Status of the CMS experiment, highlights and perspectives

Joel Nathan Butler on behalf of the CMS Collaboration

Abstract

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Chapter 1

Status of the CMS experiment, highlights and perspectives

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The Large Hadron Collider began providing proton-proton collisions at 13 TeV center-of-mass energy in 2015 and has achieved very high luminosity and reliability. By the fall of 2018, it has delivered more than 120 fb$^{-1}$ to the CMS experiment, with more than 150 fb$^{-1}$ expected before a two-year shutdown for accelerator and detector upgrades starting in December of 2018. The performance of the CMS Experiment in this running period and a selection of recent results, including the properties of the Higgs boson, mainly those related to its coupling to fermions; precision measurements of top- and b-quark properties; and searches for new particles and forces, are presented. The highlights of the High Luminosity (HL-LHC) upgrade of the CMS detector, which, after another long shutdown for a second LHC upgrade, will run from 2026-2036, are briefly outlined.

1.1 Current status of particle physics at the LHC

The Higgs boson, with mass 125.09 GeV/c$^2$, was discovered 6 years ago at the Large Hadron Collider (LHC) [1], [2]. The presence of the associated Higgs field explains how elementary particles get their masses and, in some sense, “completes” the Standard Model (SM) of particle physics. The SM describes the strong and electroweak interactions with impressive accuracy but still does not explain many of the phenomena of our physical universe, among them the
stability of the Higgs boson mass to higher order quantum effects; the baryon asymmetry of the universe; the existence of three generations of quarks and charged leptons, their mass values and mixing; the small values of the masses of the neutral leptons, i.e. the neutrinos, and the neutrino mixing pattern; the nature of Dark Matter and Dark Energy; and the connection between the strong and electroweak interactions and gravitation.

For all its successes, the SM does not explain how we have arrived at the universe that exists today. Physics beyond the SM (BSM) must exist. There are strong reasons why some of the missing pieces of this puzzle should appear at the TeV or “Tera” scale, accessible at the LHC. There are many theories and models of BSM physics but there is no clear guidance on the best place to look to find it and the “right place” may not even be on our current menu of ideas. A broad investigation on many fronts is therefore necessary. We have three strategies for exploring this large, but as yet largely uncharted, territory: studying the properties of the Higgs boson that, through its coupling directly to mass, can make contact with new particles and hidden sectors that are invisible to us otherwise; looking for deviations from the precise predictions of the SM; and searching directly for new particles and new forces. All three strategies require more data, for which particle physics has a plan based on the extraordinary capabilities of the LHC.
1.2 Brief description of the CMS detector

A schematic of the CMS detector is shown in Fig. 1.1[3]. Its purpose is to reconstruct and measure the properties of all the SM objects produced in the collisions, including electrons, muons, photons, charged hadrons, “jets” (collimated sprays of charged and neutral particles originating from quarks and gluons), and indirectly neutrinos, through the observation of the Missing Transverse Energy (MET), which they carry away from the collision without detection. The design of CMS is based on a large superconducting solenoid, 6 m in diameter and 15 m long, with a very strong magnetic field of 3.8T. All of the charged particle tracking and calorimeter systems are inside this solenoid. The tracking is based on a silicon detector which is composed of layers of silicon pixels, 100 µm×150 µm, extending to a radius of about ~20 cm, followed by layers of silicon microstrip detectors extending from ~25 cm to ~110 cm, with strips of pitch varying from 80 µm to 200 µm. The employment of an “all-silicon” tracker, composed of 200 m² of silicon diodes is a first in collider physics. The combination of the strong field and a precision charged particle tracking system results in excellent momentum resolution for charged particles. At larger radii, beyond the tracking system, there is a calorimeter made of ~76,000 lead tungstate (PbWO₄) crystals, which identifies photons and electrons and measures their energy. Beyond that, there is a calorimeter made of brass plates interleaved with plastic scintillator to identify hadronic particles and their showers and measure their energies. Outside the solenoid, in pockets in its iron return yoke, gaseous ionization detectors identify the presence of muons and, using the magnetic field of the return yoke iron, make a first measurement of their transverse momenta (p_T).

The LHC collides very intense beams of protons in the center of the CMS detector. The beams are produced in bunches with an RMS of order 5 cm along the beamline and a few tens of microns transverse to the beamline. The bunches contain about 1.2×10¹¹ protons and are spaced at 25 ns time intervals (40 MHz). About 2500 bunches fit around the accelerator ring. In a typical “bunch crossing” many collisions occur. This is shown graphically in Fig. 1.2, which is a representation of a beam crossing with about 38 reconstructed vertices. Currently, the number of collisions in a crossing, called “pileup”, is averaging about 40. The distribution of the average pileup during the 2018 data taking is given in Fig. 1.3.

The LHC produces about 2 billion inelastic collisions per beam crossing. This results in orders of magnitude more data than CMS could record or store even with very modern technology. Fortunately, the collisions that contribute to answering the questions listed above typically have high transverse momentum objects whereas the vast majority of the collisions have only “soft” low transverse momentum particles. These soft collisions are already well-characterized and can be removed by a so-called “trigger” or filtering system. The CMS trigger has two levels, a first level based only on signals from the calorimetry and muon detectors, which are relatively coarse devices, and which uses dedicated hardware to do simple computations very quickly, <4µs, on every beam crossing.
and passes about 100,000 crossings with interesting events to the next level; and a second level, or High Level trigger (HLT), which uses the full capability of the silicon tracking system in conjunction with the calorimeters and muon detectors to do much more sophisticated computations on a large cluster of thousands of modern, advanced microprocessors to chose about 1000 crossings, which contain all of the most interesting events, to record for subsequent detailed analysis. The trigger system is particularly challenging at high pileup because the extra particles from all the soft collisions tend to pollute the “hard collisions” and make them hard to recognize and to reconstruct accurately, as can be seen in Fig. 1.2, while conspiring to create “false triggers” consisting only of overlapping soft collisions.

1.3 LHC and CMS performance at 13 TeV center-of-mass energy in 2016/17/18

After running at a center-of-mass energy of 7 TeV in 2011 and 8 TeV in 2012, the LHC restarted in 2015 at 13 TeV and has produced three years of sustained high luminosity from 2016-2018 that will result in more than 150 fb$^{-1}$ by the end of the 2018 run. In this period, it has achieved a peak luminosity of $>2 \times 10^{34}$ cm$^{-2}$s$^{-1}$, twice its original design, and has operated with much higher availability, >50%, than expected for a machine of such complexity. Figure 1.4 shows the luminosity delivered from 2010 to the present and the projections through the end of 2018.

CMS has used the available time in collisions with great efficiency, as shown in Figure 1.5(left), for 2018 data-taking. From the startup in April until the end of August, just before beginning of this conference, the efficiency was 94%. With the vast amount of data collected starting in 2011, CMS has now published nearly 800 papers in the major refereed HEP physics journals, with the 2017 results just beginning to appear and 2018 data just beginning to be reconstructed. The publication record at the time of this workshop is shown by time
and topic in Fig. 1.5(right)[4].

1.4 Recent physics results

Many new CMS results have become available this summer and will be presented at this meeting. In this introduction, I cover one aspect of Higgs physics, the Higgs Yukawa couplings to 3rd generation fermions, which have all been observed in the past year. I touch briefly on top and bottom quark physics, and give a few examples of the many searches for BSM physics that have been carried out.

1.4.1 Higgs Yukawa couplings to 3rd generation fermions

The mathematics by which the Higgs mechanism for Electroweak Symmetry Breaking gives mass to the W and Z bosons does not provide masses to the fermions, i.e. the quarks and leptons of the SM. However, the Higgs field can give masses to the fermions via a Yukawa interaction [5]. This is a new force
between elementary particles, in nature, communicated by a scalar field rather than by a vector gauge boson [6]. The Yukawa force is observed via the decays of the Higgs boson to fermion pairs. Since the Higgs field couples to mass, the Yukawa coupling is expected to have a strength of \( \frac{m_f}{V} \) where \( m_f \) is the mass of the fermion and \( V \) is the Vacuum Expectation Value of the Higgs field. Since the coupling is strongest to the more massive third generation quarks and leptons, the search takes the form of looking for the decays of the Higgs to \( \tau^+ \tau^- \), \( bb \), and, since the Higgs boson is too light to be able to decay into \( tt \), the fusion of two top quarks into a Higgs boson, whose signature is \( ttH \) production. The Higgs boson cross section is very small and all the analyses must contend with very large SM backgrounds. The most successful strategy has been to consider as many decay modes and production mechanisms as possible and to “target” the analyses towards particular combinations that would have observable signals and favorable signal-to-background ratios. Figure 1.6 gives a brief summary of the various Higgs decay modes and production mechanisms as expected in the SM.

Before 2017, there was some evidence of the Higgs fermionic coupling. The observation of the Higgs boson decaying to \( \gamma\gamma \) could be taken as evidence for its coupling to the top quark through a Yukawa interaction. However, the \( \gamma\gamma \) decay is very rare and new physics could affect the decay rate, diluting this conclusion. There was also a combination of results from CMS and ATLAS [7] on the decay of Higgs boson to \( \tau\tau \) that, taken together, exceeded 5\( \sigma \).

**Higgs to \( \tau^+\tau^- \)**

The decay of the Higgs boson to a \( \tau \) pair is a promising channel to establish the Higgs coupling to fermions because it is predicted to have a 6.3\% branch-
Figure 1.7: (left) Distribution of event yields vs expected $\log_{10}(S/(S+B))$ showing an excess of data events in the bins expected to have the best signal significance; (right) plots showing the $\tau\tau$ invariant mass weighted by $S/(S+B)$ and, in the inset, the mass after background subtraction, showing a peak at the Higgs mass\cite{8}.

The $\tau$ decays fully leptonically into an $e$ or $\mu$ and two neutrinos, or into a hadron and a $\tau$ neutrino, with the hadron often a low mass resonance decaying into a few charged or neutral pions, collectively labelled $\tau_h$. For the decays of $\tau$ pairs, four final states are employed: $\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$; and $e\mu$. Three production "channels" are studied, 0-jet, "boosted" and Vector Boson fusion (VBF). Using only the 13 TeV data from 2016, a signal, shown in Fig. 1.7, is found with a significance of 4.9\,$\sigma$ observed (4.7\,$\sigma$ expected). The signal strength modifier $\mu = \sigma/\sigma_{SM}$ is $1.09^{+0.27}_{-0.26}$. When combined with the 7 and 8 TeV data, a signal is observed at the 5.9\,$\sigma$ level (5.9\,$\sigma$ expected). The signal strength modifier for all data combined is 0.98$\pm$0.18. This result \cite{8} is the first direct observation above 5\,$\sigma$ by a single experiment of the Higgs boson’s coupling to any fermion; the first observation of its coupling to a lepton; and the first observation of its coupling to a particle of the 3\textsuperscript{rd} generation.

ttH

Since the decay of the Higgs boson into a $t\bar{t}$ pair is kinematically forbidden, the coupling between the top quarks and the Higgs must be observed via the production processes shown in Fig. 1.8, in which two top quarks and a Higgs boson are observed. The top quarks are observed through their decays to $Wb$ with the $W$ decaying leptonically or hadronically. The Higgs is observed through its decays to $bb$, $\tau\tau$, $\gamma\gamma$, $WW^*$ and $ZZ^*$. For the $W$ and $Z$ decays various quark and multi-lepton channels are employed and for the $\tau$ leptons hadronic decays, $\tau_h$, are used. A total of 88 different event topologies, consisting of leptons, photons, and jets, are combined to get the results. Deep Neural Nets (DNNs), which produce increased sensitivity, are pervasive in this analysis.
Figure 1.8: (left) Feynmann diagram for fusion of two off-shell top quarks into an on-shell Higgs boson; (right) radiation, also known as “Higgs-Strahlung”, of Higgs boson from a top quark.

Figure 1.9: (left) Test statistic, $q$, vs signal strength modifier, $\mu$ for ttH. The horizontal dashed lines indicate the $p$-values for the background-only hypothesis, obtained from the asymptotic distribution for $q$; (center) Distribution of event yields vs expected $\log_{10}(S/(S+B))$ showing an excess of data events in the bins expected to have the best signal significance; and (right) $\mu$ for various Higgs decay modes and for 7+8 TeV and 13 TeV separately and for data from all three years combined[9].

The main systematic uncertainties are: experimental – lepton and b-jet identification efficiencies and $\tau_h$ and jet energy scales; theory uncertainties on background calculations – modeling uncertainties in $tt$ production in association with a $W$ or $Z$ or a pair of $b$ or $c$ jets; and theory uncertainties on the signal calculations – effect of higher order corrections on the $ttH$ cross section and uncertainty in the parton distribution functions of the proton. The $\gamma\gamma$ and $ZZ^\ast$ final states are still limited by statistics but the $bb$ and multi-lepton final states are already limited by systematics.

The results [9] are shown in Fig. 1.9. When the 13 TeV results from the 2016 (based on 35.9 fb$^{-1}$ of data) are combined with data from 7 (5.1 fb$^{-1}$) and 8 TeV (19.7 fb$^{-1}$), we obtain a significance of 5.2$\sigma$ with a signal strength modifier of $\mu = 1.26^{+0.31}_{-0.26}$.

An example of a ttH “candidate” event is shown in Fig. 1.10[10]. This is referred to as a candidate since it could also be a background event. However, we are beginning to see excesses of such events. This example links the heaviest bosons and quarks (H, W, top, b) and the heaviest lepton ($\tau$), to some of the lightest quarks and leptons, including all three flavors of neutrinos, and emphasizes the astonishing range of masses of the particles that is included in
Figure 1.10: An event candidate with two top decays and a Higgs decay into a \( \tau^+ \tau^- \) pair[10].

\[ \text{Higgs} \rightarrow b\bar{b} \]

While the branching fraction of the Higgs to \( b\bar{b} \) expected in the SM is nearly 60\%, by far larger any other decay mode, QCD produces \( b\bar{b} \) pairs near the Higgs boson mass at roughly 1000 times the rate from Higgs decay, overwhelming any signal. To observe this decay, it is necessary to target a production mechanism that avoids this QCD background. This is done by focusing on the associated production of a Higgs and a vector boson, \( W \) or \( Z \), an electroweak process which is, however, only \( \sim 5\% \) of the total Higgs production rate. Moreover, in order to select a clean sample of these “\( VH(bb) \)” decays, one has also to target clean signatures for the vector bosons, which include the three topologies shown in Fig. 1.11. The final state then contains two \( b \)-jets, identified, using various properties such as the presence of secondary vertices or tracks with significant impact parameters relative to the production vertex. The \( b \)-jets are required to be produced opposite to the leptons or MET from the vector bosons. The invariant mass of the \( b \)-dijet is obtained from the measured jet momentum vectors and one looks for a peak at the Higgs mass.

Unlike in the case of \( H \rightarrow \tau^+ \tau^- \) and \( ttH \), CMS needed to use the 2017 data to bring the observation of \( VH(bb) \) within reach. Several improvements were developed for the 2017 analysis, including increasingly heavy use of DNNs to improve the efficiency and purity of the analysis. All of the analysis techniques were validated using \( VZ(bb) \), a very similar final state.

With \( VH(bb) \) from 2016/17 at 13 TeV, using 77.2 fb\(^{-1} \), CMS obtained a
Figure 1.11: Targeted $VH(b\bar{b})$ modes: (left) $Z(\rightarrow \mu^+\mu^-)$ or $e^+e^-$ $b\bar{b}$; (center) $W(\rightarrow \mu\nu)$ or $e\nu$ $b\bar{b}$; and (right) $Z(\rightarrow \nu\nu)$ $b\bar{b}$

Figure 1.12: (left) Measured signal strength modifiers for $H\rightarrow b\bar{b}$ for various periods of CMS data taking; (right) Invariant mass of $b$-tagged di-jets produced in association with a $W$ or $Z$ boson, weighted by $S/(S+B)$. The excess in red is the signal [11].

The significance of $4.4\sigma$ observed ($4.2\sigma$ expected). By combining this with the 7 and 8 TeV data, we obtained a significance of $4.8\sigma$ observed ($4.9\sigma$ expected). Including new results from all other Run 1 and Run 2 analyses that also provide information on $H\rightarrow b\bar{b}$, such as Vector Boson Fusion, $ttH$, and Boosted ggH, we obtain $5.6\sigma$ significance observed ($5.5\sigma$ expected), with a coupling strength modifier of $\mu = 1.04 \pm 0.20$. The signal strength modifiers for various subsets of the analysis are shown in Fig. 1.12, along with a plot of the invariant mass the $b\bar{b}$ pairs. The excess of events from the Higgs boson decay is clearly evident. This is a very recent result this summer by CMS [11] and at the same time by our colleagues at ATLAS [12].

An example of a “candidate” event for the Higgs decaying to $b\bar{b}$ is shown in Fig. 1.13.

**Higgs $\rightarrow \mu^+\mu^-$**

While the Higgs couplings to the 3rd generation of fermions are now established, the measurement of the couplings to 2nd generation fermions will be very challenging. The best chance is $H\rightarrow \mu^+\mu^-$, even though the branching fraction (BF) is expected to be $2.2\times10^{-4}$, about 1/10 that of $\gamma\gamma$. CMS has looked for this in 7, 8, and 13 TeV (2016 only) data. The current 95% CL upper limit
on the BF is $6.4 \times 10^{-4}$, which is 2.92 (observed) vs 2.16 (expected) of the SM prediction [14]. There is hope that $3\sigma$ evidence for this decay will be obtained in Run 3 of the LHC, which will run from 2021 until 2024. A measurement at the 10% level will be possible only towards the end of the HL-LHC era with 3000-4000 fb$^{-1}$ of accumulated luminosity.

1.4.2 Top quark physics

The cross section for pair production of top quarks at 13 TeV has been measured to be $835\pm 33$ pb, in good agreement with the theoretical prediction of $816\pm 42$ pb. A summary of results from measurements at the Tevatron and the LHC, along with comparisons with theory is shown in Fig. 1.14[15]. This translates into a production rate of $t\bar{t}$ pairs of greater than 10 Hz. This high rate, comparable to the $b\bar{b}$ rates at recent "b-factories", gives the LHC top-quark program a very different characteristic than the program at the Tevatron at $\sim 2$ TeV. Precision measurements of single, double, and triple differential cross sections in several variables are now possible, as are searches for Rare (FCNC) decays and CP violation aimed at observing BSM physics. New measurements of the top width and more complex methods for measuring the mass can now also be performed. At 13 TeV, top pairs are mainly produced by gluon fusion, unlike at the Tevatron where quark-anti-quark annihilation is the dominant production mechanism, so the LHC provides very important information on the gluon distribution at relatively high $X_F$ of $\sim 0.25$.

The top mass measurement using traditional methods is currently systematics limited[16]. Some of the new techniques[17], most also already systematics
limited, were hoped to have different and uncorrelated systemics and so might help to reduce the overall uncertainty. So far, this has not been the case. The top mass measurement is crucial and some new ideas will be needed. A summary of CMS measurements of the top quark mass, along with the average from the Tevatron and the world average, is presented in Fig. 1.15.

Three recent results, shown in Fig. 1.16, illustrate the types of measurements that can now be made. The figure on the left shows a study of the correlation in the azimuthal angle of the muons when both $W$s from the two top quarks decay leptonically. This result\[18\] addresses the presence of the “chromomagnetic dipole moment” of the top quark. The middle figure shows that single top production by $W$-exchange in the t-channel results in a charge asymmetry because there are more $u$ than $d$ valence quarks in the colliding protons. CMS has made a precise measurement of t-channel single top cross sections and $R_{t-ch}$, the ratio of $t^+$ to $t^-$ production of $1.65\pm0.02$ (stat)$\pm0.04$ (syst)[19]. The total single top cross section is measured to be $219.0\pm1.5$ (stat)$\pm33.0$ (syst). The analysis also is able to measure the absolute value of the CKM matrix element $V_{tb}$, which is $1.00\pm0.05$ (exp)$\pm0.02$ (theo). The right side of Fig. 1.16 shows a very clean signal for the reconstruction of top quarks decaying to three jets[20] at 13 TeV. Measurements of cross sections have advanced to the point where precision doubly-differential cross sections are now appearing and being compared in detail to various simulations. A recent example[21] is shown in Fig. 1.17.

Another interesting result is the first observation of top production in proton-lead collisions at a nucleon-nucleon center of mass energy of 8.16 TeV, shown in Fig. 1.18[22]. This is based on events with an $e^+$ or $\mu^+$ from a semi-leptonic

Figure 1.14: Cross section for pair production of top quarks[15].
Figure 1.15: (left) CMS measurements of the top quark mass using the standard methods that have been developed at the Tevatron and LHC and currently contribute to the world averages. Shown also are the Tevatron and world combination[16]; (right) Measurements of the top mass in CMS based on recently developed alternative techniques[17].

Figure 1.16: (left) Differential cross section of $t\bar{t}$ production vs the difference in the azimuthal angle of the two muons from the decays of the top to $W(\mu\nu)b[18]$; (center) Single top production is initiated by $u$-quarks and anti-top-quark production is initiated by $d$-quarks, leading to a charge asymmetry since there are more $u$-quarks in the proton[19]; and (right) Invariant mass of three jets, showing a peak at the top quark mass[20].
Figure 1.17: Double-differential cross section at the particle level as a function of $M(t\bar{t})$ vs. $|y(t\bar{t})|$. The data are shown as points with light (dark) bands indicating the statistical (statistical and systematic) uncertainties. The cross sections are compared to several standard simulations. The ratios of the various predictions to the measured cross sections are shown at the bottom of each panel[21].
Figure 1.18: Observation of top-quark pair production in proton-lead collisions. (left) For events with two b-jets, the dijet mass for light quarks, showing a peak at the W mass; and (right) the mass of the light di-jet and a b-jet, revealing a clear excess over background at the top mass [22].

decay of one top along with $> 4$ jets. The $t\bar{t}$ cross section is extracted from a combined maximum-likelihood fit of the invariant mass of the two light-quark jets from the $W$-boson decay, in different categories of events with zero, one, or at least two b-tagged jets. The cross section is $45\pm8$ nb, consistent with the expectations of perturbative QCD.

1.4.3 $B$ physics

BSM physics has the capability of affecting the branching fractions and angular distributions of rare $B$ decays with flavor-changing neutral currents. In 2015, LHCb reported a mild deviation in an amplitude, known as $P'_5$ in the decay $B^{0*} \rightarrow K^{*0}\mu^+\mu^-$. CMS studied this decay and concluded that it was consistent with the SM prediction. Recently, CMS has produced a study of the related decay $B^+ \rightarrow K^+\mu^+\mu^-$ [23], whose Feynman diagrams are shown in Fig 1.19. The angular distribution depends on two quantities that are functions of $q^2$, the invariant mass of the dimuons: the forward-backward asymmetry $A_{FB}$ of the muon system; and the contribution $F_H$ of the pseudoscalar, scalar, and tensor amplitudes to the decay width. The signals as a function of $q^2$ are shown in Fig. 1.20. A fit to the angular dependence, given in Fig. 1.21, shows that they agree with the SM. This decay has recently attracted attention since its branching fraction should, in the SM, be very close to equal to that of $B^+ \rightarrow K^+e^+e^-$, but it seems to be somewhat less [24]. In its 2016 and 2017 data, CMS did not have a trigger that was designed for efficient selection of low mass di-electron states. An attempt has been made to improve the situation in 2018.

$B$ physics is also an excellent laboratory for studying QCD. The ATLAS experiment at the LHC discovered a mass bump at 10.5 GeV [25] through its
Figure 1.19: Feynman diagrams for the decay $K^+\mu^+\mu^-$. 

Figure 1.20: Invariant mass distributions of $K^+\mu^+\mu^-$ vs the dimuon mass, $q^2[23]$. 

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Figure 1.21: (left) $A_{FB}$ and (right) $F_H$ as a function of the dimuon mass $q^2$ in the decay $K^+\mu^+\mu^−$[23].

decay into $\Upsilon(1S,2S)\gamma$, where the $\gamma$ is observed through its conversion to an $e^+e^−$ pair. This bump is tentatively identified as the $\chi_b(3P)$ bottomonium state. Three such states are expected with total angular momentum $J=0, 1,$ and $2$, of which the latter two should have large branching fractions to the photon decay. However, since this is the bottomonium state closest to the continuum, it could mix with states that are just above the continuum. This could lead to a state analogous to the $X(3872)$ in the charmonium system. CMS undertook a study of this mass region[26] using the decay $\Upsilon(3S)\gamma$ and the full 2015-2017 CMS data set consisting of nearly 80 fb$^{-1}$ of data, using the dimuon decay of the $\Upsilon(3s)$ and converted photons. The spectra of $\Upsilon\gamma$ are shown in Fig. 1.22. Although the $\chi_b(3P)$ decay to $\Upsilon(3S)\gamma$ has the lowest statistics, it results in the lowest photon energy and, for reconstruction of the photon conversion using the CMS tracking system in the 3.8 T solenoidal field, gives superb mass resolution. The resulting spectrum is shown in Fig.1.22 (right side). Two peaks are clearly resolved. The mass difference of $\Delta M = 10.6 \pm 0.64(stat) \pm 0.17(syst)$ MeV is consistent with most predictions that this is a simple bottomonium state and is not significantly mixed with states in the continuum. The outstanding resolution of the CMS spectrometer and the massive amount of data analyzed were the keys to obtaining this result.

1.4.4 Searches

Many searches have been carried out to find BSM physics at the LHC but so far without success. Here, we present only a few illustrative results. The first is a classic search for a new $Z'$-like particle decaying into an $e^+e^−$ pair[27]. The invariant mass plot in Fig. 1.23 (left), based on 41.4 fb$^{-1}$ of data from 2017, shows no evidence of an excess. When combined with the data from 2016, mass exclusion limits for some models reach as high as 4.5 TeV. The second example is a less conventional search for a light $Z'$ that couples only to second- and third-generation leptons ($\mu$, $\nu_\mu$, $\tau$ and $\nu_\tau$)[28]. It can be produced from one of the muons in $Z$-decays, and observed using its decay $Z' \to \mu^+\mu^−$, shown in Fig. 1.23 (center). The resulting exclusion plot in coupling strength $g_\mu$ vs
Z’ mass is shown in Fig. 1.23 (right). This exclusion plot already eliminates some of the phase space of models that attempt to address the lepton anomaly described in the previous section.

Dark matter searches have been very popular in CMS and at the LHC. The search strategy employed was to look for missing transverse energy, corresponding to the dark matter particle, recoiling against some SM objects that were produced in the interaction. Many searches using various SM recoils were conducted but no dark matter particles were observed for masses of up to ~1 TeV. More sophisticated studies considering specific mediators soon followed. More recently, there are new theories that consider very complex dark sectors with self-interacting particles and some link through a mediator to the SM particles. These models of interacting dark matter can give rise to very new and unusual physics signatures. In one class of models\cite{29}, new fermions (dark quarks), $Q_d$, are charged under a new force in the dark sector that has confining properties similar to quantum chromodynamics (QCD) but are not charged under the forces of the SM. The mediator $X_d$ is a complex scalar. The dark quark jets
contain many displaced vertices arising from the decays of the dark pions, $\pi_d$, produced in the dark parton shower and fragmentation, producing an “emergent” jet. For models with dark hadron decay lengths comparable to the size of the detector, there can also be significant missing transverse momentum. The main background to this signature is SM four-jet production with $b$-quarks. The results of a recent CMS study[30] are shown in Fig. 1.24.

In 2010, many particle physicists thought Supersymmetry (SUSY) would be seen soon after the LHC startup, even before the Higgs boson, with as little as a few hundred $\text{pb}^{-1}$ of data. When the center-of-mass energy increased to 13 TeV in 2015, once again expectations were high but so far no evidence for SUSY has been found. Much effort has gone into identifying and eliminating scenarios whereby SUSY could avoid detection. After very many analyses, only a small sample of which is shown in Fig. 1.25, SUSY has still either not appeared or has somehow avoided detection. Recently, more attention has been given to $R$-parity violating SUSY, which can have relatively long-lived particles that can decay inside CMS. Many other models of BSM physics also have long-lived particles and the program to search for them has sometimes been called the “longevity frontier”. Typical signatures include displaced objects such as vertices, jets, dijets, conversions, displaced photons, leptons or dileptons, heavy stable charged particles (HSCP), and disappearing tracks. Some of these require special triggers and data taken up to now may not have been very sensitive to them. CMS has recently completed a search for stopped long-lived particles using the full 2015 and 2016 data sets[31]. The signature is a high energy jet in the calorimeter out of time with collisions. Gluinos with lifetimes from 10 ms to 1000 s and masses less than 1379 GeV and top squarks with lifetimes from 10 ms to 1000 s and masses less than 740 GeV are excluded. Looking ahead, Exotic and SUSY searches are shifting to lower mass and longer-lived particles.

### 1.5 HL-LHC upgrade

The LHC will operate at 14 TeV starting in 2021. After that, increases in sensitivity will come from accumulating luminosity. The LHC and its injector...
complex will be upgraded to produce more luminosity during a long shutdown that will take place in 2024-2026[32]. After that it will be able to run at a luminosity-leveled $5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ or possibly even $7.5 \times 10^{34}$. The expected pileup will be between 140 and 200 interactions per beam crossing. The expected delivery of integrated luminosity to CMS and ATLAS, including the impact of planned upgrades to the LHC and its injector chain, is shown in Fig. 1.26. The operation after the full LHC upgrade is completed in 2026 is a new era referred to as the High Luminosity LHC or, in short, the HL-LHC. The goal is to provide about 300 fb$^{-1}$ per year. CMS’s goal is to run for a decade or more and to achieve an integrated luminosity of 3000-4000 fb$^{-1}$ for the full LHC program.

CMS will have to be upgraded to survive much higher integrated radiation doses and to retain its efficiency and low background rates at pileup of up to 200 interactions per beam crossing. The problem is illustrated in Fig. 1.27, which shows a Higgs$\rightarrow \tau\tau$ event produced by Vector Boson Fusion, embedded in 200 other collisions. New triggering strategies will have to be developed and implemented and much larger data rates will have to be sustained. In addition, more data will have to be stored, reconstructed, and accessed for analysis. Every CMS sub-detector is challenged by the unprecedented conditions at the HL-LHC and will need to be upgraded or replaced.

CMS has developed a plan to meet these challenges [33]. The key elements, shown in Fig. 1.28 are that the tracker is again all silicon but now with much higher granularity, with more than 2 billion pixels and microstrips, and extends to $\eta = 4$. Tracking information is used in the lowest level trigger, called the “L1
Figure 1.26: Planned integrated luminosity provided by the LHC to CMS between now and 2038.

Figure 1.27: A simulated event with a Higgs boson produced by Vector Boson Fusion decaying into $\tau$-pairs with 200 accompanying soft collisions.
track-trigger, which permits very refined trigger algorithms to be applied. The tracker is designed to enable finding of all tracks with $p_T > 2$ GeV in under 4 µs for use in the global L1 trigger. There will also be High Granularity Endcap Calorimeters that will sample the EM-showers every $\sim$1 radiation length (28 samples) with small silicon pixels and then sample every hadron shower with $\sim$0.35 absorption lengths (24 samples) with a combination of silicon pixels and scintillating tiles to map the full 3-dimensional development of all showers ($\sim$6M channels in all) at $\eta$ from 1.5 to 3. Precision timing of all objects, including single charged tracks and electromagnetic showers, provides a 4th dimension to CMS object reconstruction to combat pileup ($>300$k sensors in barrel section) and $\sim$3M channels in each of the two endcap sections.

Significant changes will be made to the Trigger and Data Acquisition system. CMS will continue to use a two Level Trigger scheme. The first level, however, will have access to fast track reconstruction to be used in conjunction with the full granularity of the calorimeters and muon systems, to select the 750,000 most promising beam crossings each second. The Level 1 Latency will be 12.5 µs. The Level 2 Trigger will again be a cluster of high level microprocessors, perhaps combined with or augmented by more specialized processors (GPUs, FPGAs). The output rate to archival storage will be 7,500-10,000 events per second, which is to be compared to about 1000 per second in the current data run.

In addition to upgrading the current detectors to maintain the current high level of efficiency and rejection of background, CMS is planning improvements that will enhance the sensitivity of the experiment. The upgrades are not aimed only at maintaining the existing performance but will deliver fundamentally new capabilities that provide significant opportunities to improve the experiment and open it to physics that cannot be observed with the current detector.
Figure 1.29: (left) A two dimensional view in Z and time of a beam crossing with a VBF Higgs event and 200 additional soft collisions; (right) The fraction of tracks incorrectly assigned to primary (hard) collision vertex in the event as a function of the density of vertices, which is related directly to the pileup.

The MIP Timing Detector (MTD)\cite{34} is a completely new detector that will be added to CMS to help combat the high pileup. The fundamental tool used today is precision tracking of charged particles to associate them to individual collision vertices distributed over the 5 cm RMS along the beam axis. This allows the association of the correct tracks with the hard collision in the crossing, which is usually the one we are interested in. As the pileup approaches 200 interactions/crossing, the average longitudinal density of the collisions becomes $\sim 2$/mm, challenging even the high granularity precision silicon detectors planned for the HL-LHC tracker. Many tracks are associated to the wrong vertex/collision. However, because of the time it takes for the colliding beams to pass through each other, there is also a separation of the different vertices and tracks in time as well as in space. Figure 1.29 is from a simulation showing the projection of the various reconstructed vertices of these events along with their reconstructed collision times. It is very clear that the view in space and time provides a much improved understanding of the beam crossing. The number of tracks that are mis-assigned to the “primary vertex” (the one with the hard collision we want to study) is also shown in Fig. 1.29.

In order to reconstruct the time of the hard collision, it is necessary to measure the time of all charged particles traversing the detector with an accuracy of 30-60 ps. CMS plans to do this by implementing the detector shown in Fig. 1.30. It consists of a cylindrical Barrel Timing Layer (BTL) just beyond the last layer of the barrel Inner Tracker, sharing the Tracker Support Tube (TST), consisting of a thin layer of LYSO crystals whose light is recorded by Silicon Photomultipliers (SiPMs). For particles in the endcaps, the time is measured when they traverse a planar detector, called the EndCap Timing Layer (ETL), consisting of a plane of Low Gain Avalanche Detectors (LGADs), which are silicon detectors with a special implant that amplifies the signal by $\sim$5-10. The time resolution
is expected to be 30-40ps at the beginning of life, early in the HL-LHC, and to degrade to 50-60 ps, at the end of the HL-LHC program, mainly because of jitter introduced by rising dark currents from radiation exposure. Improvements to the time resolution of the CMS calorimeters will permit CMS to use timing in the reconstruction and vertex assignments for all physics objects, including photons, neutral hadrons, and jets. The timing capabilities also will improve CMS’ ability to observe long-lived particles and provide charged particle-type discrimination ($\pi$, K, p) for low transverse momentum hadrons.

1.6 Summary and outlook

Both the LHC and the CMS detector performed well in Run 2 (2015-2018). With the LHC running at 13 TeV (14 TeV after 2020) with high luminosity and availability, our discovery potential remains great. The two year shutdown in 2019/20 should give us time to catch up on analysis and assess where we really are. Discoveries may come in a few months or after several years. They might start with a striking signal appearing in a single channel or they may appear in several channels with comparable significance emerging slowly out of large backgrounds. They may appear in scenarios we have long been exploring, e.g. SUSY or Extra Dimensions, or may surprise us with signatures that we are not even looking for, or triggering on, today. They may also manifest themselves as subtle deviations from precisely measured SM processes. As investigators/researchers into the unknown we need to step back and survey the big picture and look for new, untried approaches or corners of our data that are unexplored or only dimly illuminated. Today we have <5% of the ultimate LHC data in hand. It is our mission to explore the huge new expanse of scientific territory that is available to us now and the much greater one that will open in the next
decades and learn what is there.

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Bibliography


[10] CMS Photo: http://cds.cern.ch/record/2621446


[12] ATLAS Collaboration, Observation of $H \to b\bar{b}$ decays and VH production with the ATLAS detector, *Phys. Lett.* B 786 59 (2018)

LHCTopWG, https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

CMS Collaboration, Measurement of the top quark mass using proton-proton data at $\sqrt{s} = 7$ and 8 TeV, PRD 93 (2016) 072004; and TOP-17-007 (2017)

CMS Collaboration, Combinations of the CMS alternative technique measurements of the top quark mass, CMS-PAS-TOP-15-012, https://cds.cern.ch/record/2235162?

CMS Collaboration, Measurements of $t \bar{t}$ differential cross sections in proton-proton collisions at $\sqrt{s} =13$ TeV using events containing two leptons, arXiv:1811.06625, CMS PAS TOP-17-014, submitted to *JHEP*

CMS Collaboration, Measurement of the single top quark and antiquark production cross sections in the t channel and their ratio in pp collisions at $\sqrt{s} =13$ TeV, CMS PAS TOP-17-011, http://cds.cern.ch/record/2628541

CMS Collaboration, Measurement of the top quark mass in the all-jets final state at $\sqrt{s} = 13$ TeV, CMS-PAS-TOP-17-008, https://cds.cern.ch/record/2235162?

CMS Collaboration, Measurement of differential cross sections for the production of top quark pairs and of additional jets in lepton+jets events from pp collisions at $\sqrt{s} = 13$ TeV, Phys. Rev. D 97, 112003


ATLAS Collaboration, Observation of a New $\chi_b$ State in Radiative Transitions to $\Upsilon(1S)$ and $\Upsilon(2S)$ at ATLAS, *Phys. Rev. Lett.* **108** 152001 (2012)

CMS Collaboration, Observation of the $\chi_{b1}(3P)$ and $\chi_{b2}(3P)$ and measurement of their masses, *Phys. Rev. Lett.* **121** 092002 (2018),


[31] CMS Collaboration, Search for decays of stopped exotic long-lived particles produced in proton-proton collisions at $\sqrt{s} = 13$ TeV, JHEP 05 127 (2018),

