U.S. CMS Phase-1 and HL-LHC Upgrades

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on behalf of U.S. CMS

HEPAP Meeting Nov. 21-22, 2019
Outline

- Overview of CMS and HL-LHC
- Phase-1
- HL-LHC
- Computing
- Summary
U.S. CMS and CMS

53 Countries
232 Institutes
281 Technicians *
1065 Engineers *
2942 Physicist (PHD+PHD students) *

1906 PhD Physicists *
1036 Physics Doctoral Students *
1110 Undergraduates *
(* as of Feb 2019)

US (DOE + NSF) is largely the biggest nation with close to 30% participation (incl. 2% nucl.)

... and growing
- two new institutes since last spring
- four more will be voted in December

51 U.S. Institutions on CMS
U.S. CMS plays a crucial role in CMS
LHC / HL-LHC Plan

LHC/HL-LHC Upgrade Timeline

Phase-1
CMS followed an approach of early installation of the Phase-1 upgrades and detector improvements from LS1 (2013/14) to LS2 (2019/20)

- New pixel detector installed in the EYETS 2016/17
  - DC-DC problem required repairs in the YETS 2017/18
  - Barrel layer 1 replacement (planned after Run 2) will be installed during LS2 (2020) (not U.S. Scope)
CMS Phase-1 Upgrades Cont.

- L1 Trigger upgrade installed in 2015 and data taking 2016
- Upgraded readout for hadron calorimeter
  - Forward upgrade started in LS1, completed in the EYETS 2016/17
  - Endcap front-end electronics and photo sensors upgraded un YETS 2017/18
  - Barrel upgrade completed in LS2
- The U.S. (NSF+DOE) Phase-1 contribution ~$40M
  - These upgrades were completed this summer
The HL-LHC upgrades will address three of the five P5 Science Drivers

1. Use the Higgs boson as a new tool for discovery
2. Pursue the physics associated with neutrino mass
3. Identify the new physics of dark matter
4. Understand cosmic acceleration: dark energy and inflation
5. Explore the unknown: new particles, interactions, and physical principles.

Upgrades designed to take full advantage of the HL-LHC

- Designed for 3 ab$^{-1}$ – radiation tolerance
- Operating at 200 PU – handle the high occupancy environment
- Key science requirements:
  - Maintain low trigger threshold
  - Forward jet tagging
  - Efficient Higgs reconstruction
  - PU mitigation
  - Secondary vertex tagging
- **New Si based tracker**
  - Outer tracker instrumented with $p_T$ discriminating modules for L1 tracking
    - $p_T > 2$ GeV @ 40 MHz
  - Inner tracker (‘pixel detector’) extends forward tracking to $|\eta| < 4$
Calorimeter Upgrades for HL-LHC

- New High Granularity forward calorimeter
  - High resolution 4-D reconstruction
  - 28 electromagnetic layers, silicon modules (Cu/CuW/Pb absorber, 25 $X_0$, 1.3 $\lambda$)
  - 22 hadronic layers: Si + Si/SiPM (stainless steel absorber, 8.5 $\lambda$)
- Upgraded barrel readout
  - Crystal level readout for trigger
  - Precision timing
MIP Timing Detector (MTD)

- Provide precision timing for MIP particles – mitigate PU
  - LYSO crystals + SiPMs in barrel
  - SI LGAD in endcap

MTD design overview

- Thin layer between tracker and calorimeters
- MIP sensitivity with time resolution of ~30 ps
- Hermetic coverage for $|\eta|<3$
Trigger/HLT/DAQ
- Track information in L1-Trigger
- L1-Trigger: 12.5 µs latency – output 750 kHz
- HLT output 7.5 kHz

Barrel ECAL/HCAL
- Replace FE/BE electronics
- Lower ECAL operating temp. (8 °C)

Muons Systems
- Replace DT & CSC FE/BE Electronics
- Complete Muon coverage in region 1.5<η<2.4
- Muon tagging 2.4<η<3

New Endcap Calorimeters
- Rad. tolerant – high granularity
- 3D capable

New Tracker
- Rad. tolerant – high granularity – significant less material
- 40 MHz selective readout (p_T>2 GeV) in Outer Tracker for L1 -Trigger
- Extended coverage to η=4

MIP Precision Timing Detector
- Barrel: Crystal +SiPM
- Endcap: Low Gain Avalanche Diodes
TDRs written and approved by LHCC/RRB:

- Tracker
- Muons
- Endcap Calo.
- Barrel Calo.
- MIP Timing

Next:
- L1 Trigger (2020)
- DAQ/HLT (2021)
- Beam Radiation, Instrumentation and Luminosity (2020)
- Computing (2022)
U.S. HL-LHC Approval Timeline

**DOE O 413.3B**

**Timeline:**
- **LS1** (2011-2014): Splice consolidation button collimators R2E project
- **LS2** (2019-2020): Experiment upgrade phase 1
- **LS3** (2024-2026): HL-LHC installation
- **CDR** (2020)
- **PDR**
- **FDR**

**Construction:**
- Apr 2020-Feb 2026

**Installation:**
- (not MREFC)

**DOE**
- O 413.3B
Following the P5 report in 2014 NSF formed a subcommittee (of the MPS Advisory Committee) to recommend NSF’s response to the P5 report:
- Recommended NSF pursue an MREFC for the HL-LHC upgrades
- One HL-LHC MREFC for CMS+ATLAS ($75M+$75M)

CMS has proceeded through the MREFC approval process:
- Conceptual Design Review – March 2016
- Preliminary Design Review – December 2017
- Final Design Review – September 2019

Plan is to start construction project April 1, 2020:
- National Science Board approval targeted for Feb. 2020

In addition to the MREFC funds the NSF has supported the R&D phase (~$11M) and will support installation (~4M):
- Support has come through the operations program
The CMS HL-LHC Upgrade approval process

- CD-0 (Approve Mission Needs) March 2015
- CD-3A (Early procurements) March (2020)
- CD-2 (Approve Performance Baseline) Nov. 2020

The DOE Total Project Cost (TPC) is $162M (incl. installation and commissioning)

- Early R&D supported by U.S. CMS Operations Program
- 48 Institutions involved with the HL-LHC upgrades
- Scientific labor is effort that is not on the project:
  - Graduate Students, Postdocs, Faculty/Scientists
- Graduate student and postdoc involvement is essential for the training of future scientists

Scientific Labor Effort:
141 FTE years Grad. Students
128 FTE years Postdocs
189 FTE years Scientists

Total effort 458 FTE years
At peak ~80 FTEs

We also have 94 FTE years of costed undergraduate effort

- With the tight funding for research the availability of the scientific labor is a concern for the upgrade project
- ATLAS/CMS are evaluating “Full Life-Cycle Cost”, including Computing
- Solving HL-LHC computing requires to modernize physics software
  - CPU challenge needs innovative algorithms and data structures, including ML / AI
    - New algorithms to run well at high pile-up on modern architectures for CPUs, GPUs, FPGAs
    - Will allow for cost effective computing solutions based on industry trends and emerging science infrastructures, including HPC and computing clouds
  - Storage is a cost driver, and data storage cannot be done “opportunistically”
    - Needs R&D into Data Organization, Management and Access
- Areas of Software and Computing Research Needs
- Ongoing R&D to develop the blueprint for HL-LHC Computing
  - In close coordination and collaboration in the US and internationally
  - DOE — NSF partnership is essential: US LHC Ops Programs, IRIS-HEP, CCE, etc
Phase-1 upgrades completed

- CMS HL-LHC upgrades are exciting and ambitious
  - New tracker with trigger primitive ($p_T$ discrimination) and extended forward coverage
  - New High-Granularity forward calorimeter
  - New MIP timing detector
  - Upgraded readout and trigger electronics

- HL-LHC upgrades proceeding
  - CMS/CERN approval of TDRs for major detector components
  - NSF Final Design Review held in Sept. 2019
    - Anticipate project start in April 2020
    - CD-2 expected Nov. 2020

- U.S. CMS collaboration enthusiastically engaged
Anders Ryd

NSF Scope Budget Profile at FDR

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Trends in CMS, USCMS authors by region & gender

Female author fraction
U.S. CMS Physicists:
Postdocs: 23±4%
(faculty + researchers):
Junior: 35±10%
Senior: 12±2%
Training of graduate students

- Given the large size and long time scales of CMS, we recognize our important role in the stewardship of our field, especially in terms of training and mentoring students & postdocs.

- Concerns about 15% decrease in graduate students in the last year.

- Mentoring of early-career scientists for leadership roles in the experiment & industry.
  - Most U.S. CMS students who completed their Ph.D. since 2008 have followed scientific careers and are distinguishing themselves in academic, research, and industry environments.
  - Outside academia, they have brought expertise on data science and advanced computing techniques e.g. machine learning to a diverse array of projects in high-tech industry, medicine, and other sectors.
    - Autopilot development for Tesla Motors, AI research for DeepMind
    - Educational data mining for Pearson North America
    - Software development for the National Center for Missing and Exploited Children
    - Cloud computing for Amazon Web Services, and applications in the health-care sector.
Decreasing time available for doing “Science”

- Keep total number of FTE available in FY17 (portfolio review)
- Projected operations FTE needs assumed constant per year (portfolio review)
- Projected needs for scientific labor profile for carrying out HL-HEC detector R&D and construction
- Compute “fraction of FTE available” for carrying out “Science tasks” after accounting for FTE needs by operations and upgrade
- Compared to FY17 expect ~40% decrease by FY22!!
  - Optimistic estimate as EF budgets have decreased consistently since then.

Science tasks defined as:
- performing analysis,
- developing innovative analysis techniques,
- publications,
- studies for HL-LHC,
- indulging in community activities
  - (e.g. snowmass, outreach, etc)

It is getting untenable overextension, working weekends not very conducive to increasing diversity in the field, also does not promote family friendliness.