CMS experiment: Physics overview

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Abstract. An overview of physics results from the CMS experiment at the LHC is given. The present analysis is based on data obtained for colliding proton beams at the c.m. energies of $\sqrt{s} = 8$ and 13 TeV over the period of LHC Run-1 and Run-2.

New unique data on interactions of Standard Model particles at record energies were obtained in the course of the first run of LHC operation. The Higgs boson was discovered, and investigation of its properties was initiated. Measurements were performed for Standard Model processes, including rare and previously unobserved ones. This permitted refining some parameters of the Standard Mode and setting limits on the parameters of some theoretical models beyond the Standard Model, for example, on the masses of new particles, on the fundamental energy scales, on the coupling constants, and on the cross sections for the production of new particles.

1. Introduction

This report covers recent physics results from CMS [1] including precision measurements of the Higgs boson, first observed by the ATLAS and CMS collaborations in 2012 [2],[3] and top quark properties, b-physics, and standard model (SM) phenomena; searches for new particles. It will conclude with a summary and outlook.

In 2016–2018, the LHC concentrated on providing the experiments with very high integrated luminosity. This was achieved by the LHC's reaching a peak initial luminosity of 2×10^{34} cm^{-2}s^{-1} and providing very high availability for physics.

2. Recent Physics Results

CMS has continued its prolific production of physics results. At time of The XVIII Workshop on High Energy Spin Physics (September 2019), 907 papers have been submitted to peer reviewed journals. Here, we present a few highlights of recent results.

2.1. Higgs Boson Properties

With more total luminosity and higher energy, larger samples of Higgs bosons are reconstructed, making more precise measurements and new studies possible.

Higgs boson decay to $b\bar{b}$: Recently CMS made an observation of the Higgs boson decay to bottom quarks [4]. The measurement examines the VH production process, where the Higgs boson is produced in association with a W or Z boson and decays into $b\bar{b}$. The data comprise proton-proton (pp) collisions recorded at $\sqrt{s} = 13$ TeV corresponding to a total integrated luminosity of 41.3 fb^{-1}. Higgs boson candidates are reconstructed from the pair of jets in the event most likely to originate from b quarks.

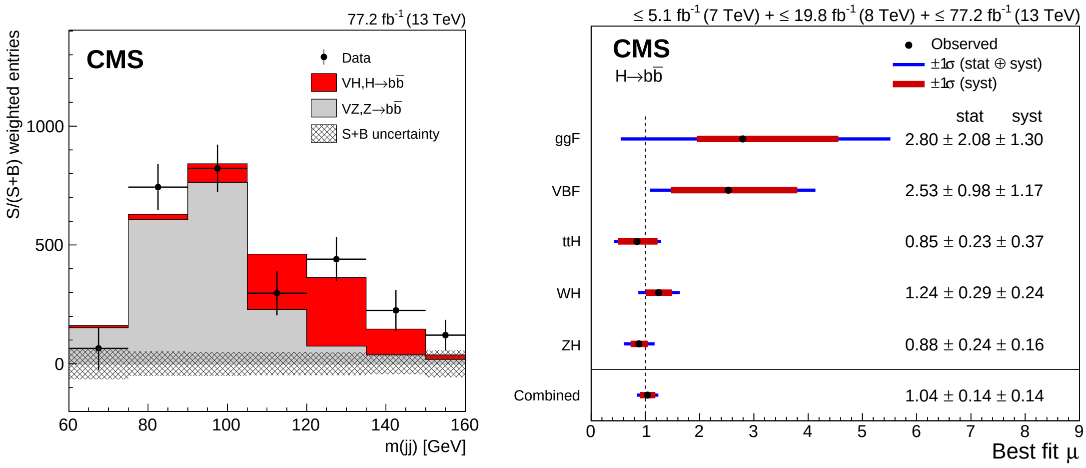


Figure 1. Left plot: dijet invariant mass distribution for events weighted by $S/(S+B)$ (left plot) [4]. Right plot: best-fit value of the $H \to b\bar{b}$ signal strength for the five individual production modes considered [4].

A combination of all CMS measurements of the VH, $H \to b\bar{b}$ process using proton-proton collisions recorded at center of mass energies of 7, 8, and 13 TeV, yields an observed (expected) significance of 4.8 (4.9) standard deviations at $m_H = 125.09$ GeV, and the signal strength is $\mu = 1.01 \pm 0.22$. Combining this result with previous measurements by the CMS Collaboration of the $H \to b\bar{b}$ decay in events where the Higgs boson is produced through gluon fusion, vector boson fusion, or in association with top quarks, the observed (expected) significance increases to 5.6 (5.5) standard deviations and the signal strength is $\mu = 1.04 \pm 0.20$. This constitutes the observation of the $H \to b\bar{b}$ decay by the CMS Collaboration. All results are summarized in Fig. 1(right plot).

Higgs boson decay to $\mu\mu$: The paper [5] presents a search for the Higgs boson decaying to two muons using data recorded by the CMS experiment at the LHC in 2016 at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 35.9 fb^{-1}.

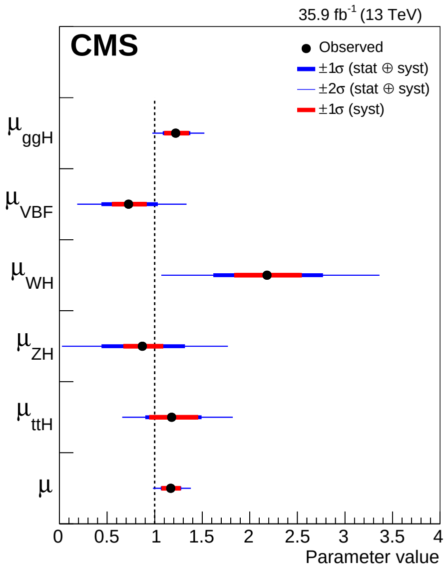
No significant evidence for the decay $H \to \mu^+\mu-$ is observed. Limits are set on the cross section times branching fraction of the Higgs boson decaying to two muons. The combination with data recorded at center-of-mass energies of 7 and 8 TeV yields a 95% confidence level observed upper limit of 2.92 times the standard model value for $m_H = 125.09$ GeV. The corresponding expected upper limit in the absence of a SM decay in this channel is 2.16, which is the most sensitive to date. Assuming standard model production cross sections for the Higgs boson, the observed limit corresponds to an upper limit of 6.4×10^{-4} on the Higgs boson branching fraction to two muons.

Higgs boson decay to charm quarks: The paper [6] presents a search for the Higgs boson decaying to a pair of charm quarks using data recorded by the CMS experiment at the LHC in 2016 at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 35.9 fb^{-1}.

Associated production of the Higgs and Z or W bosons, with leptonic decay modes of Z and W was studied. Two strategies were followed. In one, the H candidate is reconstructed via two resolved jets arising from the two charm quarks from the H decay. A second strategy identifies the case where the two charm quarks from the H decay merge to form a single jet. Both strategies make use of novel methods for charm jet identification, while jet substructure techniques are also exploited to suppress the background for the merged-jet topology. The two analyses are combined to yield an observed (expected) upper limit on the

$\frac{\sigma(VH)\times\mathcal{BR}(H\to c\bar{c})}{\sigma_{SM}(VH)\times\mathcal{BR}_{\mathcal{SM}}(H\to c\bar{c})}$) of $70(37^{+16}_{-10})$ at 95% confidence level. This result is the most stringent direct limit on $\sigma(pp \to H) \times \mathcal{BR}(H \to c\bar{c})$ to-date.

Higgs combination: A set of combined measurements of Higgs boson production and decay rates has been presented by CMS in work [7], along with the consequential constraints placed on its couplings to standard model (SM) particles, and on the parameter spaces of several beyond the standard model (BSM) scenarios. The combination is based on analyses targeting the gluon fusion and vector boson fusion production modes, and associated production with a vector boson or a pair of top quarks. The analyses included in the combination target Higgs boson decay in the $H \to ZZ, WW, \gamma\gamma, \tau\tau$, $b\bar{b}$, and $\mu\mu$ channels, using 13 TeV proton-proton collision data collected in 2016 and corresponding to an integrated luminosity of 35.9 fb^{-1}. Per-production mode and per-decay mode signal strength modifiers are presented Figure 2. Additionally, searches for invisible Higgs boson decays are included to increase the sensitivity to potential interactions with BSM particles.



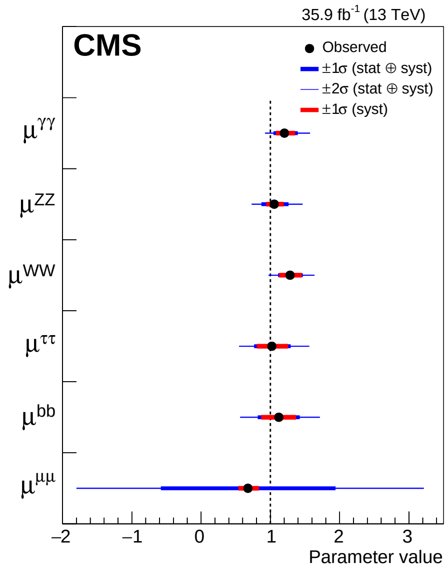


Figure 2. Summary plot of the fit to the per-production mode (left) [7] and per-decay mode (right) signal strength modifiers [7].

Measurements of the Higgs boson production cross section times branching fraction in each of the channels are presented, along with a generic parametrization in terms of ratios of production cross sections and branching fractions, which makes no assumptions about the Higgs boson total width. The combined signal yield relative to the SM prediction has been measured as 1.17 ± 0.10 at $m_H = 125.09$ GeV. An improvement in the measured precision of the gluon fusion production rate of around ∼50% is achieved compared to previous ATLAS and CMS measurements.

2.2. Top Quark Properties

The top quark t is the heaviest standard model particle with the largest Yukawa coupling to the Higgs. As physics beyond the standard model is generally expected at higher scales, the top quark is the particle with the smallest mass gap to any other not yet discovered new particle and is often expected to be produced in association with new physics, such as supersymmetry. The precise knowledge of standard model top processes is essential, as it is an important background for search analyses but also because it provides through standard model precision fits direct constraints on new physics.

Top cross sections: The cross section for $t - \bar{t}$ production as a function of center of mass energy is shown in Fig. 3(left plot). The result for 13 TeV from CMS [8] is 833±33 pb, in good agreement with theory. Summary of ATLAS and CMS measurements of the single top production cross-sections in various channels as a function of the center of mass energy is shown in Fig. 3(right plot).

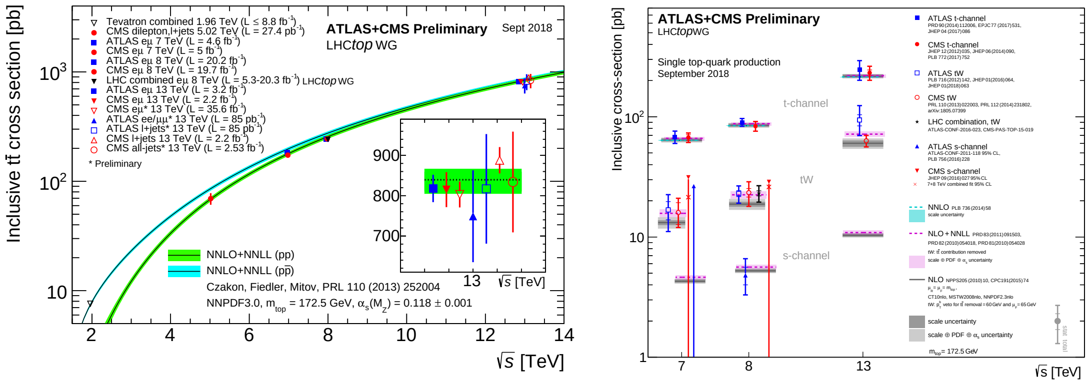


Figure 3. Left plot: top pair production total cross section vs. center of mass energy [8]. Right plot: summary of ATLAS and CMS measurements of the single top production cross-sections in various channels as a function of the center of mass energy [8].

The cross sections for the production of single top quarks and antiquarks in the t-channel, and their ratio, were measured in proton-proton collisions at a center-of-mass energy of 13 TeV using integrated luminosity of 35.9 fb^{-1} [9]. Events with one muon or electron and two jets are selected, where one of the two jets is identified as originating from a bottom quark. The ratio Rt-ch. of the cross sections is measured to be 1.65 ± 0.02 (stat)±0.04 (syst), what is in agreement with the SM predictions.

2.3. B physics

Data samples of *pp* collisions at $\sqrt{s}$ = 13 TeV, collected by CMS in the years 2015–2017, corresponding to an integrated luminosity of 80.0 fb^{-1}, were used to measure the invariant mass distribution of the $\chi_b(3P) \to \Upsilon(3S)\gamma$ candidates (see Fig. 4 left plot), with the $\Upsilon(3S)$ mesons detected in the dimuon decay channel and the photons reconstructed through conversions to *ee* pairs [10]. The measured distribution is well reproduced by the superposition of the $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ quarkonium states, overlaid on a smooth continuum (see Fig. 4 right plot). This is the first time that the two states are individually observed. Their mass difference is $\Delta M = 10.60 \pm 0.64$ (stat)±0.17 (syst) MeV, This measurement fills a gap in the spin-dependent bottomonium spectrum below the open-beauty threshold and should significantly contribute to an improved understanding of the nonperturbative spin-orbit interactions affecting quarkonium spectroscopy.

2.4. Searches for New Particles

Black Holes: A search in energetic, high-multiplicity final states for evidence of physics beyond the standard model, such as black holes, string balls, and electroweak sphalerons, is presented in work [11]. In channel with high-multiplicity final states semiclassical black holes with minimum masses as high as 10.1 TeV and string balls with masses as high as 9.5 TeV are excluded by this search.
Extra gauge bosons: A search for narrow resonances in dielectron and dimuon invariant

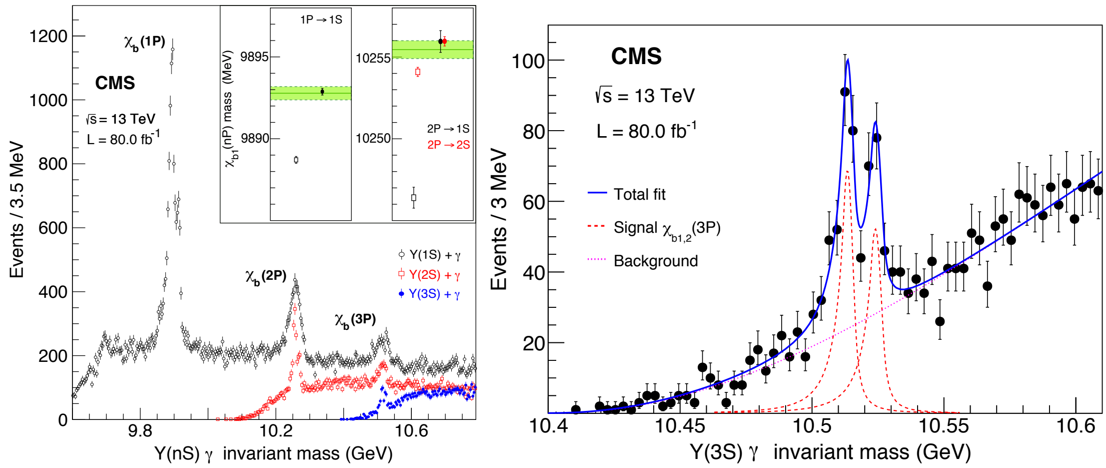


Figure 4. Left plot: the invariant mass distributions of the $\chi_{bJ} \to \Upsilon(nS)\gamma$ candidates ($n = 1, 2, 3$). The inset shows the $\chi_{b1}(1P)$ and $\chi_{b1}(2P)$ masses. The world-average values are shown by the horizontal bands, with dashed lines representing their total uncertainties [10]. Right plot: the invariant mass distribution of the $\chi_b(3P) \to \Upsilon(3S)\gamma$ candidates [10].

mass spectra has been performed using data recorded in 2016 from proton-proton collisions at $\sqrt{s} = 13$ TeV [12]. Observations are in agreement with standard model expectations (see Fig. 5). Upper limits at 95% confidence level on the product of a narrow-resonance production cross section and branching fraction to dileptons have been calculated in a model-independent manner to enable interpretation in the framework of models predicting a narrow dielectron or dimuon resonance.

Limits are set on the masses of various hypothetical particles. For the Z'_{SSM} particle, which arises in the sequential standard model, and for the superstring-inspired Z'_{ψ} particle, 95% confidence level lower mass limits for the combined channels are found to be 4.5 and 3.9 TeV, respectively. The corresponding limits for Kaluza–Klein gravitons arising in the Randall–Sundrum model of extra dimensions with coupling parameters $k/\overline{M}_{\mathrm{Pl}}$ of 0.01, 0.05, and 0.10 are 2.1, 3.65, and 4.25 TeV, respectively.

Supersymmetry: Supersymmetry (SUSY) is an extension of the SM that resolves some of its open issues: the hierarchy problem, the unification of the couplings of strong and EWK forces, and the provision of a candidate for dark matter. Many physicists expected SUSY to be seen soon after LHC startup, with as little as 100 pb^{-1} of luminosity, and to be the first major LHC discovery - before even the Higgs boson.

Now with more than 160 fb^{-1} of integrated luminosity at 13 TeV, SUSY has not yet been observed. CMS continues to pursue a broad program of SUSY searches. Searches investigate different final states and use several complementary analysis techniques [13].

3. Conclusions

The outstanding performance of the Large Hadron Collider and the CMS detector have allowed to collect a 13 TeV data set corresponding to an integrated luminosity of 160 fb^{-1} in 2016–2018. The most recent result highlights derived using this data have been presented here. So far, only of the order of 5 percent of the total expected luminosity during the lifetime of the LHC has been recorded. The data that is yet to come will allow for many more precision measurements and direct or indirect searches for new physics.

The author wishes to thank the many members of the CMS Collaboration and their technical and administrative staffs whose efforts are summarized in this report. We congratulate our

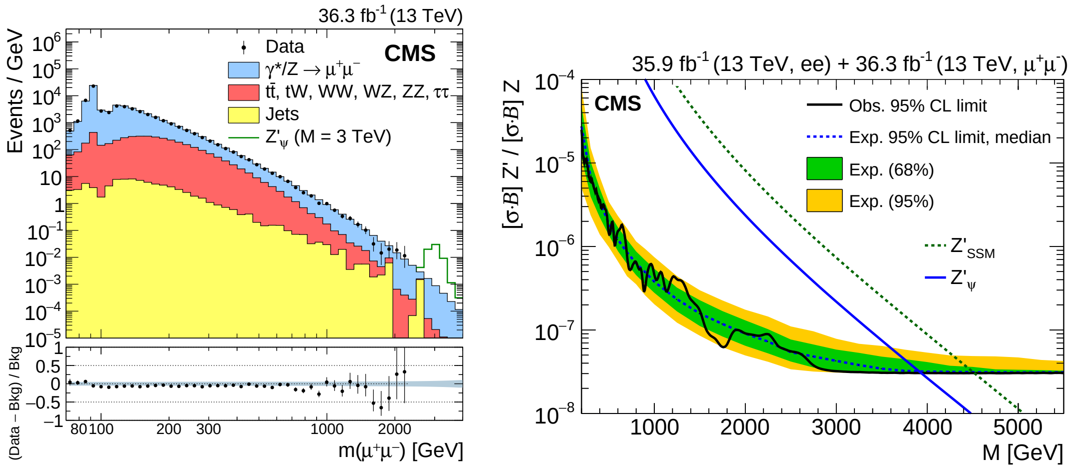


Figure 5. Left plot: the invariant mass spectra of dimuon events. The histograms represent the expectations from the SM processes. Example signal shapes for a narrow resonance with a mass of 3 TeV are shown by the stacked open histograms [12]. Right plot: the upper limits at 95% CL on the product of production cross section and branching fraction for a spin-1 resonance with a width equal to 0.6% of the resonance mass, relative to the product of production cross section and branching fraction of a Z' boson, for combination of dilectron and dimuon channels. Theoretical predictions for the spin-1 Z'_{SSM} and Z'_{ψ} resonances are shown for comparison [12].

colleagues in the CERN accelerator departments for the excellent performance of the LHC.

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