Recent CMS Results of Searches for Physics beyond the Standard Model

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Abstract—A survey of the results obtained by the CMS Collaboration in searches for physics beyond the Standard Model on the basis of a complete set of data measured at the c.m. collision energy of $\sqrt{s} = 8$ TeV in the 2012 run at the Large Hadron Collider (LHC) is given.

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The predictions of the Standard Model (SM) describe well observed particle physics. The recent discoveries of the Higgs boson [1–3] and the rare decay process $B_s \rightarrow \mu^+\mu^-$ [4, 5] did not reveal any deviations from the SM predictions beyond the currently present experimental uncertainties. At the same time, there are a great many theoretical models beyond the Standard Model that implement various ideas, such as electroweak-symmetry breaking, solving the hierarchy problem, Grand Unification, supersymmetry, and the existence of dark-matter particles [6].

The Compact Muon Solenoid (CMS) is one of the two general-purpose detectors deployed at the Large Hadron Collider (LHC). It involves a superconductor solenoid generating a magnetic field of strength 3.8 T, an internal silicon tracker, an electromagnetic calorimeter based on lead tungstate crystals, a hadron calorimeter formed by brass and scintillator layers, and a muon system in the pseudorapidity range of $|\eta| < 2.4$ (for more details, see [7, 8]). An excellent performance of the event reconstruction is illustrated in Fig. 1 for the example of the total invariant-mass spectrum of dimuons (the data were recorded using various trigger paths intended for selecting the decays of $J/\psi$, $\psi'$, $B_s$, and $T$ resonances, as well as dimuons characterized by low and high transverse momenta $p_T$). The first physics run was completed in 2012, and data with an integrated luminosity of about 5 fb$^{-1}$ at the c.m. energy of $\sqrt{s} = 7$ TeV and that of 20 fb$^{-1}$ at $\sqrt{s} = 8$ TeV were obtained.

Searches for new physics at the CMS setup were performed in various channels for various theoretical models predicting deviations from the Standard Model.

An important direction of the research is the search for narrow resonances in dilepton (dimuon and dielectron) channels, which have already established themselves as clean channels to search for new particles. Many new-physics models predict the existence of narrow resonances in the TeV region of dilepton invariant masses [9, 10]. They include (i) the Sequential Standard Model (SSM) $Z_{\text{SSM}}'$ characterized by the same values of the coupling constants as those in the Standard Model; (ii) the $Z_{\psi}'$ model predicted in Grand Unified Theories (GUT) [9]; and (iii) the Randall–Sundrum (RS1) model of a possible warped extra-dimension scenario with one extra spatial dimension, where excited Kaluza–Klein states of gravitons arise [11]. In the most recent measurements, the CMS Collaboration used the data obtained at $\sqrt{s} = 8$ TeV for the integrated luminosity of up to 20 fb$^{-1}$ both in the dimuon and dielectron channels [12]. Resonance searches were performed on the basis of an analysis of the shape of the dilepton-mass spectrum in order to rule out the dependence on the uncertainties in the absolute background-spectrum level. Since the spectra proved to be compatible with the SM predictions, upper limits were set on the products of the cross section and the branching ratios for $Z'$ decay to dileptons with respect to the cross section for $Z$-boson production in the Standard Model. In Fig. 2, the resulting upper limits on the cross-section ratio

$$R_\sigma = \frac{\sigma(pp \rightarrow Z' + X \rightarrow \ell\ell + X)}{\sigma(pp \rightarrow Z + X \rightarrow \ell\ell + X)},$$

at a 95% confidence level (C.L.) are shown for both dilepton channels and for their combination. Since no significant peaks have been found in the mass spectrum, the following lower limits on the $Z'$-resonance mass were set: 2900 GeV for $Z_{\text{SSM}}'$ and 2570 GeV for...
Fig. 1. Dimuon mass spectra measured over a broad range by using various trigger paths.

Fig. 2. Limits on cross sections for the production of $Z'$ heavy gauge bosons.

for $Z'_\psi$ [12]. The results can also be generalized to other models [12, 13].

Limits for other possible modes of $Z'$ decay were also set for the following channels: pairs of $\tau$ leptons [14], $ZZ$ dibosons [15], $tt$ pairs [16], and anomalous production of highly boosted $Z$ bosons with large transverse momentum and decaying to dimuons [17]; also, limits were set for $W'$ decay through the following channels: $l\nu$ semileptonic modes [18], $WZ$ dibosons [19], and the $bt$ heavy-quark channel [20].
Fig. 3. Distributions of the scalar sum of transverse momenta of four objects, \(S_T\), for the \(\mu\mu jj\) and \(\mu\nu jj\) channels and resulting limits on the masses of the second-generation scalar leptoquarks versus the parameter \(\beta\).

For narrow resonances in the dijet channel, limits were set on the production cross sections and masses for various hypothetical particles: string resonances, excited quarks, axigluons, colorons, \(S_8\) resonances, \(E_6\) diquarks, \(W'\) and \(Z'\) bosons, and RS gravitons up to \(1–5.1\) TeV [21].

A new analysis of the production of microscopic black holes within the Arkani-Hamed–Dimopoulos–Dvali (ADD) model [22] was performed on the basis of data at \(\sqrt{s} = 8\) TeV for the integrated luminosity of 12 fb\(^{-1}\) [23], and the exclusions of masses of semiclassical black holes below 4.3 to 6.2 TeV were set. Searches for effects of extra dimensions were also performed in the mass spectrum of diphotons [24], dimuons [25], and dielectrons [26]. This made it possible to rule out the string scale \(M_s\) below 4.94 TeV.

Leptoquarks, having both the baryon and lepton quantum numbers, arise in many Standard Model extensions, such as GUTs, technicolor theories, and composite models. For data obtained at \(\sqrt{s} = 8\) TeV with the integrated luminosity of 19.6 fb\(^{-1}\), a recent publication of the CMS Collaboration reported on the results of searches for second-generation scalar leptoquarks in events having not less than two jets and two possible leptonic channels: either two charged leptons (\(\mu\mu jj\)) or a charged lepton and a large missing energy because of a neutrino (\(\mu\nu jj\)). Second-generation scalar leptoquarks of mass below 1070 (785) GeV were excluded for \(\beta = 1\) (0.5),
where the parameter $\beta$ is the fraction of leptoquarks decaying to a charged lepton and a quark [27]. A slight excess of data in relation to the respective SM predictions was observed in the $\mu\nu jj$ channel (see the right upper panel in Fig. 3), but this excess can be explained by the systematic and statistical uncertainties. Because of this excess, the observed limit on the cross section in the $\mu\nu jj$ channel proved to be somewhat greater than the expected one, as seen in the lower panels of Fig. 3. Also shown there is the limit obtained by the ATLAS Collaboration on the basis of data corresponding to an integrated luminosity of $1.03 \text{ fb}^{-1}$ at $\sqrt{s} = 7 \text{ TeV}$ [28].

The CMS Collaboration also performed many other searches for deviations from SM predictions (on the website of this collaboration [29], the interested reader can find a compendium of resulting limits on masses and scales within various physics models beyond the Standard Model and references to the published publications). By and large, the limits obtained by the ATLAS Collaboration [30] are compatible with the CMS results presented in this report.

In conclusion, we can state that an excellent performance of the LHC and the CMS detector made it possible to accumulate a large data set for proton–proton collisions: $5 \text{ fb}^{-1}$ at $\sqrt{s} = 7 \text{ TeV}$ and $20 \text{ fb}^{-1}$ at $\sqrt{s} = 8 \text{ TeV}$. In searches for physics beyond the Standard Model, the experiment was able to exclude new particles in the region between 2 to 3 TeV in the dilepton channels and around 5 TeV in the dijet channel. This made it possible to improve the limits obtained earlier [29]. Future runs at the total LHC energy of 13 to 14 TeV would increase the accuracy of the measurements, and a data analysis would provide answers to urgent question existing in the theory. Moreover, we cannot rule out the possibility of discovering unexpected phenomena in high-energy physics that have not yet been predicted theoretically, as occurred in the past. With the data obtained at enhanced energies and luminosities, the CMS Collaboration would be able to extend the already explored region of searches for physics processes beyond the Standard Model [31].

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