Highlights and perspectives from the CMS experiment

Gautier Hamel de Monchenault

HEP 2021 — Conference on Recent Developments in High Energy Physics and Cosmology
Thessaloniki, Greece. ONLINE
Wednesday June 16, 2021
The CMS Collaboration

(May 2021)

2105 Authors

241 Institutes
(including
23 Associated and
8 Cooperating)
from
54 Countries

>5300 Members

Greece: 63 members, 32 authors
- Athens (33/12) L1-trigger, PPD, …
- Athens/NTUA (9/5) DAQ, HGCAL, …
- Demokritos (9/5) Tracker, …
- Ioannina (12/10) L1-trigger, …

MS: Italy (12%), Germany (8%), UK (3%), France (3%), Switzerland (3%),
Spain (3%), Belgium (3%) … Greece (1.5%) …
AS: India (3%), Turkey (2%) …
OS: Russia (5%), Korea (3%), China (2%), …

(May 2021)
**LS2 Activities**

**LS2 = Long Shutdown 2 since 2019**
Collisions to return mid 2022

- **Strip tracker**
  - kept cold to avoid reverse annealing
  - currently warm during beam pipe bake-out

- **Magnet**
  - at room temperature since mid 2020
  - maintenance work: free wheel thyristor, cryo-cooling, power, pumps, etc.

- **HCAL**
  - completion of Phase-I upgrades

- **Pixel detector**
  - replace first barrel layer
  - replace all DCDC converters

- **Beam pipe**
  - new version Phase-II design

- **Muon system**
  - installation of GE1/1 chambers
  - upgrade of CSC FEE to sustain HL-LHC trigger rates
  - shielding against neutron background

- **Strip tracker**
  - keep cold to avoid reverse annealing
  - currently warm during beam pipe bake-out

- **Beam pipe**
  - new version Phase-II design

- **Civil engineering at P5**
  - prepare for Phase-II assembly and logistics

- **CT-PPS**
  - upgrade of RP and moving system

- **BRIL**
  - BCM/PLT refit
  - new T2 tracker

- **Rotating Shielding**

**Work on HCAL Barrel** (SiPM readout) completed in Oct. 2019

**Muon critical path** completed in Dec. 2020

**Beam-pipe installation and bake-out** completed in May 2021

**Remaining activities:**
- pixel detector installation (starting June 22)
- yoke closing (starting July 19)
  - magnet restart (3.8T) and tests
  - comics runs at ~4T (CRAFT, 24/7)

**After Pilot Beam Test**
- Phase-II muon demonstrators
- new forward shielding
Some Highlights of LS2

New GEM detector GE1/1
- first Phase-II detector to be integrated in CMS!

New CMS beam pipe for Phase-II
- installation complete, fully aligned and leak tested
- bake-out just completed

Fully-refurbished pixel detector
- new BPIX layer 1: new chip with lower thresholds and better radiation tolerance
- replacement of DCDC converters

New HCAL SiPM readout
- improved longitudinal segmentation
- improved photon detection efficiency

A crucial CMS LS2 milestone
biggest upgrade to the experiment’s beam vacuum system since 2008

CMS fully on track for the Pilot Beam Test (Oct. 21) and for the start of Run-3 (Feb. 22)
On Nov. 24, 2020 CMS announced the publication of its 1000th paper in a peer-reviewed journal.

As of June 16, 2021

**CMS Publications**

**1068 CMS papers**
- **1040** published

**1043 papers based on collision data**
- **1015** published
  - 574 based on Run-1 data
  - 469 based on Run-2 data

**CMS titles**
- 527 “Search for”
- 39 “Observation”
- 18 “Evidence”
- 308 “Measurement”

**CMS with friends**
- **ATLAS**: 5 (4 JHEP, 1 PRL)
- **LHCb**: 1 (Nature)
- **Totem**: 3 (1 JHEP, 2 EPJC)

**CMS Highlights**

**Phys. Briefing**

**57 JINST**
**123 PRD**
**125 PRL**
**148 EPJC**
**239 PLB**

**Detector**
3%

**Heavy Ion**
10%

**FWD/QCD**
5%

**B Phys.**
6%

**Top Phys.**
11%

**Exotica**
18%

**Beyond-2d-Gen**
6%

**SUSY**
12%

**Higgs**
14%

**Standard Model**
14%

**Standard Model**
14%

**Exotica**
18%

**Beyond-2d-Gen**
6%

**SUSY**
12%

**Higgs**
14%

**Standard Model**
14%
CMS pp Data at LHC Run-2

Excellent performance of the LHC in Run-2

• max LHC luminosity (2018):
  \[ \mathcal{L}_{\text{max}} = 2.14 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \]
  (factor of 2 higher than designed $10^{34} \text{ cm}^{-2}\text{s}^{-1}$)

CMS Dataset Run-2

• 2016-2018: 137 fb$^{-1}$ of pp data “good for physics”
• data-taking efficiency > 92% (2018: 94%)
• number of pp interactions per beam crossing (PU): $< \mu > = 34$

CMS Triggers for Run-2 (1.6 kHz)

• Standard triggers (leptons, jets, MET)
• B-parking triggers (up to 5 kHz)
  10B events enriched in un-biased B decays
• Scouting triggers
  reduced events with physics objects

Luminosity measurements: 1.2% in 2016, overall 1.6% for Run-2
SM Production Cross Sections

September 2020

Production Cross Section, $\sigma$ [pb]

All results at: http://cern.ch/go/pNj7

CMS Preliminary

- 7 TeV CMS measurement ($L \leq 5.0 \text{ fb}^{-1}$)
- 8 TeV CMS measurement ($L \leq 19.6 \text{ fb}^{-1}$)
- 13 TeV CMS measurement ($L \leq 137 \text{ fb}^{-1}$)
- Theory prediction
- CMS 95%CL limits at 7, 8 and 13 TeV

νl → µl, l=e, Z

$\Delta \ln \sigma$ at 95% CL
**W Helicity Measurements**

Double-differential cross-sections in $p_T^\ell$ and $\eta^\ell$ ($\ell = e, \mu$) for $W^+$ and $W^-$

- **Run-2 2016, 35.9 fb$^{-1}$**
- **$p_T^\mu = 26$ GeV**
- **$\eta \in [-2.4, 2.4]$**
- **45 GeV**

Template fit to extract **differential cross-sections** and **charge asymmetries** for the two helicity states

- **constraints on PDFs**
- **milestone towards the W mass measurement**
Test of $\tau/\mu$ and $\tau/e$ Universality in W Decays

Using $t\bar{t}$ events in the dilepton channel, select relatively unbiased samples of on-shell W bosons

Trailing lepton $p_T$ used to discriminate between prompt $W \rightarrow e/\mu$ decays from $W \rightarrow \tau \rightarrow e/\mu$ decays in $ee, \mu\mu$, and $e\mu$ events

Branching fractions $W \rightarrow e, \mu, \tau$

result consistent with SM and with recent ATLAS (most-precise) $\tau/\mu$ result

CMS LU result is consistent with and improves on LEP/ADLO result

A long-standing LEP “tension” (>2.5$\sigma$) is gone

Run-2 2016, 35.9 fb$^{-1}$

CMS-PAS-SMP-18-011

CMS Preliminary

35.9 fb$^{-1}$ (13 TeV)

CMS

ATLAS

LEP/ADLO

$W \rightarrow e\nu_e$

$W \rightarrow \mu\nu_\mu$

$W \rightarrow \tau\nu_\tau$

$B(W \rightarrow v\tau) = (10.77 \pm 0.21)%$

$B(W \rightarrow v\tau) = (10.77 \pm 0.21)%$

$B(W \rightarrow v\ell) = (10.94 \pm 0.03)%$

$B(W \rightarrow v\ell) = (10.94 \pm 0.03)%$

$B(W \rightarrow v\ell) = (10.93 \pm 0.10)%$

$B(W \rightarrow v\ell) = (10.93 \pm 0.10)%$
Diboson Production

Precision studies of **diboson production**
- abundant samples, well-controlled backgrounds
- 3-10% level measurements at $\sqrt{s} = 7$, 8 and 13 TeV
- a new measurement at $\sqrt{s} = 5.02$ TeV

![Graph showing diboson production](image1)

- Stringent limits on anomalous triple gauge couplings in terms of dim-6 EFT operators
- First observation of **longitudinally polarized W bosons** in WZ production

![Graph showing luminosity uncertainty](image2)

- Luminosity uncertainty: 1.9% at $\sqrt{s} = 5.02$ TeV (302 pb$^{-1}$)

![Graph showing full run-2 data](image3)

- Full Run-2, 137 fb$^{-1}$
**Vector Boson Scattering**

**Same-sign W pairs**
with measurement of the polarisation

Exploiting event kinetics, extract polarisation components

**VBS signature:** two jets with large rapidity separation and dijet mass

**pp → Wγ jj**
signal significance: $4.9\sigma \,(4.6\sigma \,\text{exp})$

**pp → ZZ jj**
signal significance: $4.0\sigma \,(3.5\sigma \,\text{exp})$

**Limits on anomalous quartic gauge couplings in terms of dim-8 EFT operators**

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma B$ (fb)</th>
<th>Theoretical prediction (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W^+_L W^-_L$</td>
<td>$0.32^{+0.42}_{-0.40}$</td>
<td>$0.44 \pm 0.05$</td>
</tr>
<tr>
<td>$W^+_X W^-_T$</td>
<td>$3.06^{+0.51}_{-0.48}$</td>
<td>$3.13 \pm 0.35$</td>
</tr>
<tr>
<td>$W^+_L W^-_X$</td>
<td>$1.20^{+0.56}_{-0.53}$</td>
<td>$1.63 \pm 0.18$</td>
</tr>
<tr>
<td>$W^+_T W^-_T$</td>
<td>$2.11^{+0.49}_{-0.47}$</td>
<td>$1.94 \pm 0.21$</td>
</tr>
</tbody>
</table>

First hint the scattering of at least one $W_L$ at the $2.3\sigma \,(3.1\sigma \,\text{exp})$ level

Full Run-2, 137 fb$^{-1}$

CMS-SMP-20-006
PLB 812 (2020) 136018

CMS-SMP-19-008
PLB 811 (2020) 135988

CMS-SMP-20-001
PLB 812 (2020) 135992

Fiducial cross section:

$$\sigma_{EW}(pp \rightarrow ZZjj \rightarrow \ell \ell \ell' \ell'jj) = 0.33^{+0.11}_{-0.10} \,(\text{stat})^{+0.04}_{-0.03} \,(\text{syst}) \,\text{fb}$$

SM: $0.28 \pm 0.02 \,\text{fb}$
M. J. T. 2016

**Higgs Mass Measurements**

- **$H \rightarrow ZZ \rightarrow 4\ell$**
  
  $$m_H = 125.26 \pm 0.21 \text{ (total) GeV}$$

- **$H \rightarrow \gamma\gamma$**
  
  - using a refined calorimeter calibration
  
  $$m_H = 125.78 \pm 0.26 \text{ (total) GeV}$$

**Run-2/2016 combination**

$$m_H = 125.46 \pm 0.16 \text{ (total) GeV}$$

The Higgs boson mass measurement uncertainty is still dominated by statistics.

**Combination with Run-1 result**

$$m_H = 125.38 \pm 0.14 \text{ (total) GeV}$$

- currently the most precise measurement (1.1%)  
- central value consistently used in CMS analyses
**Higgs Decays to Fermions**

**Summer 2017:**
first observation by CMS of $H \rightarrow \tau^+\tau^-$

**Summer 2018:**
first observation by CMS of $H \rightarrow b\bar{b}$

**Winter 2019:**
Obs. (exp.) limit on $pp \rightarrow VH(H \rightarrow c\bar{c})$
70 (35) $\times$ SM (35.9 fb$^{-1}$)
$H \rightarrow \gamma\gamma$ and STXS

Clear $H \rightarrow \gamma\gamma$ signals in all four main production modes, including $pp \rightarrow t\bar{t}H$ ($5.2\sigma$)

Measurements by production mode in various kinematic regions (STXS = Simplified Template Cross Sections)

Also, strong evidence for $pp \rightarrow t\bar{t}H$ ($4.7\sigma$) in multi-lepton final states

(* already 40 analyses switched to Ultra Legacy re-reconstruction)
**ttH (H → 4ℓ) Candidate**

[Diagram showing the signature of a ttH event with four leptons (μ+μ-μ+μ-) and jets.]
$H \to ZZ^* \to 4\ell$ and STXS

CMS

VBF

$ggH$

$\mu(4\ell) = 0.94 \pm 0.07\ (\text{stat})^{+0.09}_{-0.08}\ (\text{syst})$

$\sigma_{\text{fid}}(4\ell) = 2.84^{+0.23}_{-0.22}\ (\text{stat})^{+0.26}_{-0.21}\ (\text{syst})\ fb$

SM: $2.84 \pm 0.15\ fb$

Contraints on ttH anomalous CP coupling, combining $H \to 4\ell$ and $H \to \gamma\gamma$

Also: comprehensive study of CP structure and anomalous couplings

Full Run-2, 137 fb$^{-1}$

CMS-HIG-19-009

Submitted to PRD

Phys. Briefing

CMS-HIG-19-001

Accepted by EPJC
Differential distributions unfolded for selection efficiency and resolution effects and compared to theoretical calculations

- $H \rightarrow b\bar{b}, \gamma\gamma, ZZ^*$

Run-2 2016, 35.9 fb$^{-1}$

CMS-HIG-19-002

PLB 792 (2019) 369

Also in $H \rightarrow \tau\tau$:

$$\sigma_{\text{fid}}(H \rightarrow WW^* \rightarrow e^+\mu^-\nu\bar{\nu}) = 86.5 \pm 9.5 \text{ fb} \quad (\text{SM: } 82.5 \pm 4.2 \text{ fb})$$

CMS-HIG-19-001

Accepted by EPJC

CMS-HIG-19-002

JHEP 03 (2021) 003

Phys. Briefing

Full Run-2, 137 fb$^{-1}$

CMS-HIG-17-028

PLB 792 (2019) 369
Boosted Higgs Boson to Bottom Quarks

A Deep Feed-Forward Neural Network using jet properties information and secondary vertices associated to the jets (43 input variables)

• 13% improvement in jet resolution
• 20% improvement in di-jet mass resolution (as measured in data)
First Evidence for $H \rightarrow \mu\mu$

Exclusive categories: ggH, VBF, VH and ttH
First Evidence for $H \rightarrow \mu\mu$

Analysis in VBF category
- makes use of advanced machine learning techniques
- provides sensitivity similar to that in ggH

$$\mu(\mu\mu) = 1.19^{+0.41}_{-0.39} \text{ (stat)}^{+0.17}_{-0.16} \text{ (syst)}$$

Obs. (exp.) significance: 3.0 (2.5) $\sigma$

Combining with Run-1 (7 and 8 TeV) improves significance by 1%

Full Run-2, 137 fb$^{-1}$

Drell-Yan background considerably reduced by VBF topology requirement (two forward jets)

Using $m_H = 125.38$ GeV (best CMS result)
In the kappa framework, fit for 6 coupling strength modifiers ($\kappa$) for $m_H = 125.38$ GeV

$$\kappa_\mu = 1.07 \pm 0.22 \text{ (at 68\%CL)}$$

for the first time, meaningful 68% and 95% confidence intervals for a Higgs boson coupling to a second generation fermion.

CMS p-value for SM hypothesis (all $\kappa=1$): 44%
The observation of double Higgs production is one of the main motivations for HL-LHC.

Constraints on anomalous HHH ($\kappa_\lambda$) and VVHH ($c_{2V}$) couplings

The goal in Run-3 is either to find an anomalous production (resonant or non-resonant) or to set cross-section limits closer to the SM expectation.

In the SM: $\lambda_{HHH} = \lambda = m_H^2/2v^2$

Combination of HH searches $\sigma/\sigma_{SM} < 22$ (13) at 95% CL
Search for Double Higgs Production

Full Run-2, 137 fb$^{-1}$

Inclusive $HH \rightarrow \gamma\gamma b\bar{b}$ ($\kappa_\lambda = 1$)

$\sigma/\sigma_{SM} < 7.7$ (5.2) at 95% CL

VBF $HH \rightarrow \gamma b\bar{b}$ ($\kappa_{2V} = 1$)

$\sigma/\sigma_{SM} < 225$ (208) at 95% CL

Run-2 analyses already reaching much higher sensitivity than anticipated

Best observed limit so far

Inclusive $HH \rightarrow b\bar{b}b\bar{b}$ ($\kappa_\lambda = 1$)

$\sigma/\sigma_{SM} < 3.6$ (7.3) at 95% CL

VBF $HH \rightarrow b\bar{b}b\bar{b}$ ($\kappa_{2V} = 1$)

$\sigma/\sigma_{SM} < 226$ (412) at 95% CL

CMS-HIG-19-018
JHEP 03 (2021) 257

Phys. Briefing

CMS-HIG-20-005
Top-Quark Mass Measurements

Higgs potential

\[ V_H = -\mu^2 |\phi|^2 + \lambda |\phi|^4 \]

\[ \lambda(v) = m_H^2/2v^2 \]

The value of the Instability Scale \( \Lambda (> 10^9 \text{ GeV}) \) depends on \( \alpha_S(m_Z) \) and the top-quark mass.

**Direct measurements**

**Alternative measurements**
Top-Quark Mass Measurements

From $t\bar{t}$ events

- Run-1 legacy
  \[ m(t) = 172.44 \pm 0.13 \pm 0.47 \text{ GeV} \]

- Run-2 lepton+jets
  \[ m(t) = 172.25 \pm 0.08 \pm 0.62 \text{ GeV} \]

Different phase space, different kinematics, and separate measurements of top and anti-top:

- $m(t) = 172.44 \pm 0.77 \text{ GeV}$
- $m(\bar{t})/m(t) = 0.995 \pm 0.006$
- $m(\bar{t}) - m(t) = 0.83^{+0.77}_{-1.01} \text{ GeV}$

Alternative methods

- $M_{T2}$, Dilepton $M_{\ell\ell}$, kinematic endpoints, $b$-hadron lifetime, $\ell + \text{SecVtx}$, $\ell + J/\psi$, etc.
- less precise but different systematic uncertainties
- in agreement with main measurement
Running of the Top-Quark Mass

“Pole” mass from multi-differential cross section measurements
- in $e^\pm\mu^\mp$ final state
- as functions of mass and rapidity of the $t\bar{t}$ system, and jet multiplicity
- unfolded at parton level
- compared with NLO predictions in $\overline{\text{MS}}$ scheme

$$m(t) = 170.83 \pm 0.72 \text{ GeV}$$

Evolution of the top quark mass from the differential cross section as a function of $m_{t\bar{t}}$

Top-quark running mass probed up a scale of order 1 TeV
- compared to RGE prediction at one-loop precision ($n_f = 5$)
- scale dependance found consistent with predictions at the 1.1$\sigma$ level
- no-running hypothesis excluded at the 95% CL

![Graph showing evolution of top quark mass](image)
Evidence for $t\bar{t}$ production
- in the $e\mu$ channel
- $4.0\sigma$ obs. ($6.0\sigma$ exp.)
- following a first observation in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

Top quarks are thought to decay before QGP formation
- probes for nPDF at high-x
- tools to study parton energy loss in the QGP

Observation of $B_c$ meson production
- in the decay channel $B_c \rightarrow J/\psi(\rightarrow \mu\mu)\mu\nu$ ($\gg 5\sigma$)
- bridge between charm and charmonium

- hint of soften $p_T$ spectrum
- rules out some (extreme) models of charm recombination

will help disentangle the enhancement and suppression mechanisms at play in the evolution of heavy quarks through the QGP
**Search for Heavy Resonances**

**Dilepton resonances**

- Limits on cross section × BF translate into limits on resonance masses depending on models new W’ or Z’ resonances with masses up to > 4 TeV are excluded.

**Unspecific search for New Physics**

- Model Unspecific Search in CMS

**CMS-EXO-19-008**

- Accepted by EPJC

**Phys. Briefing**

- Excellent agreement is found between the data and SM predictions

**CMS-EXO-19-019**

- Submitted to JHEP

**CMS Preliminary**

- Event class: 2μ, \( p = 0.78 \)

**CMS-EXO-19-008**

- Accepted by EPJC

**Phys. Briefing**

- Wide range of final state topologies
Search with Merged Jets in the Final State

Search for WV resonances 
(V = W, Z, H)

Search for resonances decaying in cascade through to three W bosons

Search for resonances in 3 jets final states where 2 jets are merged

boosted dijet resonance reconstructed as single jet containing jet substructure consistent with a two-body decay

CMS-PAS-EXO-20-007

CMS-PAS-B2G-19-002

CMS-PAS-B2G-20-001

Phys. Briefing
Search for Displaced Muon Mass Peak

**Scouting data:** low threshold dimuon triggers reconstructed at HLT in real time

- exclusion limits derived in different models an in a wide range of signal mass and lifetime hypotheses

**B decays to long-lived scalar**

\[ B \rightarrow \phi X \rightarrow \mu^+ \mu^- X \]

**Higgs decays to long-lived dark photons**

\[ H \rightarrow Z_D Z_D' \rightarrow 2\mu 2X \text{ or } 4\mu \]

 exclusion examples for \( c\tau = 10 \text{ mm} \)

NEW

CMS-PAS-EXO-20-014
CMS has a rich SUSY search program setting strong limits on many models
- analyses optimised to tackle difficult corners of the phase space (stop corridor, compressed scenarios)

**Current limits at the end of 2015-2018 data taking**

- slepton: 0.7 TeV
- EWK: 0.95 TeV
- stop: 1.3 TeV
- squarks: 1.85 TeV
- gluinos: 2.2 TeV

**Combined Searched for Stops**

- Full Run-2, 137 fb⁻¹

**stops excluded up to 1300 GeV**

[Diagram showing SUSY particle masses and cross-sections]
Soft Muons, Disappearing Tracks

Results interpreted in lightest neutralino degenerate with the spectra compressed mass stops electroweakinos

<table>
<thead>
<tr>
<th>Soft Muons, Disappearing Tracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>model involving weakly massive particles with nearly degenerate masses</td>
</tr>
<tr>
<td>two or three soft muons + missing transverse momentum</td>
</tr>
<tr>
<td>low-energy muons</td>
</tr>
<tr>
<td>visible recoil</td>
</tr>
<tr>
<td>unseen particles</td>
</tr>
</tbody>
</table>

Results interpreted in terms of pair-produced
- electroweakinos with compressed mass spectra
- stops nearly mass-degenerate with the lightest neutralino

AMS B model, with Wino-like DM

\[ \chi = \begin{pmatrix} \chi^+ \\ \chi^0 \\ \chi^- \end{pmatrix} \]

dark matter

Charginos excluded up to 880 GeV for a lifetime of 3 ns

Pure wino exclusion up to 490 GeV (46.4 fb)

CMS PAS SUS-18-004

Phys. Briefing

CMS Highlights

June 16, 2021

Full Run-2, 140 fb⁻¹
Search for LLPs produced in pairs
• with a mean decay length between 0.1 and 100 mm (i.e. within the beam pipe)
• each decaying into two or more quarks

Search for Higgs boson decaying to long-lived scalars
• decaying to quarks or tau leptons within the forward muon chambers
Preparation for Run-3

L1-Muon trigger
- Barrel muon track finder (BMTF) $\rightarrow$ 50% background reduction
- Kalman track finding $\rightarrow$ better efficiency for displaced muons (without vertex constraint)

Heterogeneous online reconstruction

Computing and Offline software
- increased use of opportunistic computing (HPC: 10-15%)
- 10% faster full simulation
- improved fast simulation
- development of event lighter data formats

GPUs in High-Level Trigger (HLT)
A significant (and growing) fraction of the online reconstruction code is off-loaded from CPUs to GPUs
- HCAL and ECAL local reconstruction and calibration
- pixel tracking and electron seeding
- some particle flow and jet algorithms

A significant improvement in speed (>20%) already with present 30% of Run-3 workflow
CMS Phase-II Upgrades

Tracker
- all silicon (strips and pixels)
- higher granularity (>2B channels)
- less material
- coverage extended to $|\eta| = 4$

Barrel Calorimeters
- crystal granularity readout at 40 MHz
- precise timing for $e/\gamma > 30$ GeV
- ECAL operation at low temperature ($10^\circ$)
- upgraded laser monitoring system

Endcap Calorimeter (HGCAL)
- silicon pixels (EM) and scintillators + SiPMs (HAD)
- 3D shower reconstruction with precise timing

Muon Detectors
- DTs & CSCs: new FE/BE readout electronics
- RPCs: new electronics
- new GEM/iRPC chambers
- extended muon coverage to $|\eta| = 3$

L1-Trigger
- track trigger at L1 (40 MHz)
- latency up to 12.5 $\mu$s
- triggers on displaced muons and long-lived particles

Beam Radiation Instrumentation and Luminosity (BRIL)
- BCM/PLT refit
- new T2 tracker

Yet to come (June 2021):
- See talk by Santiago Folgueras on Friday

A MIP Timing Detector (MTD)
- precision timing on single charged tracks (30 to 40 ps resolution)
- Barrel (BTL): LYSO crystals + SiPMs
- Endcaps (ETL): Low Gain Avalanche Diodes
Phase-II Tracker Upgrade

Key features
- more granularity
- lower material budget
- extended coverage
- tracking included at L1-trigger level

Material budget

Expected performance compared to present tracker

Local rejection of low $p_T$ tracks

Occupancy no larger than 3%
Muon Detectors

Barrel and Endcaps
- Replacement of readout electronics for the new L1 trigger conditions

Endcaps
- Robust trigger up to $|\eta| = 2.4$ thanks to RPC stations RE3/1 and RE4/1 and 2-layer GEM stations GE1/1 and GE2/1
- Trigger extension up to $|\eta| = 2.8$
- 6-layer GEM station ME0

Athens/Ioànnina responsible for BMT Layer-1 HW and FW

2 GEM/CSC “tandems”
- measurement of “local” $\mu$ direction (sensitive to $p_T$)
- standalone L1-trigger rate drops by factor up to 10
- important for off-pointing muon triggers (search for LLPs)
**Calorimeters**

### Barrel

New ECAL on-detector electronics
- digitisation at 160 MHz
- online pulse shape discrimination against spikes
- trigger granularity = single crystal
- 30 ps time resolution ($E_\gamma > 50$ GeV)
- cooled at 9°C to mitigate APD ageing

### Endcaps: High-Granularity Calorimeter (HGCAL)

**Electromagnetic (CE-E)**
- Cu/CuW/Pb absorbers
- Si sensors, hexagonal modules
- 28 layers
- 25.5X₀ and $1.7\lambda$

**Hadronic (CE-H)**
- steel absorbers
- High-radiation regions: Si sensors
- Low-radiation regions: scintillation tiles with SiPM readout
- 22 layers
- 9.5$\lambda$ (including CE-E)

- 6M Si channels
- 240k scint. channels
**MIP Timing Detector**

**The MTD features**
- a time resolution of 30-50 ps for MIPs
- a 4th dimension for PU rejection

**Precise timing** allows for the removal of spurious tracks from PU, this improving on
- lepton isolation and identification
- jet reconstruction and flavour tagging
- missing $p_T$ reconstruction

**Precise timing** also offers time-and-flight identification at low momenta (relevant in HI)

**The MTD uses well-established technologies**
- **Barrel:** LYSO crystals with dual end SiPM readout
- **Endcaps:** Low Gain Avalanche Detectors (LGAD)
**Highlights of Coming TDRs**

**Phase-II HLT (not aiming at demonstrating final performance)**
- Physics performance already matching expectations with thresholds similar to that of Run-2
- Timing-wise, only a factor ~2 still to be gained for Run-4

**Phase-II Luminosity**
- **Offline** bunch-by-bunch luminosity with 1% precision
- **Online** & orbit integrated luminosity with <2% precision
- even outside CMS data taking

Response-corrected MET resolution
The PUPPI algorithm (red) mitigates PU effectively.

L1T (black), L1T+HLT with Run-2 algorithm (blue), L1T+HLT with lower $p_T$ and $H_T$ thresholds and DeepCSV b-jet tagging (red) for same rate (50Hz)
Summary

Despite the pandemic, the CMS LS2 activities are progressing well
- upgrade of the Hadron Calorimeter completed
- first Phase-II muon detector installed
- new beam-pipe for Phase-II installed
- pixel detector fully refurbished

Phase-II Upgrades
- excellent progress in all projects, but tighter schedule due to the pandemic
- two upcoming TDRs: DAQ/HLT and BRIL

CMS continues to deliver physics results at a steady pace
- no indication of loss of productivity
- however, signs of stress, especially among our younger collaborators

Great physics ahead of us!

We are continuously monitoring the impact of the pandemic on our activities and our collaborators. We are mindful of the long-term effects that the pandemic may have.
It’s Only the Beginning!

CMS Run-2
\[ \sqrt{s} = 13 \text{ TeV} \]
L = 137 fb\(^{-1} \)

- H → ZZ\(^*\) → 4\(\ell\)
- Z → 4\(\ell\)
Higgs Prospects Couplings

Main contributor to the H mass measurement at Run2.

Upgraded detectors bring significant improvements:
- Increased CMS/ATLAS tracker acceptances up to $|\eta|<4$,
- new EM trigger,
- improved $\mu$ triggers,
- higher reco $\ell$ efficiency and momentum resolution in Phase2.

Resolution of the four-$\mu$ invariant mass as a function of the pseudorapidity of the most forward $\mu$.

No worsening of the mass resolution due to the pileup increase is observed.

CMS Phase-2 Simulation Preliminary, 14 TeV, 200 PU.
It’s Only the Beginning!

**LS3** = Long shutdown 3
- 2.5 years
- starting end of 2024
- installation of upgraded detectors

**HL-LHC (Run 4-5)**
- starting mid-2027
- $\sqrt{s} = 14$ TeV
- $<\mu> = 140-200$
- $\mathcal{L}$ up to $7.5 \times 10^{34}$
- $L > 3000 \text{ fb}^{-1}$

- HL-LHC ATLAS/CMS: expect 20-30 MeV resolution on Higgs boson mass
**CMS HL-LHC**

**13 TeV**

**3 ab^{-1}**

**CMS End of Run-3**

13 TeV

300 fb^{-1}

Most Higgs couplings known to better than 4%, dominated by systematic uncertainties.
for most channels, $t\bar{t}H$ is the main background

$b\bar{b}b\bar{b}$
exploit resolved and boosted $b$-jets

$b\bar{b}\tau\tau$
irreducible bkg: $Z(\tau\tau)b\bar{b}$

$b\bar{b}W^*(\ell\nu\nu)$
main bkg: $t\bar{t}$

$b\bar{b}Z\bar{Z}^*(4\ell)$
very rare but clean final state

$b\bar{b}g\gamma$
peaking $t\bar{t}H$ and non-resonant $b\bar{b}g\gamma$
HL-LHC: Higgs Self-Coupling

**ATLAS and CMS**

- **HL-LHC prospects**
  - Blue: ATLAS
  - Red: CMS
  - Black: Combination

ATLAS and CMS

- **ATLAS and CMS** HL-LHC prospects

**SM HH significance:** $4\sigma$
- $0.1 < \kappa_\lambda < 2.3$ [95% CL]
- $0.5 < \kappa_\lambda < 1.5$ [68% CL]

90k HH pairs produced

- $\kappa_\lambda$ “measured” with a precision of $\pm 50\%$

**CMS Highlights**

- Combined significance: $4\sigma$

**HL-LHC prospects**

- Combined
- $b\bar{b}\gamma\gamma$
- $b\bar{b}W^+W^-$
- $b\bar{b}tt$
- $b\bar{b}bb$
- $b\bar{b}ZZ^{(4\ell)}$

Combined uncertainty on $\kappa_\lambda$ is calculated by performing a conditional measurement with a precision of $\pm 50\%$

**HL-LHC: Higgs Self-Coupling**

- **Δ ln(L)**
- **0**
- **-2 ln(L)**
- **-4**
- **-6**
- **-8**
- **-10**
- **-12**

**HL-LHC prospects**

- **ATLAS**
- **CMS**
- **Combination**

**HL-LHC prospects**

- **3000 fb$^{-1}$ (14 TeV)**
- **99.4% CL**
- **95% CL**
- **68% CL**

**90k HH pairs produced**

- **Combined ATLAS and CMS results by channel, and the black line to their combination. The likelihoods signal+background fit to the background and SM signal.**
- **The coloured dashed lines correspond to the SM HH signal and**
- **CMS highlights.**

**CMS Highlights**

- **Combined significance:** $4\sigma$
- **90k HH pairs produced**
- **$\kappa_\lambda$ “measured” with a precision of $\pm 50\%$**

**HL-LHC prospects**

- **Combination**
- **$b\bar{b}\gamma\gamma$**
- **$b\bar{b}W^+W^-$**
- **$b\bar{b}tt$**
- **$b\bar{b}bb$**
- **$b\bar{b}ZZ^{(4\ell)}$**
Recent CMS Preliminary Results

- Search for Higgs boson pair production in the four b quark final state
  CMS-PAS-HIG-20-005
- Search for high mass trijet resonances using final states with boosted dijet resonances in proton-proton collisions at $\sqrt{s} = 13$ TeV
  CMS-PAS-EXO-20-007
- Inclusive and differential cross section measurements of single top quark production in association with a Z boson in proton-proton collisions at $\sqrt{s} = 13$ TeV
  CMS-PAS-TOP-20-010
- Measurement of the shape of the b quark fragmentation function using charmed mesons produced inside b jets from tt pair decays
  CMS-PAS-TOP-18-012
- Measurement of the inclusive and differential Higgs boson production cross sections in the decay mode to a pair of $\tau$ leptons
  CMS-PAS-HIG-20-015
- Search for flavor-changing neutral current interactions of the top quark and the Higgs boson in the diphoton decay channel in proton-proton collisions at $\sqrt{s} = 13$ TeV
  CMS-PAS-TOP-20-007
- Search for charged lepton flavor violation in top quark production and decay in proton-proton collisions at $\sqrt{s} = 13$ TeV
  CMS-PAS-TOP-19-006
- Probing effective field theory operators in the associated production of top quarks with a Z boson in multilepton final states at $\sqrt{s} = 13$ TeV
  CMS-PAS-TOP-21-001
- Search for new particles in events with energetic jets and large missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV
  CMS-PAS-EXO-20-004
- Measurement of multi-differential cross sections for the production of a Z boson in association with jets in proton-proton collisions at $\sqrt{s} = 13$ TeV
  CMS-PAS-SMP-19-009
- Search for long-lived particles decaying into two muons in proton-proton collisions at $\sqrt{s} = 13$ TeV using data collected with high rate triggers
  CMS-PAS-EXO-20-014
- Search for Higgs boson decays into long-lived particles in associated Z boson production
  CMS-PAS-EXO-20-003
- Search for long-lived particles decaying in the CMS endcap muon system in proton-proton collisions at $\sqrt{s} = 13$ TeV
  CMS-PAS-EXO-20-015
- Observation of the $B_{c}^{+}$ meson in PbPb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV
  CMS-PAS-HIN-20-004
- Strange particle collectivity in pPb and PbPb
  CMS-PAS-HIN-19-004
- Luminosity measurement in proton-proton collisions at 5.02 TeV in 2017 at CMS
  CMS-PAS-LUM-19-001
- Measurement of mass dependence of the transverse momentum of Drell Yan lepton pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV
  CMS-PAS-SMP-20-003
- Search for resonances decaying to triple W-boson final states in proton-proton collisions at $\sqrt{s} = 13$ TeV
  CMS-PAS-B2G-20-001
Absolute luminosity scale measured for individual bunch crossings

Obtained relative precision
• 1.6% in 2015 (2.2 fb^{-1})
• 1.2% in 2016 (36.3 fb^{-1})

Main sources of uncertainties
• differences between measured beam positions and the ones provided by the LHC
• factorizability of the transverse spatial distributions of proton bunches
• modelling of interactions among protons in the colliding bunches

And also:
• 1.9% in 2017 at $\sqrt{s} = 5.02$ TeV (302 pb^{-1})
Observation of 3-Boson Production

Leptonic final states

Observation of VVV production (5.7σ), evidence for WWW and WWZ (3.3σ)

CMS-SMP-19-014
PRL125 (2020) 151802

Phys. Briefing
Signal strength modifiers for the production × decay mode

**Production**

<table>
<thead>
<tr>
<th>Process</th>
<th>Observed</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggH</td>
<td>86%</td>
<td>90%</td>
</tr>
<tr>
<td>VBF</td>
<td>7%</td>
<td></td>
</tr>
<tr>
<td>WH</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td>ZZ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ttH</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Decay**

<table>
<thead>
<tr>
<th>Process</th>
<th>Observed</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZZ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WW</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ttH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W/Z</td>
<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**CMS-PAS-HIG-19-005**
**ttH Measurements**

Multi-lepton final states (e, \(\mu\), \(\tau\_h\))

mostly \(H \rightarrow WW, ZZ, \tau\tau\)

Activation value of the ANN output node

with the highest activation value

\[\mu(t\bar{t}H) = 0.92 \pm 0.19 \text{ (stat)} + 0.17 \text{ (syst)}\]

Obs. (exp.) significance: 4.7 (5.2) \(\sigma\)

\[\mu(tH) = 5.7 \pm 2.7 \text{ (stat)} \pm 3.0 \text{ (syst)}\]
$H \rightarrow \tau\tau$ and STXS

Full Run-2, 137 fb$^{-1}$

3.2σ exclusion of pure CP-odd

Phys. Briefing
**tt+Z and tt+γ**

Events with one $Z(\rightarrow \ell\ell)$ plus at least one lepton (e or $\mu$), $N_j > 0$ and $N_b \geq 0$

$$\sigma(ttZ) = 0.95 \pm 0.05 \text{ (stat)} \pm 0.06 \text{ (syst)} \text{ pb}$$

$$\sigma(tt\gamma, p_T > 20 \text{ GeV}) = 0.800 \pm 0.007 \text{ (stat)} \pm 0.046 \text{ (syst)} \text{ pb}$$
Jet Structure in Heavy Ion Collisions

Study of in-medium modification of jets structure in back-to-back di-jets events in PbPb versus pp collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV

- jet shape (normalised distance to jet axis $\Delta r$) in bins of jet unbalance $x_j$ and centrality

Excess of low-pT particles in PbPb compared to pp

- larger excess in subleading jets

Redistribution of energy from smaller to larger angles in PbPb vs pp

- larger for leading jets

new constraints to the theoretical models
Angular Analysis of $B_s^0 \rightarrow J/\Psi \phi$ Decays

Run-2 2017-18, 96.4 fb$^{-1}$

48,500 signal
$B_s^0 \rightarrow J/\Psi \phi (K^+K^-)$ events

Combining with Run-1 (8 TeV, 19.7 fb$^{-1}$):
- CP phase:
  $\phi_s = -21 \pm 45$ mrad
- decay width difference:
  $\Delta \Gamma_s = 0.1073 \pm 0.0097$ ps$^{-1}$

novel opposite-side muon tagger based on deep neural networks
(tagging power $\sim$10%)

Phys. Briefing