

Highlights and perspectives from the CMS experiment

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Highlights of the CMS experience are presented. A status of the detector installation in preparation for the LHC Run-3, which will start in early 2022, is given. Some of the key CMS physics results of the past year are recalled. The most recent results, included those presented at this conference, are also mentioned. A brief description of the ongoing CMS upgrade activities is provided.

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1. Introduction: status of the experiment

Since 2018, the CMS detector [1] is in its maintenance and upgrade phase, called the Long Shutdown 2 (LS2). LS2 activities continue as planned, with only minor delays mainly due to periods of confinement and travel restrictions. Some LS2 upgrade activities to highlight are:

- the replacement of the front-end electronics of the CSC muon chambers in the end-cap regions, needed to sustain HL-LHC trigger rates. This major LS2 work was completed in 2020, with few months delay due to the pandemic;
- the installation of a new layer of high-granularity muon chambers based on Gas Electron Multipliers (GEM), complementing the first station of muon chambers in the end-cap regions. This GEM layer, which covers the pseudo-rapidity range from 1.6 to 2.1, is the first Phase-2 upgrade detector installed in CMS. Together with another layer, to be integrated during LS3 to complement the second station, the GEM muon chambers will allow a reduction of the L1 trigger rate on muons in the forward regions by a factor of at least 10, as well as an improved trigger efficiency on forward displaced muons;
- the completion of the Phase-1 upgrades of the hadronic calorimeter (HCAL). These consisted in the replacement of the previous readout based on hybrid photo-diodes by a more efficient readout based on silicon photomultipliers, with a much improved longitudinal segmentation both in the barrel and end-cap regions;
- the installation of a much lighter beam pipe, completely redesigned for the high luminosity phase of the LHC. The new CMS beam pipe was fully aligned and leak tested, and the bake-out was completed the week before the start of the conference. This crucial milestone for CMS constitutes the biggest upgrade of the experiment's vacuum system since 2008;
- the refurbishment of the pixel detector, including a new barrel layer closer to the interaction point, with a more radiation tolerant electronics, and the replacement of all the DCDC converters. The re-installation of the pixel detector in CMS was completed successfully a couple of weeks after the conference;
- the successful implementation of a heterogeneous computing architecture in the High Level Trigger (HLT), with a mixture of GPUs and CPUs, already yielding significant speed improvement.

The CMS magnet is expected to be fully commissioned at 3.8 T for the two-week Pilot Beam Test run scheduled on the second part of October 2021. Then, the experiment will be re-opened for relatively minor interventions, including the installation of muon chamber demonstrators for HL-LHC. CMS is fully on track for the restart of the LHC for Run-3 in February 2022, after several weeks of commissioning with cosmic rays at nominal magnetic field (CRAFT).

The goal of Run-3 is to collect proton-proton (pp) collision data at $\sqrt{s} = 13.6$ TeV with similar pileup conditions than in 2018, as well as heavy ion collision data. The Run-3 pp dataset is expected to be equivalent to that of Run-2 in integrated luminosity, but with enhanced trigger capabilities. Furthermore, the analysis methods have considerably improved in recent years, with the generalised

usage of advanced machine learning techniques, capable of boosting the sensitivity of physics analyses. From CMS perspective, the physics case for Run-3 is considerable.

2. Physics results

The physics output of CMS is unprecedented in high-energy physics. At the date of the conference (June 2021), a total of 1043 papers based on collision data had been published (or submitted) by CMS, beyond the symbolic number of one thousand. In addition to standard high energy physics journal publications, several CMS papers have now been published in dedicated machine learning journals, illustrating the development of such tools inside the collaboration. Most recent publications are based on the entire Run 2 data set (data taken in years 2016-2018), corresponding to a total integrated luminosity of 137 fb^{-1} [2, 3].

As many as seventeen preliminary physics results were presented for the first time at the conference [4–20]; they are described in detail elsewhere in these proceedings. Here, we highlight some results published or released since the last edition of the conference.

2.1 Highlights on standard model studies

In a paper published in 2020 [21], CMS has conducted a thorough study of W-boson production and decay in the muonic channel with 2016 data (13 TeV , 36 fb^{-1}). The measurement of double-differential cross sections in 19 bins of muon transverse momentum (p_T^μ) between 26 and 45 GeV and 48 bins of pseudo-rapidity (η^μ) between -2.4 and 2.4 , are used to extract differential cross-sections and charged asymmetries separately for two the W-boson helicity states, W_L and W_R , which are compared to predictions at the next-to-leading order (NLO) in QCD. These results help constrain parton density functions (PDFs) and constitute an important milestone towards the eventual measurement of the W-boson mass in CMS.

A recent preliminary result [22] exploits a pure sample of $t\bar{t}$ events in the dilepton channel to measure the W-boson leptonic branching fractions. The p_T spectra of training leptons in ee , $e\mu$ and $\mu\mu$ events are used to disentangle prompt $W \rightarrow e/\mu$ from $W \rightarrow \tau \rightarrow e/\mu$ decays. Despite being as precise as and consistent with, the CMS results do not confirm the slight departure (2.5σ) from lepton universality implied by LEP combined results.

The inclusive diboson production cross-sections ($pp \rightarrow WW$, WZ and ZZ) are now measured with 3-10% precision at $\sqrt{s} = 7, 8$ and 13 TeV , and recently at 5.02 TeV [23]. The excellent agreement with NNLO (QCD) and NLO (EWK) calculations puts stringent limits on anomalous triple gauge couplings. An abundant and pure sample of events with full Run-2 data is used to observe, for the first time, longitudinal polarisation of W bosons in WZ production [24]. There is conclusive signals of vector boson scattering (VBS) in all $VV'jj$ final states ($V^{(\prime)} = \gamma, W$ or Z) [25–27]. Exploiting event kinematics to study the polarisation components in same-sign W pair VBS production, CMS reports a first hint (2.3σ obs., 3.1σ exp.) of the scattering of at least one W_L boson [25]. This is an important step towards probing unitarity restoration in longitudinal boson scattering at the electroweak symmetry breaking energy scale.

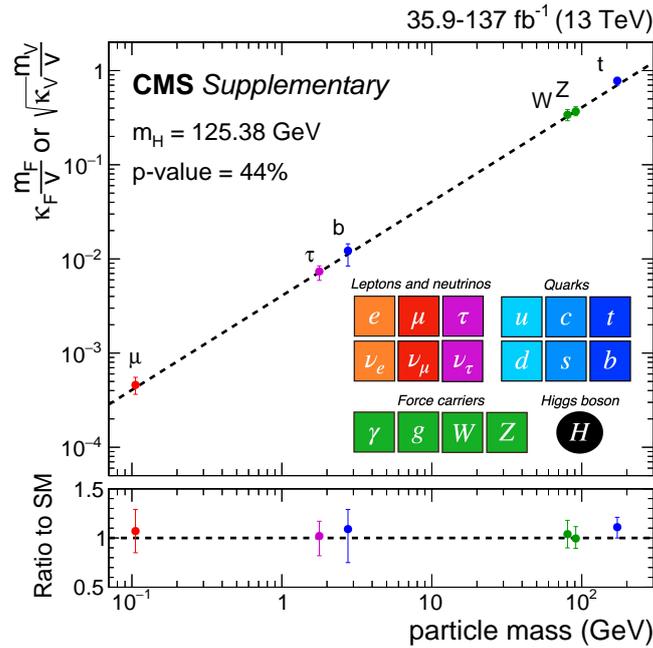


Figure 1: Reduced Higgs couplings as a function of particle mass. The points and error bars represent central values and 68% CL intervals, respectively. The dashed line indicates the standard model prediction. The coupling with the muon, measured for the first time, is shown in red. The lower panel shows ratios of measured values to standard model predictions. Within the used κ -framework model, the data are consistent with the standard model predictions with a p -value of 44%. From [28].

2.2 Highlights on Higgs boson studies

The Higgs-boson mass measurements in the $Z \rightarrow 4\ell$ [29] and $H \rightarrow \gamma\gamma$ [30] decay modes with Run-2/2016 data are independently consistent with and more precise than the Run-1 combination. The overall combination, $m_H = 125.38 \pm 0.14$ GeV, most precise to date, is used consistently in all CMS analyses. The 0.11% total uncertainty remains dominated by statistics.

The study of Higgs couplings intensifies, in the context of the Simplified Template Cross Section (STXS) framework, in particular in the $\gamma\gamma$ [31] and ZZ^* [32, 33] decay modes. The kinematic complementarity of the two modes is exploited to study for the first time the CP structure of the $t\bar{t}H$ coupling [34]. The recent evidence for the decay into muons [28] allows to establish for the first time meaningful 68% and 95% confidence intervals for a Higgs boson coupling to a second generation fermion (Fig. 1).

Impressive progress is made on the road to the observation of double-Higgs production. Limits at the 95% CL are now at 7.7 obs. (5.2 exp.) times the standard model expectation in the $b\bar{b}\gamma\gamma$ mode [35], and even 3.6 obs. (7.3 exp.) in the $b\bar{b}b\bar{b}$ mode in a result presented at this conference [6].

2.3 Highlights on top-quark mass measurements

The top-quark mass is a crucial fundamental parameter of the standard model. To complement the measurements in the main $t\bar{t}$ lepton+jets and dilepton channels, many alternative methods are developed, with different sources of systematic uncertainties. An example is the measurement of the

top-quark mass in single-top events, which is quite precise in itself (0.77 GeV in total uncertainty) and in addition allows separate measurements for the quark and antiquark [36]. Progress has been made also in extracting the top-quark pole mass from the comparison of inclusive and multi-differential $t\bar{t}$ cross section measurements with NLO predictions in the $\overline{\text{MS}}$ scheme [37]. Using similar techniques, the measurement was performed in four bins of $m_{t\bar{t}}$, establishing the running of the top-quark mass up to a scale of 1 TeV, in good agreement with RGE predictions [38].

2.4 Highlights on heavy quarks studies in heavy ion collision

The production of heavy quarks in lead-lead collisions is also studied. Following a previous observation in proton-lead collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV, CMS now reports evidence for $t\bar{t}$ production in lead-lead collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV at 4.0σ obs. (6.0σ exp.) [39]. Because they decay before QGP formation, top quarks are complementary to other probes and constitute a potential tool to study parton energy loss in the unconfined medium.

The B_c production, observed with $\gg 5\sigma$ in the $B_c \rightarrow J/\psi(\rightarrow \mu\mu)\mu\nu$ decay mode as a bridge between charm and charmonium, provides a new tool to help disentangle enhancement and suppression mechanisms at play in the evolution of heavy quarks through the QGP [14]. The nuclear modification factor, measured in two p_T bins, already excludes some of the most extreme models of charm recombination.

2.5 Highlights of beyond the standard model searches

Searches for the production of new heavy particles promptly decaying to pairs of leptons [40] or vector bosons [41] with the full Run-2 data set, have been performed. In the latter case, one of the bosons is a W decaying leptonically, while the other one (W, Z or H) is boosted and detected as a *merged* jet with substructures. Many other searches are exploiting the novel boosted boson or top-quark detection techniques (for instance [17, 20, 42]). CMS has also developed a systematic search for deviations from the standard model predictions [41] in several hundred final states and kinematic distributions, in events containing at least one lepton.

CMS pursues a rich programme of search for super-symmetry, setting strong limits on many models. Most recent analyses are optimised to tackle difficult corners of the phase space (stop corridor, compressed scenarios), as for instance [43–45].

Since recently, lots of efforts go into searches for long-lived massive particles (LLPs) [19, 46]. One of these, presented at the conference, exploits special low threshold displaced dimuon triggers reconstructed at HLT level, called "scouting data", to set limits on scalar particles from B-meson decays or dark photons from Higgs-boson decays [18].

3. Medium and long-term perspectives

CMS is preparing for the Run-3 of the LHC, which will last three years (2022-2024), with, among other physics goals, improved precision on Higgs coupling measurements, observation of the $H \rightarrow \mu^+\mu^-$ and $H \rightarrow Z\gamma$ ultra-rare decays, and progress towards the observation of double-Higgs production. The trigger strategy has been refined in order to be sensitive to new exotic topologies, as displaced muons from LLP decays. The computing performances have been considerably

improved, with, noticeably, the increased use of opportunistic high-performance computing and the deployment of GPUs to complement CPUs in the online compute farm.

For the longer term, CMS is actively working on upgrade projects for the high-luminosity phase-2 of the LHC, known as HL-LHC. The experimental challenges of HL-LHC are formidable. The increase in instantaneous luminosity will result in up to five-fold pile-up and radiation levels. The phase-2 upgrades of the CMS detector are designed to mitigate this unprecedented experimental environment, with the goal of integrating 3 to 5,000 fb⁻¹ of high-quality $\sqrt{s} = 14$ TeV pp collision data (2027-2038). The key elements of the CMS phase-2 upgrade programme are:

- a completely new central tracker, again all-silicon but with much higher granularity (2 billion pixels and micro-strips), a coverage extended to $\eta = 4$ and level-1 track-trigger capability;
- a new high-granularity calorimeter between 1.5 and 3 in pseudo-rapidity (HGCAL), which will sample EM-showers every radiation length (28 samples) with small silicon pixels, and hadron showers every 0.35 absorption length (24 samples) with a combination of silicon pixels and scintillating tiles, mapping the full development of all showers (a total of 6M channels) in 3 dimensions;
- precision timing on all particles, either neutral (ECAL and HGCAL) or charged (Mip Timing Detector, or MTD), providing reconstruction with a fourth dimension in order to mitigate the effects of pile-up;
- an improved trigger system, exploiting specialised processors (FPGAs at level-1, GPUs at HLT), with an output rate of 7.5 kHz (compared to 1 kHz in Run-2).

With this ambitious programme, described in detail elsewhere in these proceedings, CMS will not only be able to maintain the existing performance in the new, much harsher conditions at HL-LHC, but will even out-perform the current detector with new capabilities (for example, extended tracking acceptance or particle identification), which will significantly improve the physics reach of the experiment.

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