Title: CMS Status Report

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Affiliation: on behalf of the CMS Collaboration

Event: 138th LHCC Open Meeting, June 5, 2019

Outline:

- Status of CMS
- Recent physics highlights
- Preparation for Run3
- Longer term upgrades (Phase-2)
Outline

• Activities during LS2
• Subsystem status
• Planning toward Run-3 & HL-LHC
• Physics highlights
• Conclusions
Activities during LS2

Good progress on planned work @ P5

Completed Phase-1 upgrades
- new L1 trigger
- new pixel detector
- HCAL endcap
- muon electronics & detector upgrades

**HCAL barrel** (last Phase-1):
install SiPM+QIE11-based 5Gbps readout

**Pixel detector:**
- replace barrel layer 1
- replace all DCDC converters

**MAGNET (stays cold!) & Yoke Opening**
- Cooled freewheel thyristor+power/cooling
- New opening system (telescopic jacks)
- New YE1 cable gantry (Phase2 services)

**Muon system (already Phase-2):**
- install GEM GE1/1 chambers
- Upgrade CSC FEE for HL-LHC trigger rates
- Shielding against neutron background

**Keep strip tracker** cold to avoid reverse annealing

**Install new beam pipe** for Phase-2

**Civil engineering on P5 surface to prepare for Phase-2 assembly and logistics**
- SXA5 building
- temporary buildings for storage/utility

**Near beam & Forward Systems**
- BRIL BCM/PLT refit
- New TOTEM T2 track detector
- PPS: RP det & mechanics upgrade

**Coarse schedule:**
- 2019: Muons and HCAL interleaved
- 2020: beam pipe installation, then pixel installation
Pixel

- New barrel layer 1
  - Received all wafers of readout ASICs (PROC600 + TBM10)
    - Latest version of PROC600 to be validated before summer closure of company: last but one version is already production ready
  - Sensor module production will start soon after company summer closure

- Replace all DCDC converters
  - Received (by CERN EP-ESE) latest version of ASIC (FEAST v2.3)
    - To be validated by end of August
  - DCDC converter modules will be produced in Fall/Winter 2019

- On track for detector ready for installation in Fall 2020
HCAL

• Barrel electronics upgrade, last Phase-1 upgrade
  ✦ Corresponding endcap upgrade completed in 2018

• Replacement of HPDs with SiPM
  ✦ Improve noise levels, light yield & radiation tolerance
  ✦ Maintain physics performance for jets & MET

• On track to complete installation & commissioning before Dec 2019

**HCAL segmentation:**
- **HCAL segmentation: pre-2018**
- **HCAL segmentation: 2018**
- **HCAL segmentation: Run3 (post-LS2)**

**Legend:**
- HPD = Hybrid PhotoDetectors
- SiPM = Silicon Photo-Multipliers
Muons (1)

- Maintenance work
  - RPC gas leak repair campaign ongoing
  - Shielding to reduce background on top part of detector
  - Progressing well & according to schedule

- CSC electronics upgrade
  - Longest LS2 work for CMS
  - First station (minus side) extracted & brought to surface, now being tested+reinstalled
    - 26/36 already reinstalled, 3 fully commissioned
  - Work on schedule!
Muons (1)

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**Muons (2)**

- **Install GEM GE1/1 chambers**
  - Chambers
    - All built & validated
  - FE electronics
    - Design change to improve spark protection, production underway
  - Two chamber assembly (super chamber=SC)
    - 7/72 assembled with final electronics: cooling, gas, etc. OK
    - Final validation on cosmic test stand - expect to test 10 SC per month
  - Services (power, gas, cooling, cables)
    - Production on schedule

- On schedule to start installation in July

GEMs to improve muon capabilities around $1.5<|\eta|<2.0$
Computing & PPD

• Since last LHCC, focus on ...
  ✦ MC production for full Run-2 analyses
  ✦ Preparation for ultra legacy full Run-2 processing & MC with best possible alignments, calibrations, performance
  ✦ Also started processing B-parking dataset

• Preparations for Run-3 & Phase-2
  ✦ MC production
    • ... to study physics performance with luminosity/PU/aging detectors corresponding to end of Run-3
    • ... for Phase-2 L1 trigger TDR (PU=200)
  ✦ Upgrade infrastructures for Run-3
    • New Run Registry, monitoring systems, ML integration to DQM, ...
  ✦ Phase-2: Adapt to GPUs, FPGAs, via a heterogeneous framework
L1 trigger plans for Run 3

No major upgrades planned for Run 3, but significant improvements foreseen

• Algorithms and menu
  ✦ Preserve core trigger menu while creating new seeds for unexplored physics
    • New displaced muon trigger in barrel, develop targeted multi-object paths
  ✦ Use upgraded detector inputs to reduce rate in high-pileup conditions
    • e.g. depth segmentation in HCAL, extra GEM muon detectors in endcap

• Operations and monitoring
  ✦ With HLT, overhaul trigger menu editor to enable fast modifications
  ✦ Integrate monitoring data from trigger systems with central monitoring
  ✦ Build automated tests for monitoring data, pointing to appropriate actions

Phase-1 upgrades already completed
Continue exploiting these to improve algorithms
HLT plans for Run 3

• Trigger strategy in Run 2 worked well, review & improve for Run 3
  ✦ Main challenge: control rate/CPU time, while ensuring physics perf.
  ✦ GPU-based HLT reconstruction may help in this direction
    • First tests on pixel tracking, ECAL/HCAL local reconstruction promising

• Reconstruction performance on GPUs (pixel tracking)
  ✦ A single Tesla T4 GPU has better performance than a full HLT node (dual Xeon Gold 6130 with a total of 32 cores) at a fraction of the cost

[Diagram showing event throughput with Patatrack CMS Open Data 2018]
HL-LHC upgrade overview

Technical proposal CERN-LHCC-2015-010 [Link]
Scope Document CERN-LHCC-2015-019 [Link]

L1-Trigger/HLT/DAQ
[Link]
- Tracks in L1-Trigger at 40 MHz
- PFlow-like selection 750 kHz output
- HLT output 7.5 kHz

Barrel Calorimeters
[Link]
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

Calorimeter Endcap
[Link]
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Muon systems
[Link]
- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC 1.6 < η < 2.4
- Extended coverage to η = 3

Tracker
[Link]
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to η = 3.8

MIP Timing Detector
[Link]
Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

New paradigms (design/technology) for an HEP experiment to fully exploit HL-LHC luminosity
MTD: MIP Timing Detector

• High precision time measurement of MIP particles
  • 30-50 ps precision with nearly hermetic coverage (up to $|\eta|<3.0$)
  ✦ Identify which pp interaction vertex track is coming from
  ✦ Provide other unique features: sensitivity to slow particles, particle ID, etc

TDR submitted 29.03.2019
Scientific review June 3
Goal - full approval in 09/2019
MTD performance studies

- Significant impact on the HL-LHC program from pileup reduction
  - 20-30% increase in effective integrated luminosity, leveraging gains over full pseudo-rapidity coverage and cross a wide range of observables
- Unique discovery potential for long-lived particles
- Extended potential for heavy-ion physics through particle ID

**Prompt efficiency**

**MTD**

**no MTD**

**MTD, σ₁ = 40 ps**

- **Z → μμ**
- **rel chIso < 0.08**

**Muons**

- **p_T (GeV)**
- **Normalized entries**

**M(χ^0) [GeV]**

- **long-lived neutralino (GMSB)**
- **Simulation**
  - **Hydjet**
  - **|η| < 1.5**

**PbPb (5.5 TeV)**

- **Simulation**
- **p [GeV]**
- **1/β**
- **K, π, p**

**Phase-2 Simulation**

- **Z → τν**
- **M(τ) = 1000 GeV, M(χ^0) = 700 GeV, M(ző) = 1 GeV**
- **M(τ) = 1000 GeV, M(χ^0) = 700 GeV, M(zzo) = 1 GeV**

Recent physics highlights
Publication status

• CMS recently submitted its **900th** paper!!

• Now at 907 submitted papers, of which 882 on collider data

• First full Run-2 paper published
  ✦ Highlighted as PRL Editors’ suggestion

• Full details: http://cms-results.web.cern.ch/cms-results/public-results/publications/
Run-2 luminosity

• Several results presented using full 2016-2018 dataset (137 fb⁻¹)

• **Thanks to the LHC for the excellent performance!**

• **Preliminary** uncertainties
  ✦ 2.3-2.5% for pp collisions @ 13 TeV in single year
  ✦ 2018 dominant systematics due to x-y correlation
  • Study ongoing to measure bias, expect improved uncertainty after correction

![CMS Integrated Luminosity, pp, √s = 13 TeV](image)

- LHC Delivered: 162.85 fb⁻¹
- CMS Recorded: 150.26 fb⁻¹

![Best/second best measurement](image)

- 2018 PRELIMINARY
- Excellent luminometer stability
Physics highlights

• >50 new results since last LHCC, including 9 results with full Run-2 data

• Next slides highlighting a few recent results
  ✦ Highlight from heavy ions
  ✦ Precision EW measurement
  ✦ SM ZZ & H→ZZ production
  ✦ Update on ttH (with H→bb) & SM tt+bb production
  ✦ Select new physics searches

  ✦ Emphasis on maximizing physics potential through ...
    • Unconventional triggering
    • Innovative strategies & probing new topologies
    • Precision measurements with full Run-2 dataset
Highlight from heavy ion

- Measurement of $\Lambda_c$ baryons in pp & PbPb collisions at 5.02 TeV
  - Hint of suppression in central PbPb collisions compared to pp ($R_{AA}$)
  - $\Lambda_c/D_0$ ratio consistent between pp & PbPb
  - Coalescence process may not play a significant role in $\Lambda_c$ baryon production for $10 < p_T < 20$ GeV

Hadron production via coalescence:
Partons combine while traversing QGP medium

$R_{AA} = \frac{\text{[yield in PbPb]}}{\text{[yield in pp]}, \text{scaled by number of nucleon-nucleon interactions}}$
Precision EW

- \(Z/\gamma^*\) production cross section @ 13 TeV
  - SM precision test, constrain PDFs, input to \(m_W\)
  - Fiducial + differential measurements vs \(p_T, y, \phi^*\) (incl. double-diff!)
    - Systematic uncertainties: luminosity (2.5%) + lepton ID (ee 1.4%, \(\mu\mu\) 0.8%)
    - Compare to state of the art (N)NLO calculations

<table>
<thead>
<tr>
<th>Cross section</th>
<th>(\sigma B) [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma_{Z\rightarrow\mu\mu})</td>
<td>(694 \pm 6) (syst) (\pm 17) (lumi)</td>
</tr>
<tr>
<td>(\sigma_{Z\rightarrow ee})</td>
<td>(712 \pm 10) (syst) (\pm 18) (lumi)</td>
</tr>
<tr>
<td>(\sigma_{Z\rightarrow \ell\ell})</td>
<td>(699 \pm 5) (syst) (\pm 17) (lumi)</td>
</tr>
</tbody>
</table>

\[\sigma_{Z\rightarrow \ell\ell} = 682 \pm 55\) pb \quad \text{MadGraph5.AMC@NLO} \]
\[\sigma_{Z\rightarrow \ell\ell} = 719 \pm 8\) pb \quad \text{FEWZ} \]

\[
\phi^* = \tan\left(\frac{\pi - \Delta \phi}{2}\right) \sin(\theta^*_\eta) \\
\cos(\theta^*_\eta) = \tanh\left(\frac{\eta^- - \eta^+}{2}\right),
\]

\[
\eta^- = |\eta| - 0.0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4
\]

\[
\text{Data, aMC@NLO, POWHEG, FEWZ}
\]
SM ZZ & H→ZZ

- **Measurements** utilizing 137 fb⁻¹
- **SM ZZ** production cross section
  - $\sigma_{\text{tot}}(pp\rightarrow ZZ) = 17.1 \pm 0.3(\text{stat}) \pm 0.4(\text{syst}) \pm 0.4(\text{theo}) \pm 0.3(\text{lumi})$ pb
    - consistent with SM predictions, total measurement uncertainty of ~4%
- **H→ZZ** fiducial + differential measurements

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**SMP-19-001**

Reduced from ~4.1% (2016) to ~2.3%
**ttH, H → bb**

- **ttH production with H → bb,** challenging final state
  - Sophisticated MVA techniques to distinguish signal from background
  - Several improvements in 2017 data analysis w.r.t. previous result (2016 data): new b-tagging, refined analysis methods, ...
  - Main systematic: tt+HF modeling, QCD background, b-tagging
- Best-fit signal strength (combining 2016+2017): \( \hat{\mu} = 1.15^{+0.15}_{-0.15}(\text{stat})^{+0.28}_{-0.25}(\text{syst}) \)

**Obs (exp) significance 3.9\(\sigma\) (3.5\(\sigma\))**

![Graph showing data and fit comparison for ttH production](image)

**Figure 7: Best fit values of the signal strength modifiers**

<table>
<thead>
<tr>
<th>Channel</th>
<th>FH combined</th>
<th>SL combined</th>
<th>DL 4 jets</th>
<th>FH 4 b-tags</th>
<th>FH 3 b-tags</th>
<th>FH+SL+DL combined</th>
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<tr>
<td>2016</td>
<td>0.2</td>
<td>1.84</td>
<td>1.57</td>
<td>1.36</td>
<td>1.49</td>
<td>1.69</td>
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<tr>
<td>2017</td>
<td>0.35</td>
<td>1.73</td>
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<td>1.41</td>
<td>1.54</td>
<td>1.69</td>
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<td>Combined</td>
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<td>1.54</td>
<td>0.59</td>
<td>0.45</td>
<td>0.45</td>
<td>0.6</td>
</tr>
</tbody>
</table>

Contact: cms-pag-conveners-higgs@cern.ch

**Table 5: Best fit value of the signal strength modifier**

- CMS Physics Analysis Summary (13 TeV)
- A measurement of the associated production of a standard model Higgs boson with a top quark-antiquark pair (t\(t^\bar{t}\)) also split into their statistical (inner error bar) and systematic components.
- Figure 7: Best fit values of the signal strength modifiers and expected (exp) significance in standard deviations in the fully-hadronic (FH), single-lepton (SL), and dilepton (DL) combined fit of the 2016 and 2017 datasets per channel and dataset and hypothesis.
- Combined with previous results obtained with 36.9 fb\(^{-1}\) corresponding to an observed (expected) significance of 3.7 (2.6) standard deviations.
SM \( ttbb \)

- Measurement of SM \( ttbb \) production
  - Important background to \( ttH(bb) \) & \( tttt \), test QCD predictions
  - Fully hadronic final state \((35.9 \text{ fb}^{-1})\)
    - Various MVA techniques to reduce multijet background & identify signal
    - 2D fit to b-tagging discriminator scores to extract cross section
    - Measurement high w.r.t. theory predictions -- input needed from theory community to improve modeling

![Graph showing data and predictions](image)
Probing the very rare

- **SM four top production**, yet unobserved process ($\sigma_{SM} \sim 0.01 \text{pb}$)
  - Same-sign + multileptons with $137 \text{fb}^{-1}$, highest LHC sensitivity search
  - Observed (expected) significance of $2.6\sigma$ ($2.7\sigma$)
    - Measure $\sigma = 12.6 \pm 5.8/-5.2$ fb
    - Constrain top Yukawa coupling: $|y_t / y_t^{SM}| < 1.7$

**Figure 1:** Single top quark event Feynman diagrams at leading order. The vertex labelled $tZq$.

**Figure 2:** Top quark pair Feynman diagram at leading order. The vertex labelled $tZq$ is the sought-for FCNC interaction.
**Searches with 137 fb⁻¹**

**Dark photons**
- Massless dark photons coupling to a Higgs boson through charged dark sector particles
  - Signal extraction from fitting $m_T$ in $|\eta^\gamma|$ regions + background control regions
  - No excess observed
    - For $m_H = 125$ GeV: $\text{BR}(H \rightarrow \gamma + \text{inv}) < 4.6\%$ ($3.6^{+2.0}_{-1.2}\%$ expected) at 95% CL, vs $m_H$
Searches with 137 fb\(^{-1}\)

**Delayed jets**

- BSM scenarios (SUSY, hidden valley, ...) with long-lived particles may result in “delayed” jets
  - First search for such jets using ECAL timing!
    - Dedicated reconstruction to extract jet timing
    - “Unusual” backgrounds
    - No excess, interpret in context of GMSB
Searches with 137 fb⁻¹

Disappearing tracks

- Search for prompt & long-lived SUSY particles
  - Exploit $p_T$ imbalance w. $M_{T2}$ in jets+MET events
  - *Long-lived particle that decays in tracker volume*
- No excess, constrain:
  - **Displaced:** gluinos ~2.5 TeV
  - **Prompt:** gluinos ~2.1 TeV, stop/sbottom ~0.9 TeV

... and more

- Search for SUSY with two same-sign dileptons or ≥3 leptons & jets
- Search for new physics in multilepton final states (≥3 leptons)
Low-mass resonances

- Generic vector resonance coupling to quarks
  - Predicted in SM extensions, incl. DM models
  - Boosted dijet + ISR tag => trigger to probe low-mass
    - 95% CL upper limits on quark coupling $g_q'$ vs resonance mass for leptophobic $Z'$

![Graph showing observed and expected limits for $g_q'$ coupling](image)

- Excess around 120 GeV from 2016 data, not confirmed in 2017 dataset

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**References**

- L. Anchordoqui et al., "Dijet signals for low mass strings at the LHC" (2014).
- G. Busoni et al., "Recommendations on presenting LHC searches for missing transverse energy" (2016).
- M. Czakon et al., "Low-mass resonances in $Z'$ physics" (1990).
- G. Busoni et al., "Recommendations on presenting LHC searches for missing transverse energy" (2016).
Conclusions

• Much work on different fronts for CMS!
  ✦ LS2 activities
    • Ongoing work (pixel, HCAL, muons) progressing well
    • Detectors on track for re-installation as scheduled
  ✦ Preparation for Run-3 underway
    • Both preparing detector & physics analysis
  ✦ Installing first upgrades for HL-LHC

• ... and in parallel, analyzing Run-2 dataset!
  ✦ Already several new physics results using full Run-2 data
  ✦ Exploit innovative strategies, probe new topologies, ...
BACKUP
Control room UPS fire

• Overnight between May 25-26, UPS battery rack providing assured power to CMS control room at P5 caught fire
  • On surface, in separate room adjacent to CMS control room
    • As consequence of fire, subsequent cut to DSS, etc, water mist system was triggered in control room & upstairs DAQ/server computer farm
    • Temporary fully-functional control room in place

• Many thanks to especially CERN Fire Brigade & EN-EL/CV for their prompt response & difficult work in extinguishing the fire

• CMS will fully recover from this incident within a few weeks
  Impact on LS2 program will be very limited and mostly due to delays in test and commissioning activities inhibited while the SCX DAQ area is recovered

UPS = Uninterruptible Power Supplies  
SCX = Surface Control eXperiment building
SM ZZ, H→ZZ
Run-2 luminosity

- *Preliminary* systematic uncertainties for 13 TeV pp luminosity measurement

<table>
<thead>
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<th>Normalization</th>
<th>Systematic</th>
<th>Correction (%)</th>
<th>Uncertainty (%)</th>
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<td>Length scale</td>
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<tr>
<td>Dynamic-$\beta^*$</td>
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<td>Ghosts and satellites</td>
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<td>Scan to scan variation</td>
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<td>Cross-detector consistency</td>
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