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CMS collaboration results: Higgs boson and search for new physics

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1. Introduction

Predictions of the Standard Model (SM) describe well the observed elementary particle physics phenomena. An important part of the SM is the Brout–Englert–Higgs mechanism, which introduces the scalar Higgs field with a nonzero vacuum expectation as a result of spontaneous symmetry breaking. Due to interaction with this field, particles acquire nonzero masses and, because of the quantum excitations of the Higgs field, a new elementary particle appears: the Higgs boson. But until recently there was no experimental evidence for the existence of the Higgs boson. One of the main physics goals of constructing the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN, Switzerland) was to determine whether the Higgs boson exists, what its mass is, and whether its characteristics agree with those expected in the SM. Certain discoveries were expected to happen at the full design center-of-mass energy of colliding protons $\sqrt{s} = 14$ TeV and the originally planned integrated luminosity $\mathcal{L}\,dt = 300\ \text{fb}^{-1}$: either the Higgs boson or other new strong effects, because otherwise, at the energy above 1 TeV, a perturbative unitarity violation in the scattering of the intermediate vector bosons would occur [1]. Other major physics goals of the LHC construction were the search for physics Beyond the SM (BSM), implementing various ideas, such as electroweak symmetry breaking, the hierarchy problem, incorporation of gravity into quantum theory, grand unification, supersymmetry, the existence of dark matter particles, etc. [2, 3].

This summary report provides an overview of the most interesting recent results of the CMS Collaboration, including the discovery of the Higgs boson [4, 5] and the rare decay $B_s \to \mu^+\mu^-$ [6], and the search for BSM physics using a full dataset of the first run held in 2011–2012 at the LHC at energies $\sqrt{s} = 7$ and 8 TeV.

2. CMS detector

The Compact Muon Solenoid (CMS) is one of the two general-purpose detectors located at the LHC (Fig. 1). Its name originates from the world's largest superconducting solenoid with an inner diameter of 6 m, length of 12.5 m, and magnetic field of 3.8 T, cooled by liquid helium to $-269\,^{\circ}$C. In the center, around the interaction point of proton beams with an energy of 4 TeV, there is a silicon tracker that reconstructs interaction vertices and momenta of charged particles by the curvature of the tracks in the magnetic field up to the pseudorapidity $|\eta| < 2.5$ (i.e., for a polar angle up to $\theta > 9.4^{\circ}$ in accordance with the definition of the pseudorapidity $\eta = -\ln[\tan(\theta/2)]$). Ionization calorimeters are located around the tracker: 1) an electromagnetic calorimeter based on lead–tungstate ($PbWO_4$) crystals reconstructing the position and energy of electromagnetic showers and in this way determining the position and energy of photons, electrons, and positrons up to the pseudorapidity $|\eta| < 3$; 2) a hadron calorimeter based on layers of brass and a scintillator determining the parameters of hadronic showers and hadronic jets. The tracker and calorimeters are located inside the superconducting solenoid surrounded by a steel magnetic return yoke and a muon system in the range $|\eta| < 2.4$ and consist of a barrel part based on drift tubes and an endcap part based on cathode strip chambers, as well as resistive planar chambers for making a fast muon trigger in the range $|\eta| < 1.6$. The system ensures reconstruction of muon tracks with a precision $\sigma(p_T)/p_T < 0.05$ for the transverse momenta up to $p_T < 1$ TeV in the barrel part. A detailed description of the detectors and the characteristics is given in [7,8]. The full spectrum of the invariant mass of the muon pairs in Fig. 2 displays the known resonances in the range from 1 to 100 GeV; due to a good momentum resolution, there is a distinct separation of the individual peaks from the ground state of the Upsilon meson $\Upsilon(1S)$ and the radial excitations $\Upsilon(2S)$ and $\Upsilon(3S)$. The first physics run was completed in 2012, with the respective integrated luminosities ~ 5 and 20 fb^{-1} obtained at $\sqrt{s} = 7$ and 8 TeV. The luminosity reached $\mathcal{L} = 7 \times 10^{33}\ \text{cm}^{-2}\,\text{s}^{-1}$ and the average number of interactions per proton–proton collision reached 21. The CMS detector effectively operated with these occupancies and recorded over 90% high-quality data, which made it possible to discover the Higgs boson and other interesting physics.

[1] On behalf of the CMS collaboration.

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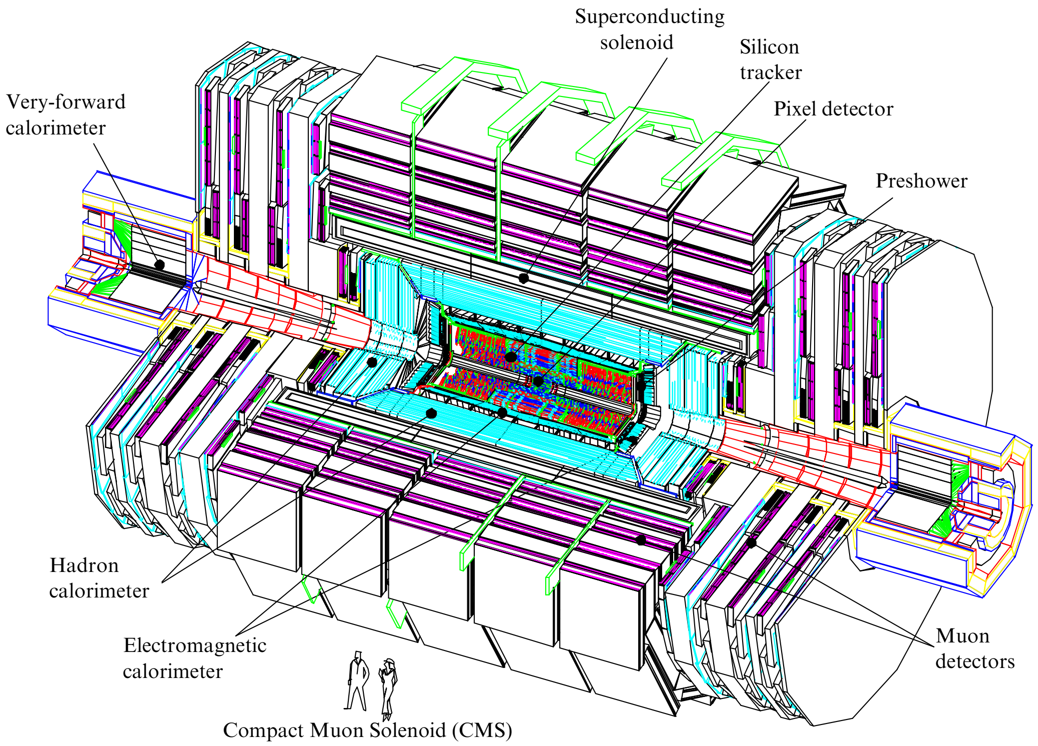

Figure 1. Subdetectors of the Compact Muon Solenoid (CMS).

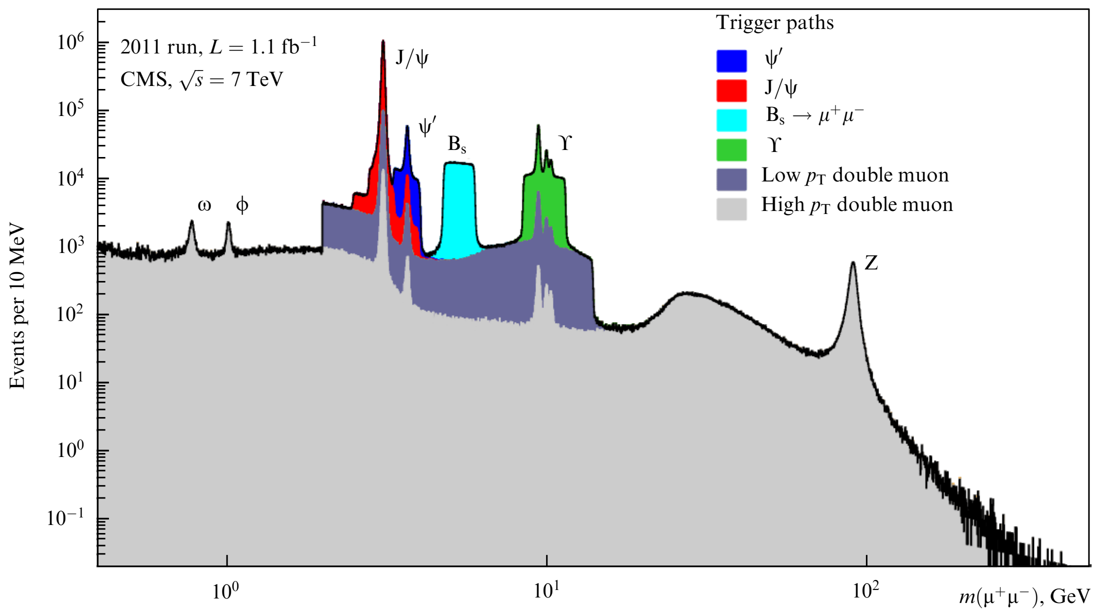

Figure 2. Measured dimuon invariant mass spectra in a wide range with different trigger paths.

3. Discovery of the Higgs boson

The SM is based on the Brout–Englert–Higgs mechanism of spontaneous symmetry breaking by introducing a scalar field with a nonzero vacuum expectation that gives nonzero masses to fundamental particles, while remaining within a renormalizable field theory [9, 10]. The milestones of the search for the Higgs boson at CERN and the CMS were as follows [11]. In the early 2000s, experiments at the Large Electron–Positron collider at $\sqrt{s} = 209$ GeV excluded an SM Higgs boson mass less than 114.4 GeV [12]. A fit of the precision electroweak measurements led to the prediction of $m_{\rm H} = 99^{+28}_{-23}$ GeV [13]. Data obtained by the CMS in 2011 pointed to the existence of a peak at 125 GeV in the mass distribution with a statistical significance of 2.8 standard deviations (σ), and excluded the mass range 127–600 GeV [14]. Combined data from the Fermilab experiments at $\sqrt{s} = 1.96$ TeV in 2012 had an excess that was incompatible with the background hypothesis by approximately $3\,\sigma$ [15]. On 4 July 2012, at a special seminar at CERN, the ATLAS (A Toroid LHC ApparatuS) and CMS collaborations, using data with an integrated luminosity of approximately 10 fb^{-1} and $\sqrt{s} = 7-8$ GeV, reported an observation of a new boson

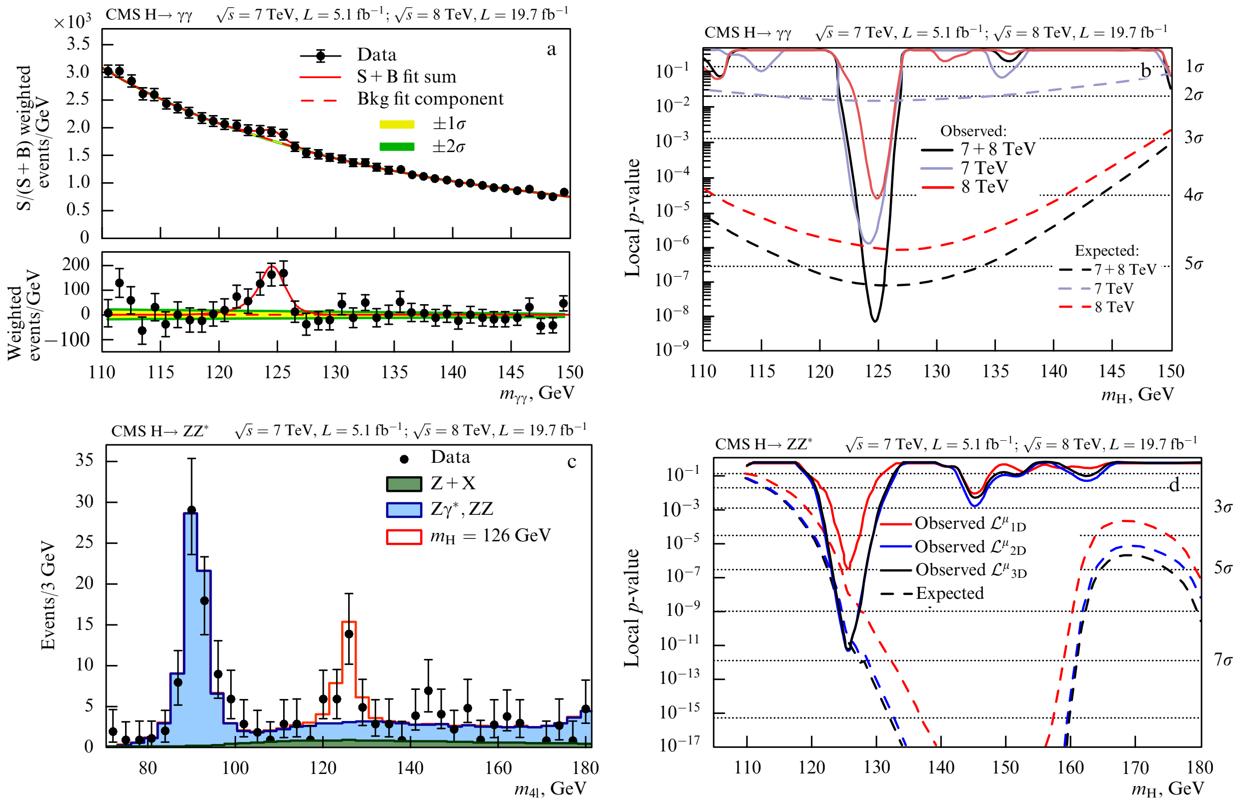

Figure 3. (a, c) Mass spectra and (b, d) the dependence of p-values on mass for channels (a, b) $\gamma\gamma$ and (c, d) ZZ^* of Higgs boson decays.

with a mass of approximately 125 GeV with $\sim 5\sigma$ significance (in each experiment), consistent with the SM Higgs boson; the results were sent to *Physics Letters* at the end of July [4, 16]. Subsequently, using the full 2012 data, the accuracy was significantly improved, leading to the determination of the spin and parity of the boson and evidence of the decay channels to fermions ($\tau\tau$, $b\bar{b}$) [17], as well as to a significantly better accuracy of the measurements. Later in this section, we describe the results obtained by the CMS collaboration using the full 2011–2012 data with an integrated luminosity up to 5.1 fb^{-1} at $\sqrt{s} = 7$ TeV and 19.7 fb^{-1} at $\sqrt{s} = 8$ TeV.

The search for the Higgs boson was conducted in five major decay channels with the highest expected significance at the LHC: $\gamma\gamma$, $ZZ^* \to 4l$, $WW^* \to l\nu\, l\nu$, $\tau\tau$, $b\bar{b}$, where the asterisk $(*)$ denotes virtual particles and $l = e^{\pm}, \mu^{\pm}$. The first two channels provide the best significance and separation of signal from background due to a good mass resolution ($\sigma_M/M = 1-2\%$); other channels have the largest decay branching ratios. In order to avoid unintentional biases, all the selection criteria have been fixed before analyzing the signal region (so-called 'blind analysis').

(1) The search for the decay channel $\gamma\gamma$ used multivariate analysis techniques (boosted decision trees) for the selection and classification of events [18]. The multivariate analysis has allowed increasing the expected significance by 15%, compared with the independent analysis virtually identical to that described in the 2011 data analysis using simple criteria based on cutoffs. The weighted histogram with the mass spectrum is shown in Fig. 3a, where, in spite of the large combinatorial background, we can see a clearly visible peak at 125 GeV [19]. Figure 3b shows the corresponding p-value, i.e., the probability of a background fluctuation being at least as large as the observed maximum excess; at 125 GeV, the deviation has a statistical significance of 5.6σ [20]. Signal strength, defined as the ratio of the cross section times the corresponding branching ratio to the SM expectations, is $\mu = \sigma/\sigma_{\rm SM} = 1.13 \pm 0.24$ [20].

(2) The search in the 'golden' channel ZZ^* used the three possible subchannels of Z boson decay to lepton pairs: 4μ, 2μ 2e, and 4e. Two pairs of opposite-sign isolated muons or electrons from the same primary vertex were selected. The channel was clean enough: the main backgrounds included irreducible ZZ production and reducible backgrounds: Z + jets, $Zb\bar{b}$, $t\bar{t}$, WZ production. The resulting mass spectrum in Fig. 3c clearly shows a narrow peak around 125 GeV [21].

Because the decay $H \to ZZ^* \to 4l$ occurs under the threshold for a system of two Z bosons ($2m_Z \approx 182$ GeV $> m_H \approx 125$ GeV), the decay branching ratio is small: ${\rm Br}(H \to ZZ^* \to 4l) = 1.26 \times 10^{-4}$ at 125 GeV [22]. To improve the signal extraction, a method using the difference between the matrix elements for the SM Higgs boson and background — the matrix element likelihood approach (MELA) — was applied [23, 24]. Using all five angles of the four leptons and the masses of both Z candidates, M_{Z_1} and M_{Z_2}, one can construct a kinematic discriminant $K_D = P_{\rm sig}/(P_{\rm sig} + P_{\rm bkg})$ based on the probability ratio of the signal and background hypotheses, which can be used in the general likelihood function, to increase the expected significance by 15–20%. The two-dimensional distributions for the expected background and signal of the SM Higgs boson (Fig. 4) show that the experimental points are well described by the SM Higgs boson signal hypothesis (Fig. 4b), especially for large discriminant values. The resulting dependence of p-values shown in Fig. 3d [21] corresponds to the

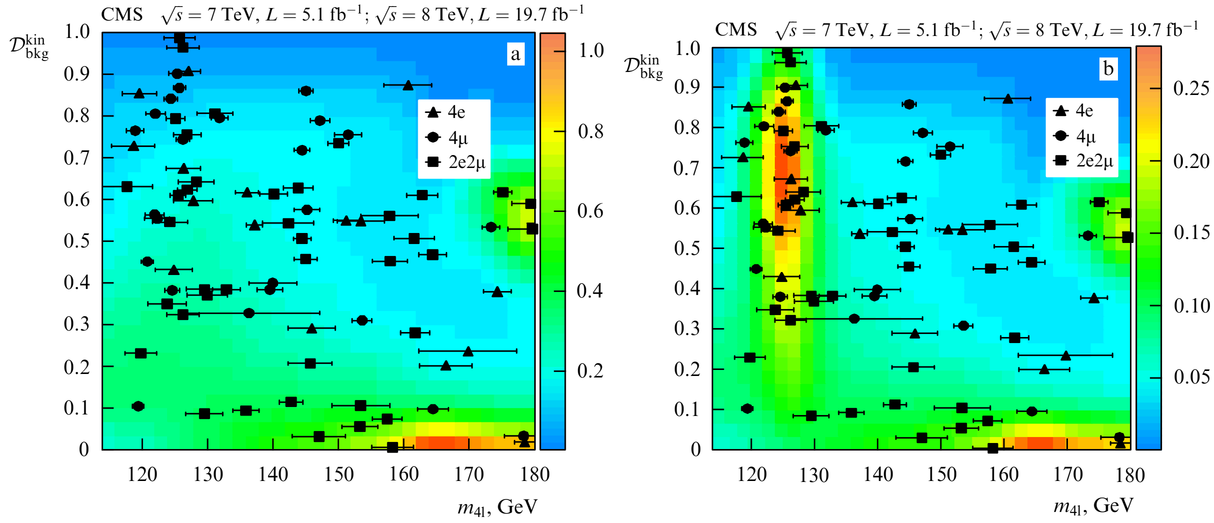

Figure 4. (Color online.) Distribution of events $ZZ^* \to 4l$ for the kinematic discriminant K_D versus m_{4l}; the color-coded regions show the event density expected from (a) the background and (b) the SM Higgs boson. Events are shown as filled symbols defined in the legend; horizontal error bars indicate the estimated mass resolution.

significance of $6.5\,\sigma$ [20]. The signal strength for ZZ^* is $\mu = \sigma/\sigma_{\text{SM}} = 1.00 \pm 0.29$ [20].

The peak width was measured by direct peak fitting as not exceeding 3.4 GeV [21], but using Higgs boson events outside the mass shell up to the invariant mass of 800 GeV, the width limit can be reduced by a factor of 150 to 22 MeV [25], i.e., a value which is five times larger than the theoretical value of the Higgs boson width in the SM: 4.15 MeV [26].

(3) In the decay channel $H \to WW^*$, where W bosons decay into charged leptons and neutrinos, the latter are not recorded in the detector and lead to the appearance of a large missing transverse energy E_T^{miss}. This results in an excess of signal over background in a wide range of transverse mass M_T with a statistical significance of $4.7\,\sigma$. The signal strength is equal to $\mu = \sigma/\sigma_{\text{SM}} = 0.83 \pm 0.21$ [20, 27].

(4) Decay channels into fermions $\tau\tau$ and $b\bar{b}$ have high branching ratios, but suffer from a large background from the SM [17]. In the $\tau\tau$ channel, the statistical significance is equal to $3.8\,\sigma$, and the signal strength is $\mu = 0.91 \pm 0.27$ [20, 29].

(5) The $b\bar{b}$ channel requires two jets from b quarks; the background is reduced by demanding an associated production of W and Z bosons. The significance was equal to $2.0\,\sigma$, and the signal strength was $\mu = 0.93 \pm 0.49$ [20, 29].

The combination of all five channels in the fit (see Table 1) gives the signal strength $\sigma/\sigma_{\text{SM}} = 1.00 \pm 0.13$ [20], compatible with the expectations for the SM Higgs boson. The signal strengths for the different channels are also compatible with the SM. Measurement of the mass of the new boson gave the value $m_H = 125.03^{+0.26}_{-0.27}(\text{stat.})^{+0.13}_{-0.15}(\text{syst.})$ GeV [20]. Figure 5a shows a two-dimensional graph of the signal versus mass.

In order to check whether the properties of the discovered boson coincide with the properties of the SM Higgs boson, it is necessary to measure its coupling constants with various fields. The first result of such a check was the fit of the set of constants for the vector particles (κ_V) and fermions (κ_F), which gave values $\kappa_V \in [0.88,\ 1.15]$ and $\kappa_F \in [0.64,\ 1.16]$ [20]. The full set of constants for particles τ, b, W, Z, and t [20] has been measured, and it turns out that the constants are directly proportional to the particle masses (Fig. 5b), as it should be for a boson that is the quantum fluctuation of the Higgs field that gives mass to fundamental particles. It is difficult to imagine that such a precise proportionality on the scale of two orders of magnitude in mass could arise for some other reason.

Table 1. Summary of the results for the various decay channels of the Higgs boson and their combination: observed and expected local p-values for $m_H = 125$ GeV (expressed in an appropriate number of standard deviations of the observed excess for the hypothesis of pure background), as well as signal strengths and masses obtained by fitting the experimental data [20].

Decay channel	Significance (σ)		Signal $\mu = \sigma/\sigma_{\text{SM}}$	Mass M_H, GeV
	Obs.	Exp.		
ZZ	6.5	6.3	1.00 ± 0.29	$125.6 \pm 0.4 \pm 0.2$
γγ	5.6	5.3	1.13 ± 0.24	$124.70 \pm 0.31 \pm 0.15$
WW	4.7	5.4	0.83 ± 0.21	$128.2^{+6.6}_{-5.3}$
ττ	3.8	3.9	0.91 ± 0.27	
$b\bar{b}$	2.0	2.3	0.93 ± 0.49	
Combination of all channels:			1.00 ± 0.13	$125.03^{+0.26+0.13}_{-0.27-0.15}$

Finally, using the angular distribution of the decay products, it is necessary to check the hypotheses of different spins and parities. The SM requires the $J^{PC} = 0^{++}$ state. It is known that spin 1 is excluded due to the Landau–Yang theorem [30–32] (paper [30] was included in the collected works of Landau [31]), since the boson decays into a pair of photons. Because of the same decay, C parity must be positive. The distribution of the logarithm of the ratio of the likelihood functions for the hypotheses of positive and negative P parities is shown in Fig. 5c. We can see that the CMS data point corresponds to a positive P parity, and a negative P parity is 99.9% ruled out [21]. Similarly, spins 1 and 2 are excluded with a probability greater than 99%.

As a result of the discovery of the Higgs boson and the determination of its characteristics, the 2013 Nobel prize in physics was awarded jointly to Peter W Higgs and François Englert "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle,

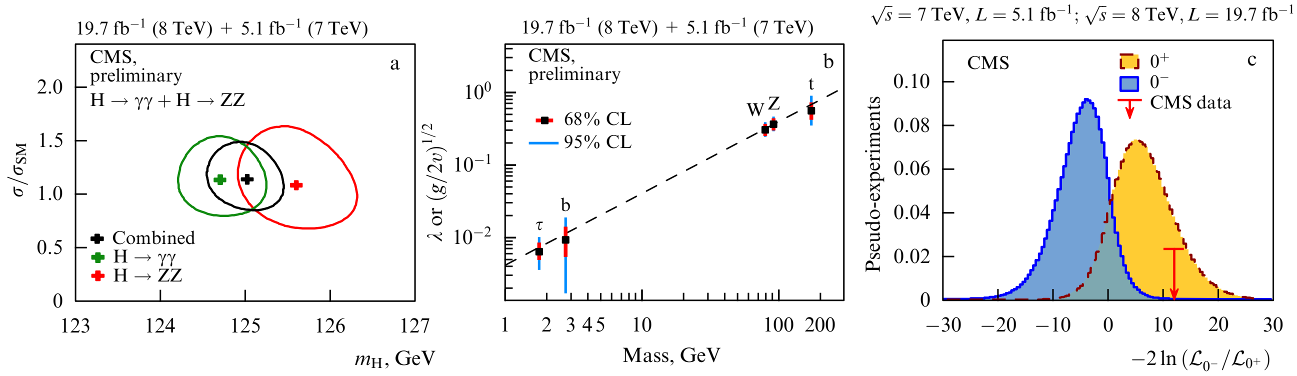

Figure 5. (Color online.) (a) Two-dimensional graph of the signal strength versus the boson mass. (b) Dependence of the coupling constants of fundamental particles to the boson on their mass. (c) Distribution of the logarithm of the likelihood function for the hypotheses of positive and negative parity of the boson; an arrow indicates the CMS data point.

by the ATLAS and CMS experiments at CERN's Large Hadron Collider'' [33].

Studies of other decay modes of the Higgs boson are under way, e.g., the search for the rare decay $H \to \mu^+\mu^-$ which has the branching ratio $\mathrm{Br}(H \to \mu^+\mu^-) = 2.2 \times 10^{-4}$ in the SM. At 25 fb^{-1}, the limit $\mu = 7.4$ was found (the expected limit is $\mu = 5.1$) at a 95% confidence level (CL) [34]. It is expected that the decay $H \to \mu^+\mu^-$ can be discovered with $\int \mathcal{L}\,dt \approx 1000$ fb^{-1} at $\sqrt{s} = 14$ TeV. Searches for an additional Higgs boson with the properties as in the SM have been performed and the excluded mass range is up to 1 TeV at a 99% CL [35]. There is no evidence of the Higgs boson beyond the SM yet.

Thus, the results of searches can be summarized as follows: the new particle is very similar to the boson predicted by the simple Brout–Englert–Higgs model: it is a scalar field with coupling constants that are proportional to the particle masses. It has all the properties of the SM Higgs boson, within the current uncertainties. At the end of the LHC phase 2, in 20 years, an integrated luminosity of ~ 3000 fb^{-1} with $\sqrt{s} = 14$ TeV is expected, enabling further tests and studies of the physics of the Higgs boson, in particular, reaching 2–5-percent accuracy in the measurement of Higgs boson coupling constants for γ, Z, and W [36]. Perhaps the most important measurement after the Higgs boson discovery itself will be of the constants of the Higgs potential, which is possible in the study of simultaneous production of two Higgs bosons using data from an integrated luminosity of 3000 fb^{-1} in the promising channels with large branching ratios of decays like $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ [36]. Future data will allow a more rigorous test of the new boson properties and studies that indicate whether the properties of the new particle imply a BSM physics.

4. Study of processes in the Standard Model

The discovery of the Higgs boson at the LHC has once again confirmed the triumphant progress of the SM in elementary particle physics. Another important CMS result was the discovery of the rare decay $B_s^0 \to \mu^+\mu^-$, which had been searched for by different experiments for 30 years with gradually improving precision. This decay is suppressed in the SM because it is described by the penguin and box loop diagrams, and, moreover, is helicity suppressed. The decay branching ratio in the SM is $\mathrm{Br}(B_s \to \mu^+\mu^-) = (3.6 \pm 0.3) \times 10^{-9}$; therefore, this process is sensitive to BSM physics searches [37]. In November 2012, the LHCb collaboration was the first to report an observation of this decay at a significance level of $3.5\,\sigma$ [38]. In July 2013, at the European Physical Society Conference on High Energy Physics in Stockholm, the CMS collaboration presented the results $\mathrm{Br}(B_s \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$ (significance of $4.3\,\sigma$) and an upper limit $\mathrm{Br}(B^0 \to \mu^+\mu^-) < 1.1 \times 10^{-9}$ at 95% CL [6]. Both results are in agreement with the SM predictions, leading to the exclusion of part of the phase space for some supersymmetric models.

The combination of the results of the CMS and LHCb has been obtained: $\mathrm{Br}(B_s \to \mu^+\mu^-) = (2.9 \pm 0.7) \times 10^{-9}$, compatible with the SM with a $5\,\sigma$ statistical significance [39]. Data processing and analysis at the full integrated luminosity of 3000 fb^{-1} with $\sqrt{s} = 14$ TeV in the LHC phase 2 should allow CMS to reach a statistical significance of more than $5\,\sigma$ for the decay $B^0 \to \mu^+\mu^-$ [40].

The heaviest quark, top quark t, with a mass of approximately 173 GeV, was discovered in 1995 at the Tevatron collider (Batavia, US). In recent years, the LHC can also be regarded as a 'top factory', where a few million top quarks have been produced. In the ATLAS and CMS experiments, with 5 fb^{-1} at $\sqrt{s} = 7$ TeV, the accuracy of measuring the mass M_t, which is important from the standpoint of vacuum stability [1], reached the precision of the Tevatron, the combined data analysis from all the experiments yielding the value $M_t = 173.34 \pm 0.76$ GeV [41]. The cross section of the top quark pair production at $\sqrt{s} = 8$ TeV, $\sigma_{t\bar{t}} = 239 \pm 2\,(\mathrm{stat.}) \pm 11\,(\mathrm{syst.}) \pm 6\,(\mathrm{lumi})$ pb [42], has been measured in good agreement with the SM prediction $\sigma_{t\bar{t}} = 237.5 \pm 13.1$ pb, as was a single top quark production cross section in the electroweak interaction processes in different channels: $\sigma_t = 83.6 \pm 2.3 \pm 7.4 \pm 20.0$ pb [43], $\sigma_{tW} = 23.4^{+5.5}_{-5.4}$ pb [44], $\sigma_s = 6.2^{+8.0}_{-5.1}$ pb [45]. Many other interesting results in top-quark physics and in electroweak physics and other fields of the SM have also been obtained.

In 2010, at $\sqrt{s} = 7$ TeV, the discovery was made of the so-called 'ridge effect' in pp collisions, which consisted in observing particle correlations in a narrow range of $\Delta\phi \approx 0$ (the azimuthal angle around the beam axis) but in a wide range of $\Delta\eta$ (the polar angle relative to the beam axis) in high-multiplicity events [46]. Thus, some pairs of particles with large $\Delta\eta$ were oriented in their directions along the same azimuthal angle φ, as if such particles were coherently produced at the proton interaction point. This discovery led to a range of possible explanations by various mechanisms:

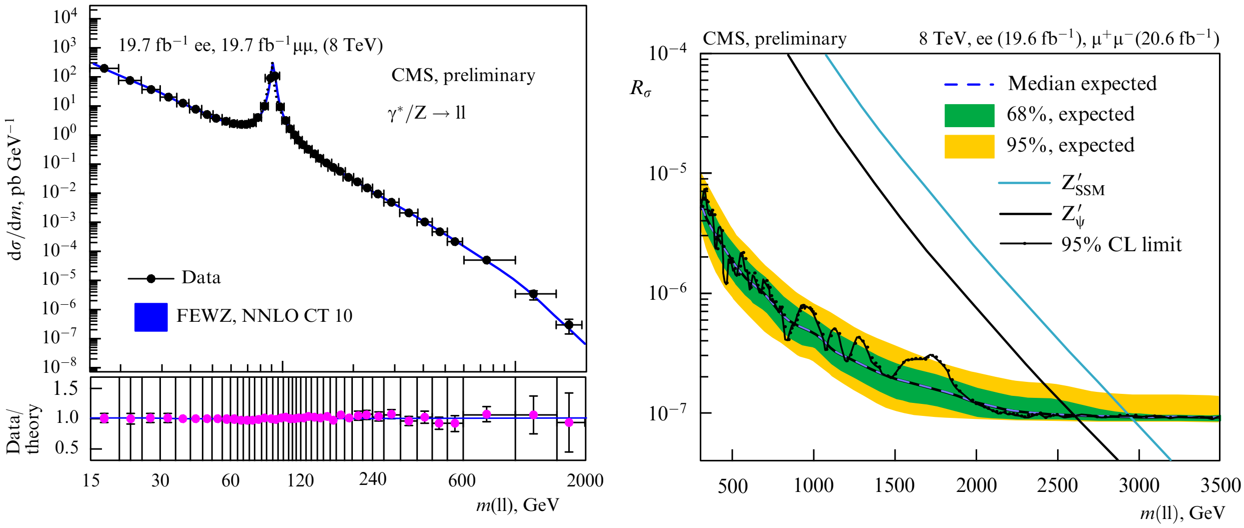

Figure 6. (a) Drell–Yan invariant mass spectrum as measured by the CMS and as predicted by NNLO calculations for the full phase space. (b) The obtained limits for narrow dilepton resonance production cross sections as a function of the invariant mass and a comparison with the predictions of BSM physics models.

color glass condensate, multiple interactions, a hydrodynamic description, etc. [47]. Later, this effect was confirmed by the ATLAS and ALICE (A Large Ion Collider Experiment) collaborations, and observed with higher correlations in proton–nucleus (p Pb) and nucleus–nucleus (Pb Pb) interactions in the CMS [48, 49].

Production of lepton pairs in proton–proton collisions is described in the SM by the exchange of γ^*/Z in the s channel (Drell–Yan process); theoretical calculations are carried out in the next-to-next-to-leading order (NNLO) of QCD and are sensitive to the partonic contents of the proton. Differential cross sections of the Drell–Yan process $d\sigma/dm$ were measured in the CMS in the mass range from 15 to 2000 GeV (Fig. 6a), as were the double differential cross sections $d^2\sigma/dm\,d|y|$, where y is the dilepton rapidity; the results are in good agreement with SM predictions [50, 51]. Measurement of SM processes is important for testing the SM and for improving predictions of future measurements, because these processes are the background for other measurements as well as for the search for the new physics.

5. Search for physics beyond the Standard Model

The search for the new physics at the CMS has been conducted in various channels for different theoretical models predicting deviations from the SM. One important area is the search for narrow resonances in two-lepton channels (dimuon and dielectron), which has already established itself as a clean channel to search for new particles. Many BSM new physics models predict the existence of narrow resonances in the TeV mass scale of a pair of charged leptons [52,53]. These models include, in particular: (1) the Sequential Standard Model Z'_{SSM} with the same coupling constants as in the SM; (2) the Z'_ψ model predicted in grand unified theories [52]; (3) the Randall–Sundrum model (RS1) of a possible warped extra-dimension scenario with one extra spatial dimension, where excited states of Kaluza–Klein gravitons arise [54]. A recent CMS measurement used the data at $\sqrt{s} = 8$ TeV with the integrated luminosity up to 20 fb^{-1} in both the dimuon and dielectron channels [55]. Resonance searches were based on the shape analysis of the dilepton mass spectrum in order to be robust against uncertainties in the absolute background level. Because the spectra were consistent with SM expectations, the upper limit of the product of the cross section and branching ratio of Z' decays into lepton pairs relative to the SM production has been estimated. The obtained upper limits on the cross section ratio,

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

at 95% CL are shown in Fig. 6b for the combination of both dilepton channels. Since there are no significant peaks in the mass spectrum, the following lower limits on the mass of Z' resonances have been obtained: 2960 GeV for Z'_{SSM} and 2600 GeV for Z'_ψ [55]. The results can also be generalized to other models [56]. Limits for other possible decay modes of Z' have also been established. In the future, for dimuons at $\sqrt{s} = 14$ TeV, we plan to reach masses of 4.6–5.2 TeV at an integrated luminosity of 300 fb^{-1} (for $Z'_\psi - Z'_{SSM}$ models), and 5.6–6.2 TeV at 3000 fb^{-1} [36].

One of the most spectacular predictions of theories with low-scale quantum gravity is the possibility of microscopic black hole production in proton–proton collisions at LHC energies [57, 58]. Such models are motivated mainly by the puzzling large difference between the electroweak scale (~ 0.1 TeV) and the Planck scale ($M_{Pl} \sim 10^{16}$ TeV), known as the hierarchy problem. A new analysis of the production of microscopic black holes in a model with n large, flat, extra spatial dimensions (Arkani-Hamed–Dimopoulos–Dvali model, ADD) [59] was performed using data at $\sqrt{s} = 8$ TeV with an integrated luminosity of 12 fb^{-1} [60], which led to limits on masses below 4.3–6.2 TeV for semiclassical black holes. The search for effects of extra dimensions [61] was also carried out in the mass spectrum of diphotons [62], dimuons [63], and dielectrons [64], which excluded the string scale M_s up to 4.94 TeV.

Great interest is aroused by the search for dark matter particles (weakly interacting massive particles, WIMPs) at colliders. In CMS, the search was performed in events with the energetic jet $+E_T^{miss}$ [65] or energetic lepton $+E_T^{miss}$ [66], as well as in the channel with the associated t quark production [67]. The number of events was consistent with SM expectations, and the limits of the dark-matter–nucleon scattering cross sections for different models were obtained.

As is known from baryogenesis theories, baryon number violation (BNV) is one of the necessary conditions for the observed baryon asymmetry [68–70] (paper [68] was reproduced in *Physics–Uspekhi* [69]). Strong BNV effects have been predicted in many BSM models. In the CMS, BNV has been studied in the top quark decay $t \to \bar{b}\,\bar{c}\,\mu^+$, while another top quark in the event has a usual decay $\bar{t} \to W^- \bar{b} \to d\,\bar{u}\,\bar{b}$. A limit of 0.0015 at 95% CL has been set for the branching ratio of a hypothetical BNV decay $t \to l + 2j$ [71].

One of the most popular models of the new physics on the TeV energy scale is supersymmetry, where, for each SM particle, there is a superpartner with the same quantum numbers but with the spin different by 1/2. This model makes it possible to cancel the quadratic divergence of the radiative corrections to the Higgs boson mass, to unify the gauge coupling constants of strong, weak, and electromagnetic interactions, and to ensure the existence of dark matter particles. Without fine tuning of the theory (the 'naturalness' criterion), superpartner masses should not be much larger than 1 TeV [72]. The search for supersymmetric particles in various channels has not yet come to fruition. For example, for a gluon superpartner (gluino $\tilde{g}$), a mass limit $m_{\tilde{g}} \geqslant 1.3$ TeV has been established. For an integrated luminosity of 300 fb^{-1} with $\sqrt{s} = 14$ TeV, it is planned to increase the limit on the gluino mass to 2 TeV [36].

Many other BSM searches have also been performed in the CMS: summaries of the obtained limits for the masses and scales for various models of BSM physics and references to the published papers are available at the collaboration website [73].

6. Conclusion

In conclusion, due to the excellent performance of the LHC and the CMS detector, a large dataset of proton–proton collisions has been obtained: 5 fb^{-1} at $\sqrt{s} = 7$ TeV and 20 fb^{-1} at $\sqrt{s} = 8$ TeV. In the search for the SM Higgs boson, a new particle with a mass of approximately 125 GeV has been observed in the analysis involving five decay channels. Strong signals with a statistical significance of more than 5σ have been found in the analysis of the decay channels $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$, while results in other decay channels are also fully consistent with the SM expectations. The new particle is very similar to the boson predicted by the simple Brout–Englert–Higgs model: it is a scalar field with coupling constants that are proportional to the particle masses. It has all the properties of the SM Higgs boson, within the current uncertainties. Future data will allow a more rigorous test of the new boson properties and studies that indicate whether the properties of the new particle imply physics beyond the SM.

Measurements of SM processes and the search for new physics beyond the SM have been carried out, a long-awaited discovery of the rare decay $B_s \to \mu^+\mu^-$ has been made, and an unexpected 'ridge effect' in the proton–proton collisions of particle correlations for a large difference in polar angles has been found. The SM results are used for extracting parton distribution functions and theoretical calculations at the higher orders of the perturbation theory. In the search for BSM physics, the experiment could, in particular, exclude new particles in the 2–3 TeV mass range in the dilepton channel and up to 5 TeV in the dijet channel, improving the limits obtained in previous studies [73]. Future runs at the full LHC energy of 13–14 TeV will increase the measurement accuracy, and data analysis will provide answers to the current topical issues in the theory. We cannot ignore the possibility of the discovery of unexpected phenomena in high-energy physics, not yet predicted by theory, as has already occurred in the past. With data at increased energy and luminosity, the CMS collaboration will be able to expand the scope of the BSM physics search [36].

The CMS collaboration had published approximately 300 articles as of the spring of 2014 in scientific journals, and the number continues to grow. This summary report provided an overview of the most interesting recent results of the CMS; more information can be found, for example, at the CMS website for public physics results [73].

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The Higgs boson is found: what is next?

D I Kazakov

1. Introduction

The discovery of the Higgs boson in 2012 [1, 2] and the awarding of the Nobel Prize in 2013 have marked an important step in elementary particle physics. The mechanism of fundamental particle mass generation, the Brout–Englert–Higgs mechanism [3, 4], theoretically predicted nearly 50 years ago, is experimentally confirmed. Thus, the Standard Model of fundamental interactions has been logically completed and obtained the status of Standard Theory. By the Standard Model, we understand the description of strong, weak, and electromagnetic interactions between quarks and leptons based on the gauge group $SU(3)_c \times SU(2)_L \times U(1)_Y$. Here, quarks are triplets and leptons are singlets with respect to the color group $SU(3)_c$, the left components of quarks and leptons are doublets, the right components are singlets with respect to $SU(2)_L$, and all of them have a hypercharge with respect to the $U(1)_Y$ group. The set of matter fields and the carriers of four fundamental forces of the SM are shown in Fig. 1. To the particles already known, all of which were discovered in the 20th century, we should add the Higgs boson, discovered in the 21st century.

In the SM, we have six quarks and six leptons forming three generations and three types of interactions: strong, weak, and electromagnetic, mediated by the quanta of the

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