# **CMS status** & plans





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## **Talk Outline**

- Current status of CMS
  - > Detector
  - > Physics
- CMS detector upgrade plans to exploit High Luminosity LHC ( $\geq$  2026)

(both with emphasis on CMS/UK activities ...).



### Current Detector Status: Data Taking

- Data taken:
  - >  $\int s = 7-8$  TeV: 30/fb in 2010-2012.
  - >  $\int s = 13 \text{ TeV}$ : 45/fb in 2015-2016 + 45/fb expected in 2017.





#### **Current Detector Status:** New Pixel Tracker Installation

- Major upgrade in 2016/17 shutdown:
  - > New silicon Pixel Tracker.
  - One extra layer --- improved b tag performance.



- > 97% of tracks passing through 4 layers produce hits in at least 3 of them.



#### Current Detector Status: UK responsibilities

- UK constructed ECAL endcap, Tracker readout electronics & L1 trigger.
  - > Ongoing responsibility to maintain them.
- Senior CMS coordination roles of UK people reflect this:
  - > ECAL (+  $e/\gamma$  reconstruction)
  - High Granularity calorimeter (HL-LHC)
  - > L1 Trigger
  - Run coordinator
  - Exotica Physics

- Example maintenance work:
  - e.g. Calibrating & understanding ECAL





#### **Current Detector Status: UK** responsibilities

UK led L1 trigger system upgrade in 2015/16 shutdown, to handle higher luminosity.





#### **CMS** Physics Publications



- √s = 13 TeV since 2015, with rapidly increasing luminosity.
  - Exciting period!

• CMS has published 628 physics papers.

Number of citations	Number of papers
Renowned papers (500+)	12
Famous papers (250-499)	26
Very well-known papers (100-249)	124
Well-known papers (50-99)	175

 I'll now give examples of physics studies with UK involvement.



#### Example SUSY search at √s = 13 TeV with UK leadership





#### Dark Matter searches at √s = 13 TeV with UK involvement

- Theoretical motivation for dark matter to have weak scale mass & couplings.
  - Search for heavy mediator decays to invisible DM particles (EtMiss) or SM particles (e.g. di-jets).





#### Example Exotica Search at √s = 13 TeV with UK leadership

- Extra electroweak gauge bosons (W',Z') predicted by many SM extensions.
- Search for  $Z' \rightarrow$  dileptons: mass limit ~4 TeV.
  - > Strong UK input to e+e- channel, using our ECAL experience.





#### Example Higgs Boson studies at √s = 13 TeV with UK leadership

- Improved LHC performance giving access to more challenging SM Higgs decays.
- > First observation of Higgs  $\rightarrow \tau + \tau a \pm 5.9\sigma$ . 35.9 fb<sup>-1</sup> (13 TeV) S/(S+B) weighted events / GeV CMS 35 Preliminary 30ł Observed H→ττ (μ=1.06) Ζ→ττ 25 W+iets Exotic Higgs searches: QCD multijet 20 Others Bkg. unc. > MSSM Higgs  $\rightarrow \tau + \tau -$ 15 [CMS-PAS-HIG-16-037] VBF:  $e\tau_h$ ,  $\mu\tau_h$ ,  $e\mu$ 10 Higgs decaying invisibly: B.F. < 24%. [JHEP 02 (2017) 135] 5 **CMS-PAS-EXO-16-043** 50 250 100 150 200 300 0 m<sub>ττ</sub> (GeV)



#### Example Top Quark studies at Js = 13 TeV with UK leadership





#### ✤ From 2026 onwards, LHC luminosity increases to 5—10 x nominal.



Major upgrades to CMS required to cope with higher data rates, occupancies, pile-up & radiation.



### Summary of CMS Upgrades for HL-LHC



#### Summary of CMS-UK Upgrades for HL-LHC



#### UK Objectives: (shown in yellow)

Tracker readout ASIC & barrel ECAL opto-links.

Off-detector Track-Finder, Calorimeter Trigger Primitive & "L1 correlator".

> All using same (or similar) FPGA-based electronics board.



## Generic FPGA-based Board for HL-LHC

- History:
  - UK developed "MP7" μTCA board, with Virtex7 FPGA & with 1 Tb/s capacity.
  - Supplied firmware/software framework, for easy use.
  - General purpose: used in several trigger subsystems (calorimeter, muon, global).
  - > Variant (FC7) used by pixels + ....



- For HL-LHC, we plan a new "generic FPGA-based board", targeting calorimeter, trigger & tracker.
  - > Maximum impact for minimum cost!



## Generic FPGA-based Board for HL-LHC: Research & Development

- Built two boards to gain experience with latest Ultrascale FPGAs, 16 (25) Gb/s links & ATCA cards.
  - "MP-ultra" board: PCIe, Kintex Ultrascale FPGA & 16 Gb/s opto-links.
    - Test new PCB manufacturing techniques ...



- 2) "ATCA service card"
  - Test ATCA services, powering, cooling, on-board CPU, 25 Gb/s test structures ...

Will produce prototype of final board design, meeting CMS needs by ~2019.



#### Tracker Upgrades for HL-LHC

- Reconstruct tracks for use in L1 trigger (new!).
  - Only 4µs to find tracks in events arriving at 40MHz!
  - Drives silicon tracker design.
- Tracker has "Pt modules" (UK concept).
  - "CBC" ASIC (UK) finds pairs of hits ("stubs") from particles of Pt > 2 GeV.
  - Stubs sent off-detector for use by L1 track-finder (UK).







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#### Tracker Upgrades for HL-LHC: "CBC" ASIC Readout Chip

- "CBC" ASIC is UK responsibility.
  - Reconstructs & transmits "stubs" (for every 40MHz LHC event) & individual hits (for L1-triggered events).





#### Tracker Upgrades for HL-LHC: L1 Track-Finder

- UK proposed FPGA-based solution to reconstruct tracks.
  - > Hough transform (HT) for fast, rough tracking in r- $\varphi$  plane.
  - Kalman filter (KF) to fit & clean tracks in 3-D.
- Exploits "time-multiplexing":
  - Several identical tracking processors take it in turn to analyse events, so each has enough time to reconstruct tracks.
- Demonstrated using several "MP7" cards, equipped with Virtex7 FPGA.





#### Tracker Upgrades for HL-LHC: L1 Track-Finder

• Demonstrator system successfully processed stubs from emulated HL-LHC events.



#### Future:

Simulated track  $\eta$ 

- > UK convener of CMS L1 tracking group.
- UK major role in final system hardware (based on "generic FPGA-based board"), firmware, algorithm design & installation.
- > Expect prototype of final L1 tracking board by ~2019.



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#### Calorimeter Upgrades for HL-LHC: High Granularity Calorimeter

Endcap calorimeter (ECAL+HCAL) to be replaced by High Granularity Calorimeter (HGcal).
 > HGcal concept & project leadership from UK.





### Calorimeter Upgrades for HL-LHC: Reconstruction of "Trigger Primitives"

- UK will reconstruct calorimeter "trigger primitives" (clusters) for use in L1 trigger, (within ~5µs, for each 40 MHz LHC event!).
  - > HGcal: algorithm design & firmware + FPGA-based board.
    (where electronics is our "generic FPGA-based board")
  - > ECAL barrel: algorithm design & firmware.
- For HGcal, 2-step process foreseen:
  - 1) Reconstruct 2-D clusters within each layer of silicon/scintillator.
  - Reconstruction of 3-D clusters by combining 2-D ones.



- For ECAL barrel, will reconstruct clusters.
  - ECAL will be read out with full granularity, for every LHC bunch crossing, to improve L1 trigger performance.



#### L1 Trigger "Correlator" for HL-LHC



- UK person.
- UK interested in "L1 Correlator", besides producing "trigger primitives" for Calorimeters & Tracker.
- L1 correlator combines primitives: e.g. Track + ECAL cluster = electron.
  - > Latency target ~3.5  $\mu$ s.



#### L1 Trigger "Correlator" for HL-LHC

- For "L1 Correlator", we wish to provide electronics (= "generic FPGA-based board"), algorithm design, software & firmware.
  - > Studies of system architecture underway.
  - Studies of some algorithms started
    (e.g. primary vertex reconstruction, track-jets, particle flow).
- As L1 trigger entirely off-detector, schedule later than for CMS sub-detectors.
  > e.g. Technical Design Report in early 2020.



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- Exciting time for CMS:
  - > Physics results arriving from greatly increased 2016 luminosity in  $\int s = 13$  TeV regime.
  - > UK leadership in studies of Z' bosons, dark matter, Higgs bosons, SUSY ...
- Recent improvements to detector enhance its performance:
  - > New pixel tracker
  - Upgraded L1 trigger (major UK involvement)
- CMS upgrade plans for HL-LHC becoming clear:
  - > TDR's of most sub-detectors this year & for L1 trigger in early 2020.
  - UK expects to provide "L1 trigger primitives" (calorimeter & tracker)
    + "L1 trigger correlator" that combines them.

- Developing generic FPGA board, targeting these applications.

- > UK also providing Tracker readout chip ("CBC") & ECAL opto-links.
- UK senior CMS leadership roles in several domains: Exotica physics, Run Coordination, L1 trigger, ECAL, HGcal, L1 track & L1 trigger upgrades.





## Motivation of HL-LHC: European Strategy for Particle Physics

#### Quotation:

"The discovery of the Higgs boson is the start of a major programme of work to measure this particles properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme.

Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030.

This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma"



#### LHC Long-Term Schedule



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#### Examples of Physics Motivations for HL-LHC

**Precise Higgs couplings (including**  $\mu\mu$ H & HHH coupling sensitivity)



★ Improved exotica & SUSY sensitivity (especially for rare processes). > e.g. Mass range almost doubles for  $\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0 \rightarrow WH \tilde{\chi}_1^0 \tilde{\chi}_1^0$ ★ 7 observation of  $B_d^0 \rightarrow \mu^+ \mu^-$ .



#### CMS Top-Level Upgrade Schedule for HL-LHC



• Sub-detector Technical Design Reports in 2017 (except trigger = 2019)



### High Granularity Calorimeter: additional details

- Silicon sensors are hexagonal to make best use of silicon wafers (6" or 8").
- Scintillator read out by Silicon Photomultipliers.
- Entire HGcal cooled to -30°C to reduce radiation damage.
- Absorber is copper/tungsten (at front) or steel (at back).
- Time-of-flight measurement (to identify particles from pileup or discover long-lived exotica):
  - HGcal also measures time-of-flight.
    Resolution for high energy photons may reach < 10ps.</li>
  - > P.S. ECAL barrel electronics upgrade should also improve its timing resolution.
  - > P.S. CMS also expects to build dedicated time-of-flight detector.



- UK CBC responsibilities include module tests & integration.
- More info about pixel tracker commissioning in "CMS highlights" talk from EPS conference.



#### Status of CMS/UK detector upgrade funding bid for HL-LHC

- We submitted a proposal in Oct. 2016, giving advanced warning of what we were likely to be bidding for.
- This was approved by the LHC tensioning review, & subsequently by Science Board.
- We will be submitting a formal bid to PPRP in late 2017, to get funding for the CMS/UK upgrade project from 2019-2024.



#### 750 GeV Diphoton Resonance [PRL 117 (2016) 051802]

