets. The data are compared to a QCD prediction from PYTHIA, which includes a simulation of the CMS detector and the jet energy corrections [3]. The PYTHIA prediction agrees with the data within the jet energy scale uncertainty, which is the dominant systematic uncertainty. The measured dijet mass spectrum is a smoothly falling distribution as expected within the SM and there is no indication of narrow resonances in the data. Figure 1 (left) also shows the predicted dijet mass distribution for string resonances and excited quarks models.
Figure 1: (Left) Dijet mass spectrum (points) compared to a smooth fit (solid) and to PYTHIA predictions including detector simulation of QCD (short-dashed), excited quark signals (dot-dashed), and string resonance signals (long-dashed). The errors are statistical only. The shaded band shows the effect of a 10% systematic uncertainty in the jet energy scale. (Right) 95% CL upper limits on $\sigma \times BR \times A$ for dijet resonances of type gluon-gluon (open circles), quark-gluon (solid circles), and quark-quark (open boxes), compared to theoretical predictions for string resonances, excited quarks, axigluons, colorons, $E_6$ diquarks, new gauge bosons $W'$ and $Z'$, and Randall-Sundrum gravitons.

Predicted mass distribution exhibits a Gaussian core from jet energy resolution and a tail towards low mass from QCD radiation.

Since no significant excess over the SM prediction is observed, CMS presents generic upper limits at the 95% C.L. on the product of the resonance cross section, branching fraction into dijets, and acceptance, as a function of the new particle mass, for narrow resonances decaying to dijets with partons of type quark-quark ($qq$), quark-gluon ($qg$), and gluon-gluon ($gg$) \cite{5}. These generic limits are used to exclude new particles predicted in the following specific models: string resonances (S), excited quarks ($q^*$), axigluons (A), flavor universal colorons (C), and $E_6$ diquarks (D).

In Figure 1 (right) CMS compares these upper limits to the model predictions as a function of resonance mass. CMS excludes at the 95% C.L. new particles in mass regions for which the theory curve lies above upper limit for the appropriate pair of partons. For string resonances CMS uses the limits on $qq$ resonances to exclude the mass range $0.50 < M(S) < 2.50$ TeV. For comparison, previous measurements \cite{5} imply a limit on string resonances of about 1.4 TeV. For excited quarks CMS excludes the mass range $0.50 < M(q^*) < 1.58$ TeV, extending the previous exclusion of $0.40 < M(q^*) < 1.26$ TeV \cite{6}. For axigluons or colorons CMS uses the limits on $qq$ resonances to exclude the mass intervals $0.50 < M(A) < 1.17$ TeV and $1.47 < M(A) < 1.52$ TeV, extending the previous exclusion of $0.12 < M(A) < 1.25$ TeV \cite{5}. For $E_6$ diquarks CMS excludes the mass intervals $0.50 < M(D) < 0.58$ TeV, and $0.97 < M(D) < 1.08$ TeV, and $1.45 < M(D) < 1.60$ TeV, extending the previous exclusion of $0.29 < M(D) < 0.63$ TeV \cite{5}. For $W'$, $Z'$ and RS gravitons CMS does not expect any mass limit, and does not exclude any mass intervals with the present data. The systematic uncertainties included in this analysis reduce the excluded upper masses by roughly 0.1 TeV for each type of new particle.
3. SEARCHES FOR QUARK COMPOSITENESS

In the SM production of dijet events, the pseudorapidity $\eta$ of the jets depends on the angular distribution of the scattered partons predicted by QCD. New physics beyond the SM, including models of quark compositeness, typically produces more isotropic angular distributions than those predicted by QCD, resulting in more dijets at lower absolute values of pseudorapidity.

CMS has searched for quark compositeness in the framework of quark contact interactions, based on the dijet centrality ratio, $R_\eta = N(|\eta| < 0.7) / N(0.7 < |\eta| < 1.3)$, which is the number of events with the two leading jets in the region $|\eta| < 0.7$ (inner events) divided by the number of events with the two jets in the region $0.7 < |\eta| < 1.3$ (outer events), using a data sample corresponding to $120 \pm 13 \text{ nb}^{-1}$ of integrated luminosity [7]. Since many sources of systematic uncertainty cancel in this ratio, the dijet ratio provides a precise test of QCD and is sensitive to new physics. This analysis is closely related to the CMS search for dijet resonances in the dijet mass spectrum, described in Section 2. Though the centrality ratio analysis is less sensitive in the case of resonances, it is more sensitive to the presence of contact interactions.

Figure 2 (left) shows a comparison of the measured dijet centrality ratio with the predictions of NLO QCD and various new physics models. The dijet centrality ratio in data is nearly flat as predicted by QCD. To quantitatively test for the presence of new physics in the dijet centrality ratio, CMS uses a log-likelihood-ratio statistic ($R_{LL}$) that compares the null hypothesis (SM only) to the hypothesis that new physics effects are present in addition to the SM. Given this consistency of the data with the QCD hypothesis, CMS has determined 95% CL limits on the contact interaction scale $\Lambda$. Figure 2 (right) shows $R_{LL}$ versus $\Lambda$ for the data and for the SM expectation (with $1\sigma$ and $2\sigma$ bands) along with the highest value of $R_{LL}$ excluded at the 95% CL with the CL$_s$ method [8]. CMS excludes quark compositeness described by a contact interaction between left-handed quark fields at energy scales of $\Lambda < 1.9$ TeV at the 95% C.L.

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4. SEARCH FOR STOPPED GLUINOS

CMS has searched for long-lived gluinos which have stopped in the CMS detector after being produced in 7 TeV pp collisions from LHC [9]. CMS looked for the subsequent decay of these particles during time intervals where there were no pp collisions in the CMS experiment. In particular, CMS has searched for decays during gaps between crossings in the LHC beam structure, and recorded such decays with a dedicated calorimeter trigger. In a dataset with a peak instantaneous luminosity of $1.3 \times 10^{30}$ cm$^{-2}$s$^{-1}$, an integrated luminosity of 203 - 232 nb$^{-1}$, depending on the gluino lifetime, and a search interval corresponding to 115 hours of LHC operation, no significant excess above background was observed. In the absence of a signal, CMS set a limit at 95% C.L. on gluino pair production over 14 orders of magnitude of gluino lifetime. For a mass difference $m_\tilde{g} - M_{\chi_1^0}$ maintained at 100 GeV; results are only presented for $M_{\chi_1^0} > 50$ GeV.

These results extend existing limits from the Tevatron, which exclude lifetimes between 30 $\mu$s and 100 hours [10]. Furthermore CMS excludes gluino masses $m_\tilde{g} < 229$ GeV/c$^2$ with a lifetime of 200 ns using the time-profile analysis and $m_\tilde{g} < 225$ GeV/c$^2$ with a lifetime of 2.6 $\mu$s in a counting experiment. This result is consistent with the complementary exclusion provided by our direct HSCP search [11]. As more luminosity is delivered by the LHC the reach of this analysis will improve rapidly. In particular, since the only backgrounds to this search are independent of luminosity, this sensitivity will increase significantly when the LHC peak instantaneous luminosity increases to $10^{32}$ cm$^{-2}$s$^{-1}$ expected later this year.

5. SEARCH FOR HEAVY STABLE CHARGED PARTICLES

Heavy Stable (or long-lived) Charged Particles (HSCPs) appear in various extensions to the SM, arising from a new symmetry, a weak coupling, a kinematic constraint, or a potential barrier. If the lifetime is long compared to the transit time through the detector, then the particle may escape the detector, thereby evading the limits imposed by direct searches for decay products. Nevertheless, a HSCP will be directly observable in the detector through the distinctive signature of a slowly moving, high momentum ($p$) particle. The low velocity results in an anomalously large ionization-energy loss rate ($dE/dx$).

In this analysis, a signature-based search is performed for HSCPs produced in pp collisions at $\sqrt{s} = 7$ TeV, using

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Figure 4: Observed 95% C.L. upper limits on the cross section for production of the different models considered and predicted theoretical cross sections. (Left) Analysis of the muon identification plus tracker candidates; (Right) Analysis of the tracker-only candidates. The bands represent the theoretical uncertainty on the cross section values.

high transverse momentum muon, jet, and missing transverse energy (MET) trigger data corresponding to 198 nb$^{-1}$ of integrated luminosity [11]. The analysis isolates HSCP candidates by selecting tracks reconstructed in the inner tracker detector with high $dE/dx$ and high $p_T$. Additionally, tracks passing muon identification requirements are also analyzed for this signature. For both selections, the candidate’s mass is then calculated from the measured $p$ and $dE/dx$. In both cases, no event passes the selection criteria with an expected background of less than 0.1 events. From this result, an upper limit at 95% C.L. on the production cross section of pairs of stable gluinos, hadronizing into R-gluonballs in 10% of the cases, and top squarks is set at around 10 pb starting from a mass of 130 and 200 GeV/$c^2$, respectively. For the case of gluinos a mass lower limit of 382 (190) GeV/$c^2$ can be set at 95% C.L. with the analysis that uses muon identification. This limit becomes 375 (183) GeV/$c^2$ when no muon identification is required. Cross section upper limits are also set for some benchmark points in the framework of the mGMSB model, predicting the existence of stable staus.

6. EARLY LHC DATA PREPARATION FOR SUSY SEARCHES

CMS will perform a broad range of searches for SUSY particles. The initial searches will be performed in a variety of inclusive final states involving jets, leptons, photons, and MET. These searches require careful control over backgrounds from SM processes. Several methods for data-driven background determinations were developed and tested on early LHC data collected by CMS experiment [12]. These data allow us to study QCD backgrounds, to evaluate methods to suppress the effects of jet-energy mismeasurement, to validate data-driven methods for predicting the background MET distribution, and to measure background contributions from processes producing non-prompt leptons or hadrons misidentified as leptons.

The prospects for the discovery reach are studied with two values of the integrated luminosity, 100 pb$^{-1}$ and 1 fb$^{-1}$ of simulated data at $\sqrt{s} = 7$ TeV and are shown in the mSUGRA model in Figure 3 for the all-hadronic channel (left) and for the like-sign dilepton channel (right) [13]. These results indicate that in the 7 TeV run, CMS should have sensitivity to regions of SUSY (mSUGRA) parameter space beyond the current Tevatron limits. Both of the channels shown here (all-hadronic and like-sign dileptons) should be able to yield interesting sensitivities well before 1 fb$^{-1}$.
Figure 5: (Left) Estimated 95% C.L. exclusion limits for the all-hadronic SUSY search, expressed in mSUGRA parameter space. (Right) Estimated 95% C.L. exclusion limits for the like-sign dilepton SUSY search, expressed in mSUGRA parameter space. The expected SM background at 100 pb$^{-1}$ (1 fb$^{-1}$) is 0.4 (4.0) events; an observed yield of 1 event (4 events) is assumed for the purpose of setting these exclusion limits.

7. CONCLUSIONS

The CMS experiment has searched for evidence of different models of new physics in several channels using early LHC data and already explored new territory beyond the Tevatron. No evidence for new physics signature has yet been observed in the early LHC data. The CMS collaboration expects to collect 1 fb$^{-1}$ of data by the end of 2011. This new data will make significant advances across a wide range of physics channels and will provide a great opportunity for new physics discovery.

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