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

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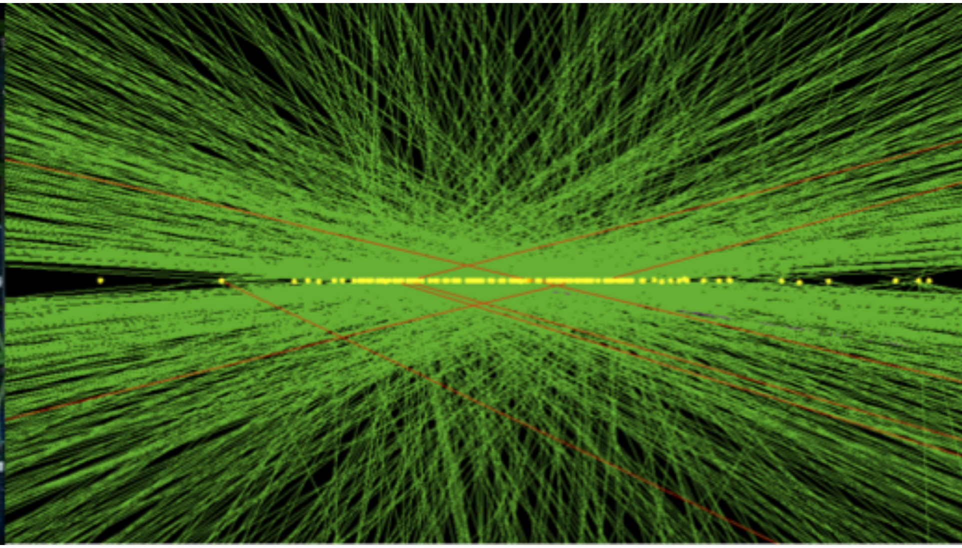
on behalf of U.S. CMS

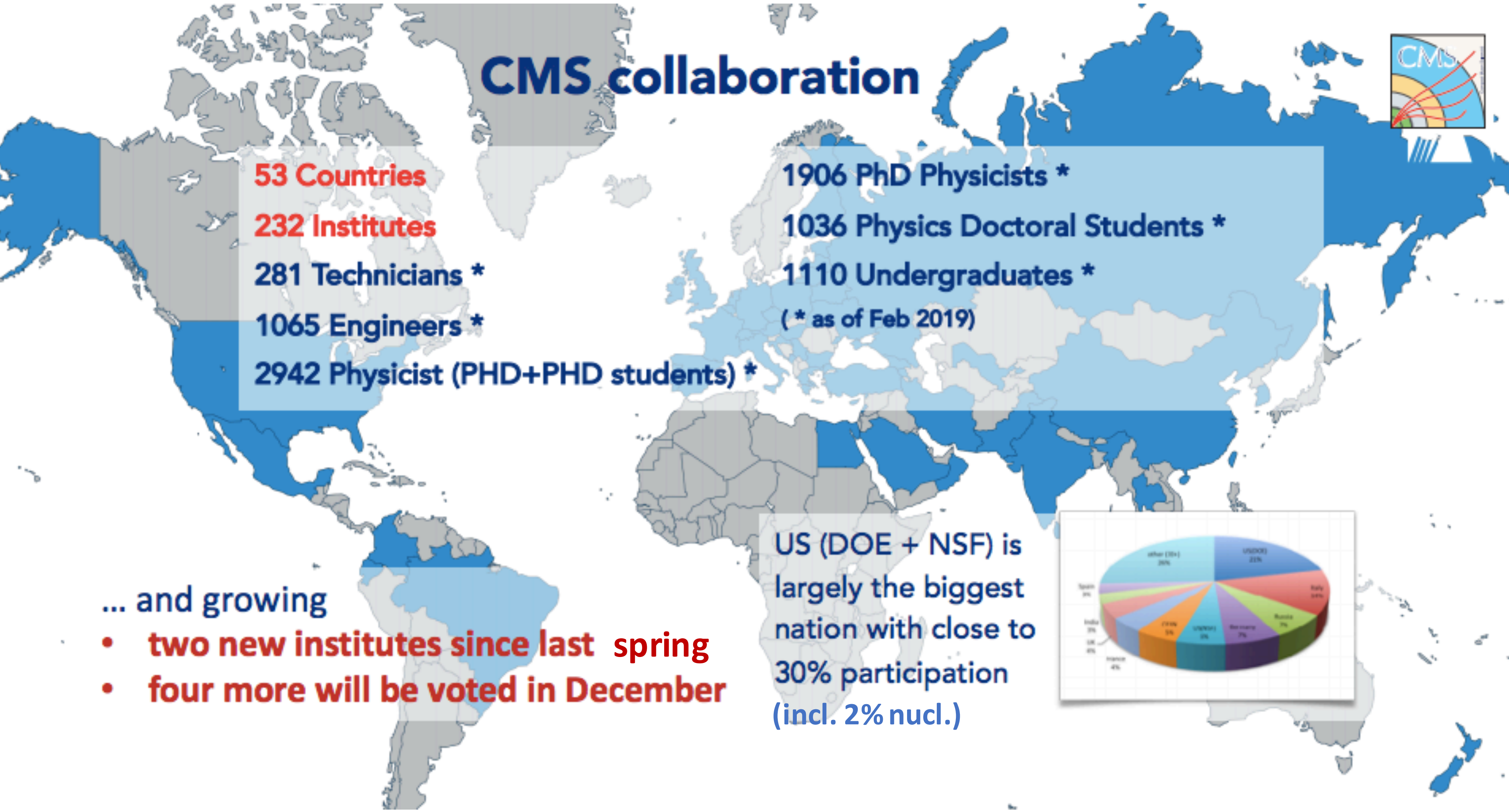
HEPAP Meeting Nov. 21-22, 2019

Outline

- Overview of CMS and HL-LHC
- Phase-1
- HL-LHC
- Computing
- Summary

U.S. CMS and CMS

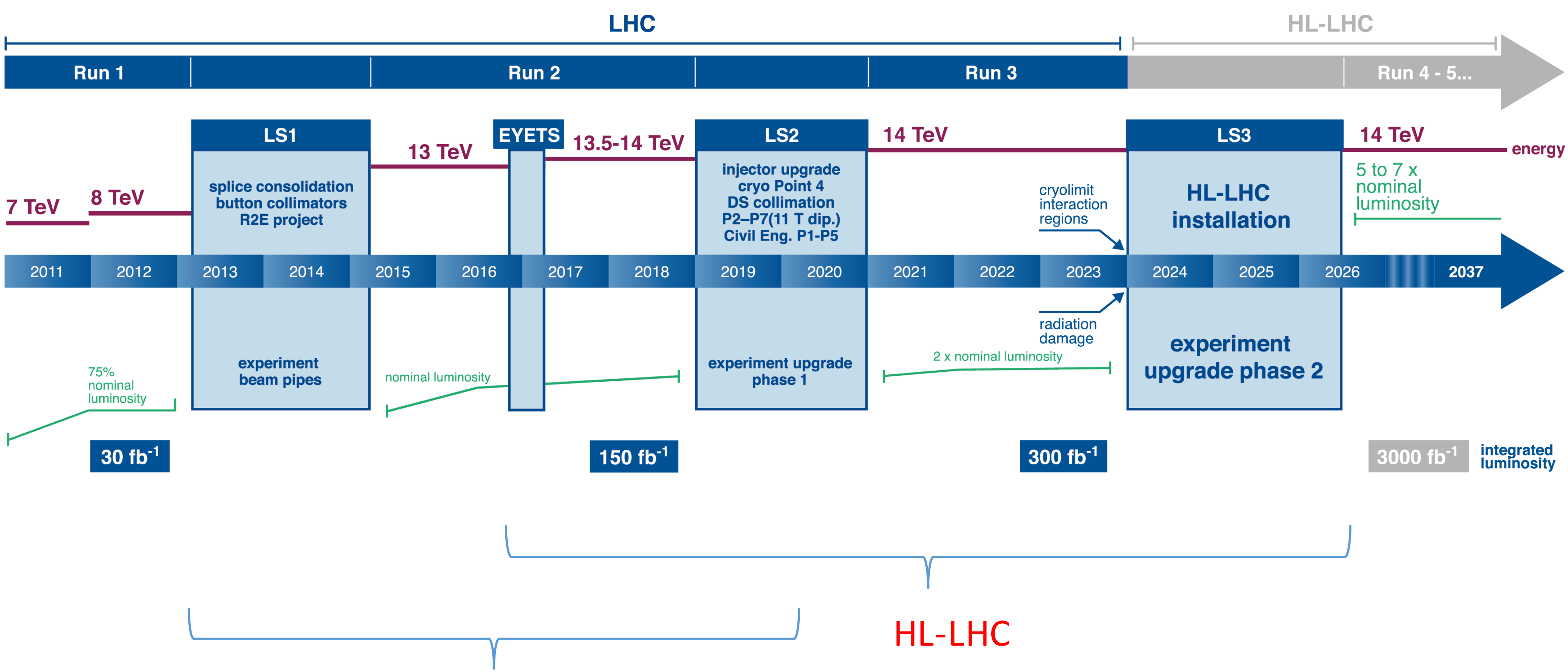


51 U.S. Institutions on CMS

U.S. CMS plays a crucial role in CMS

LHC/HL-LHC Upgrade Timeline

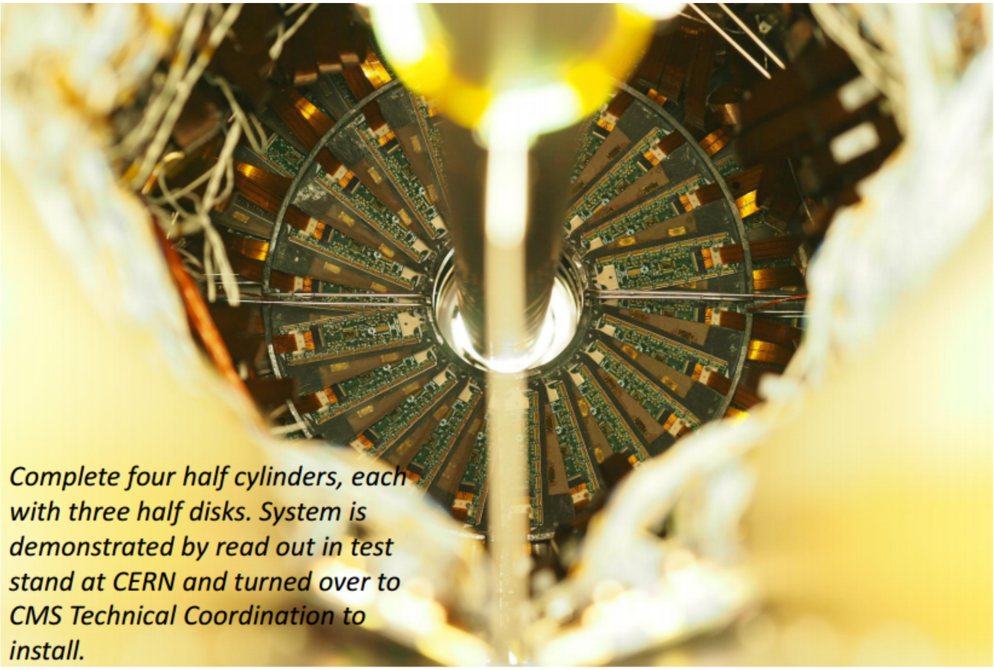
LHC / HL-LHC Plan



Phase-1

CMS Phase-1 Upgrades

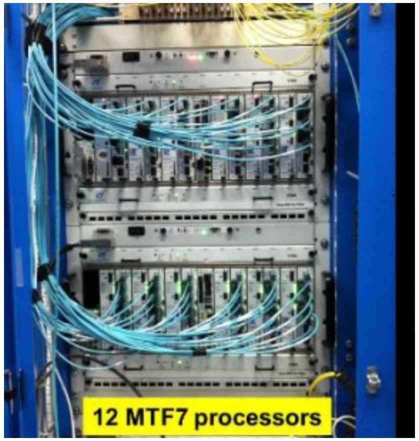
- CMS followed an approach of early installation of the Phase-1 upgrades and detector improvements from LS1 (2013/14) to LS2 (2019/20)
- New pixel detector installed in the EYETS 2016/17
  - DC-DC problem required repairs in the YETS 2017/18
  - Barrel layer 1 replacement (planned after Run 2) will be installed during LS2 (2020) (not U.S. Scope)

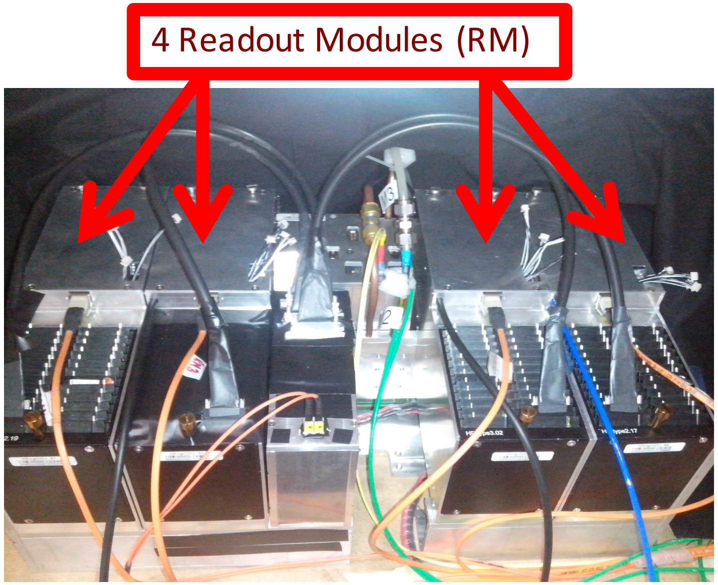


Complete four half cylinders, each with three half disks. System is demonstrated by read out in test stand at CERN and turned over to CMS Technical Coordination to install.

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





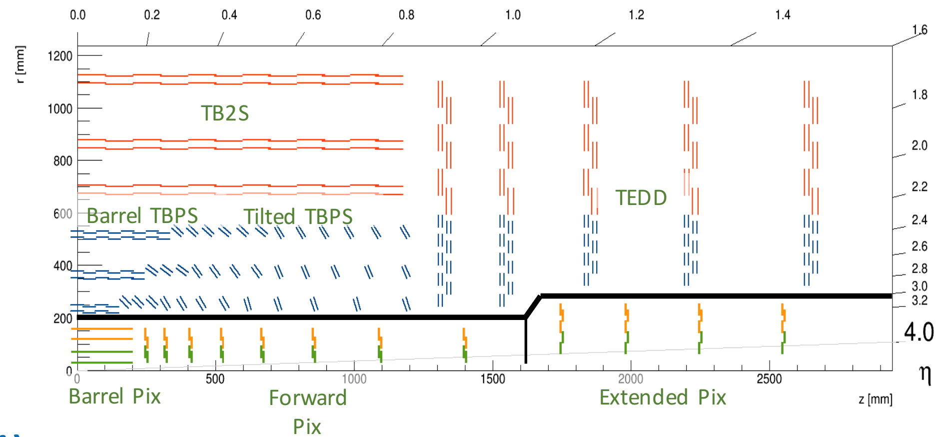
- The U.S. (NSF+DOE) Phase-1 contribution ~$40M
  - These upgrades were completed this summer

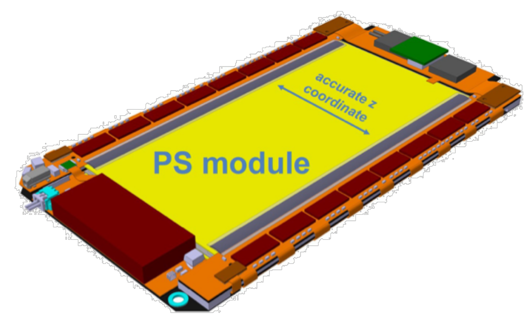
CMS HL-LHC Upgrade Goals

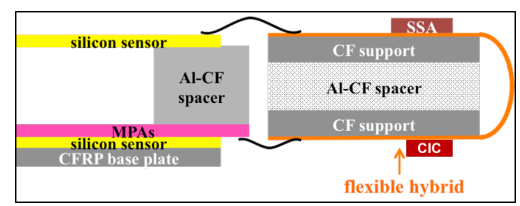
- The HL-LHC upgrades will address three of the five P5 Science Drivers
  1. Use the Higgs boson as a new tool for discovery
  2. Pursue the physics associated with neutrino mass
  3. Identify the new physics of dark matter
  4. Understand cosmic acceleration: dark energy and inflation
  5. Explore the 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

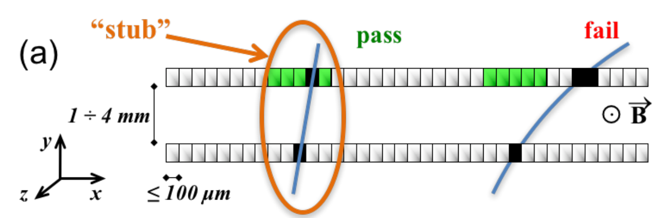
Tracking Upgrades for HL-LHC

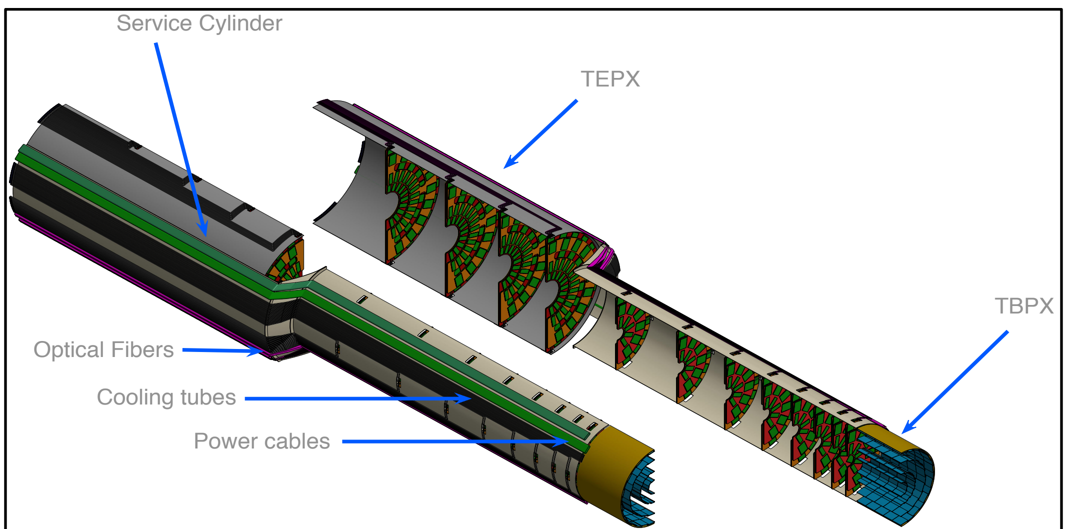
- New Si based tracker
  - Outer tracker instrumented with p_T discriminating modules for L1 tracking
    - p_T>2 GeV @ 40 MHz
  - Inner tracker ('pixel detector') extends forward tracking to $|\eta|<4$





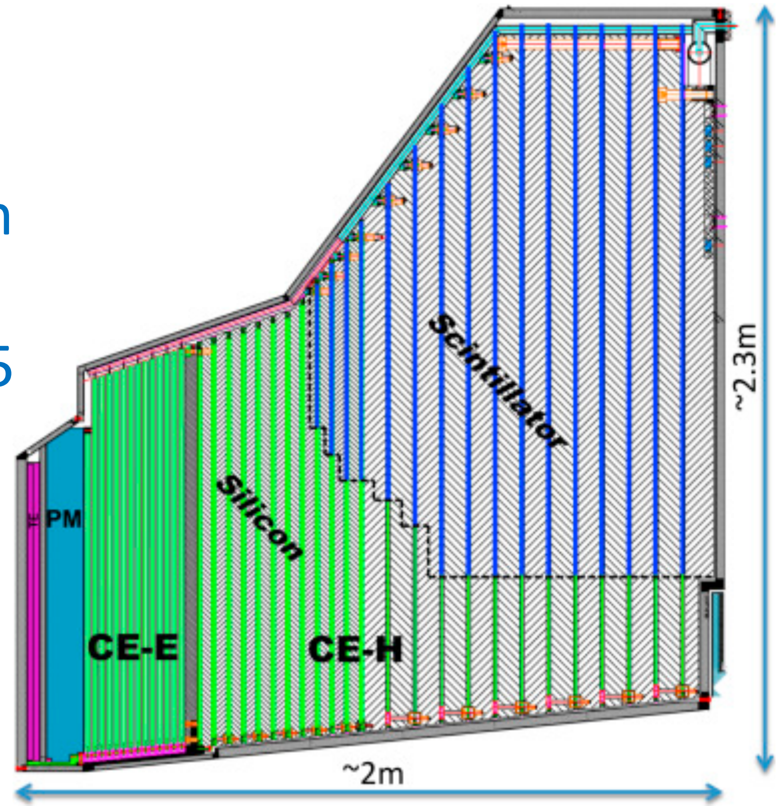


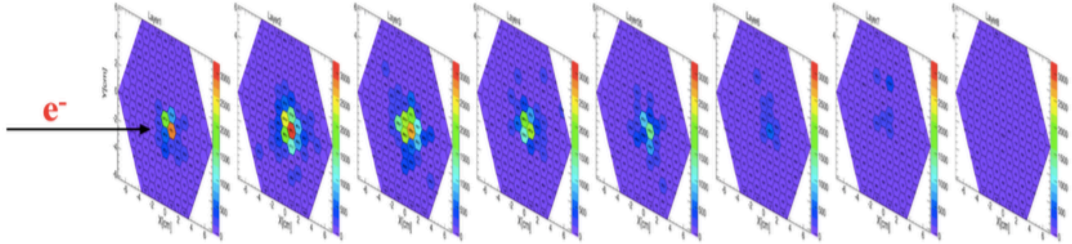




Calorimeter Upgrades for HL-LHC

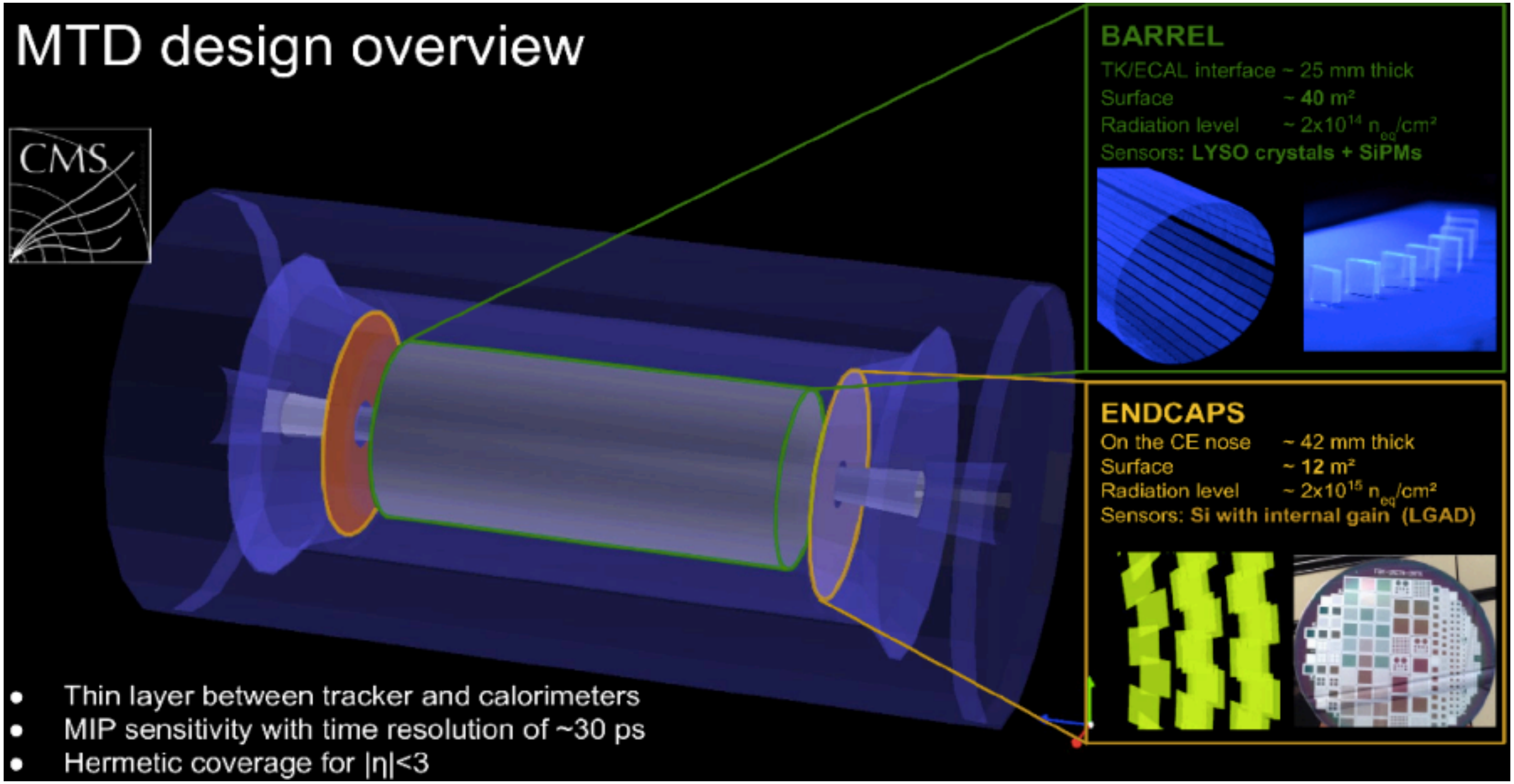
- New High Granularity forward calorimeter
  - High resolution 4-D reconstruction
  - 28 electromagnetic layers, silicon modules (Cu/CuW/Pb absorber, 25 X_0, 1.3 λ)
  - 22 hadronic layers: Si + Si/SiPM (stainless steel absorber, 8.5 λ)
- Upgraded barrel readout
  - Crystal level readout for trigger
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





MIP Timing Detector (MTD)

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



Summary of CMS HL-LHC Upgrades

DOE and NSF

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

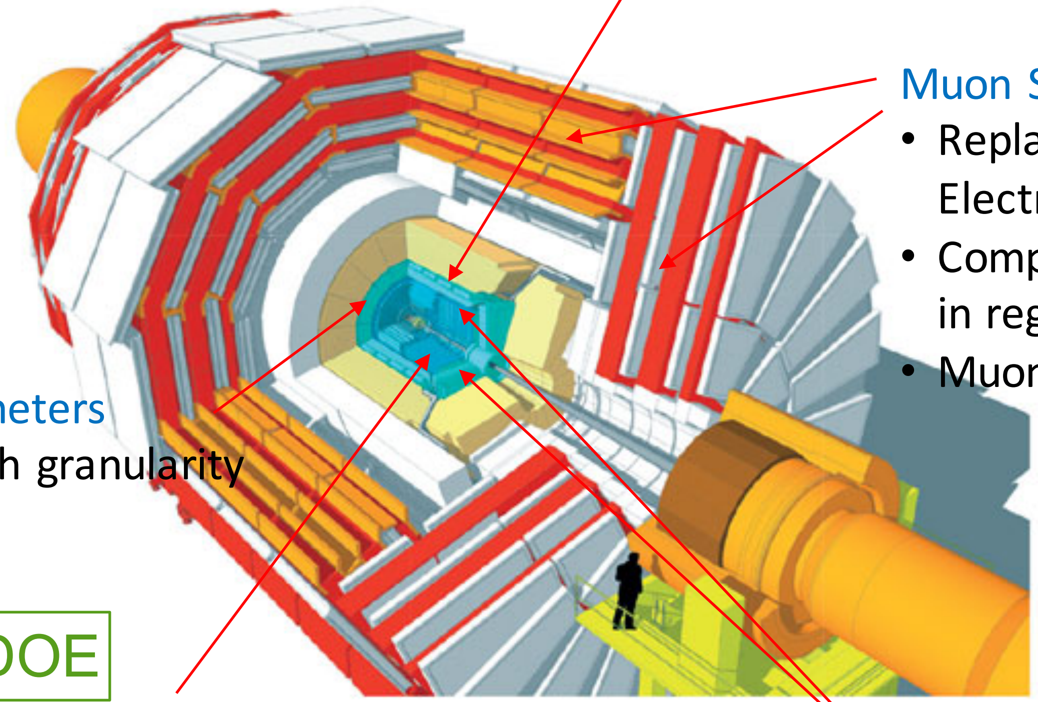
NSF

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

Muon Systems

NSF

- Replace DT & CSC FE/BE Electronics
- Complete Muon coverage in region $1.5<\eta<2.4$
- Muon tagging $2.4<\eta<3$



DOE

New Endcap Calorimeters

- Rad. tolerant – high granularity
- 3D capable

New Tracker

DOE

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

NSF

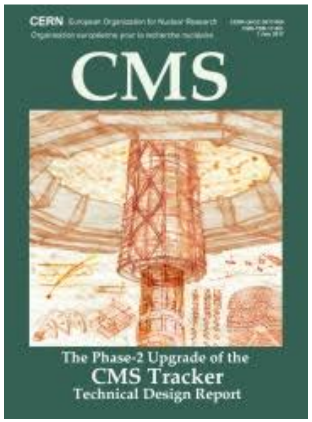
MIP Precision Timing Detector

DOE

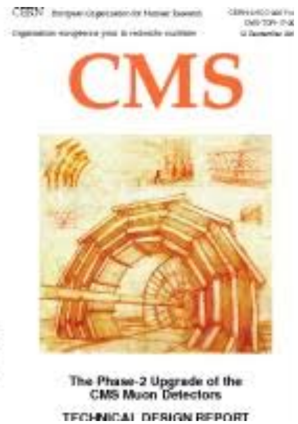
- Barrel: Crystal +SiPM
- Endcap: Low Gain Avalanche Diodes

CMS and CERN HL-LHC Approval

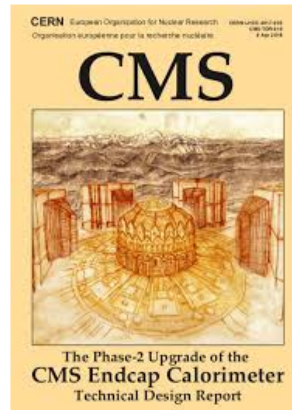
- TDRs written and approved by LHCC/RRB:



Tracker



Muons



Endcap Calo.

Barrel Calo.

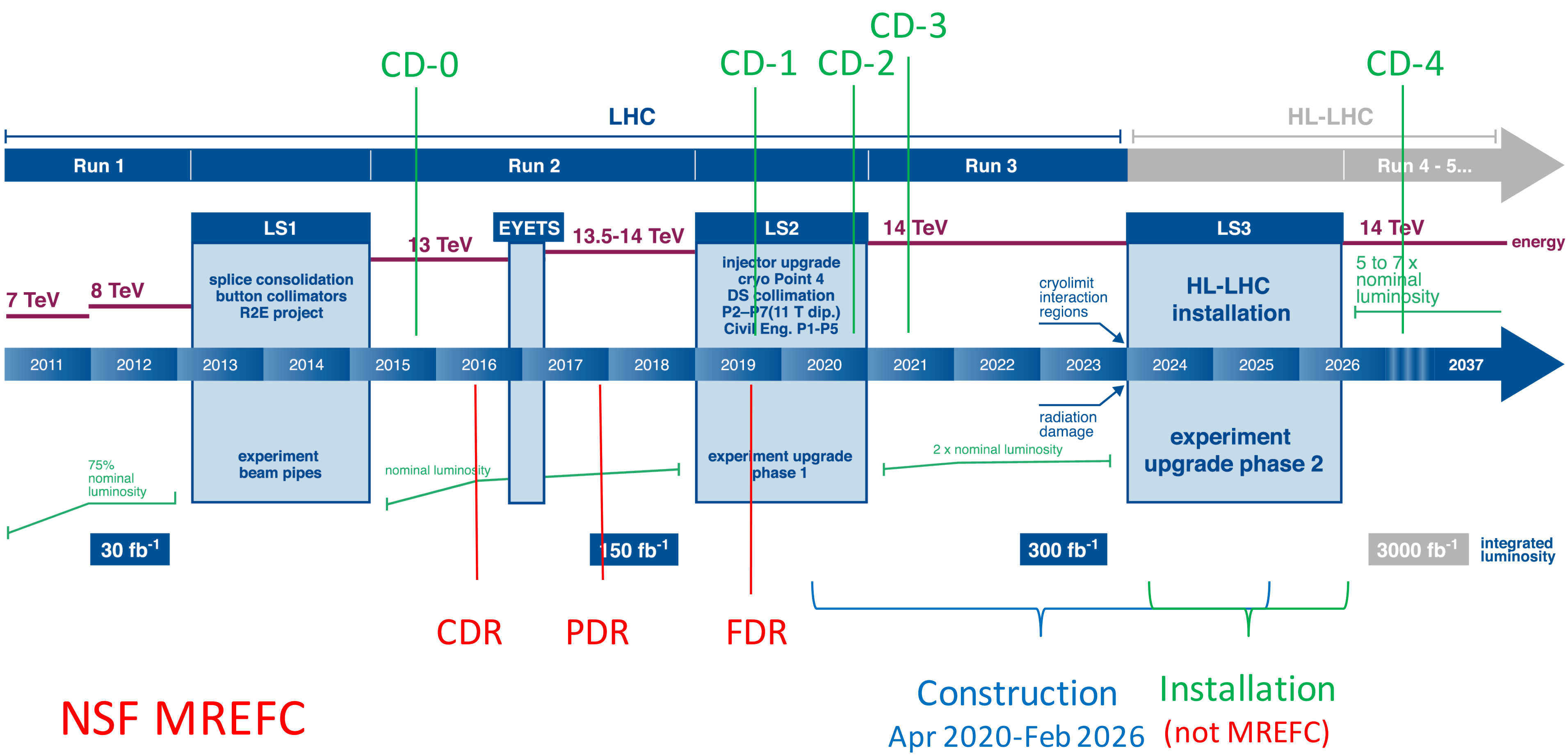
MIP Timing

- Next:
  - L1 Trigger (2020)
  - DAQ/HLT (2021)
  - Beam Radiation, Instrumentation and Luminosity (2020)
  - Computing (2022)

Interim TDRs in 2017 (L1 Trigger, DAQ/HLT)

U.S. HL-LHC Approval Timeline

DOE O 413.3B



NSF MREFC

NSF - Status for HL-LHC Upgrades

- 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

DOE – Status of HL-LHC Upgrades

- The CMS HL-LHC Upgrade approval process
  - CD-0 (Approve Mission Needs) March 2015
  - CD-1 (Approve Alternative Selection and Cost Range) Oct. 2019
  - 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

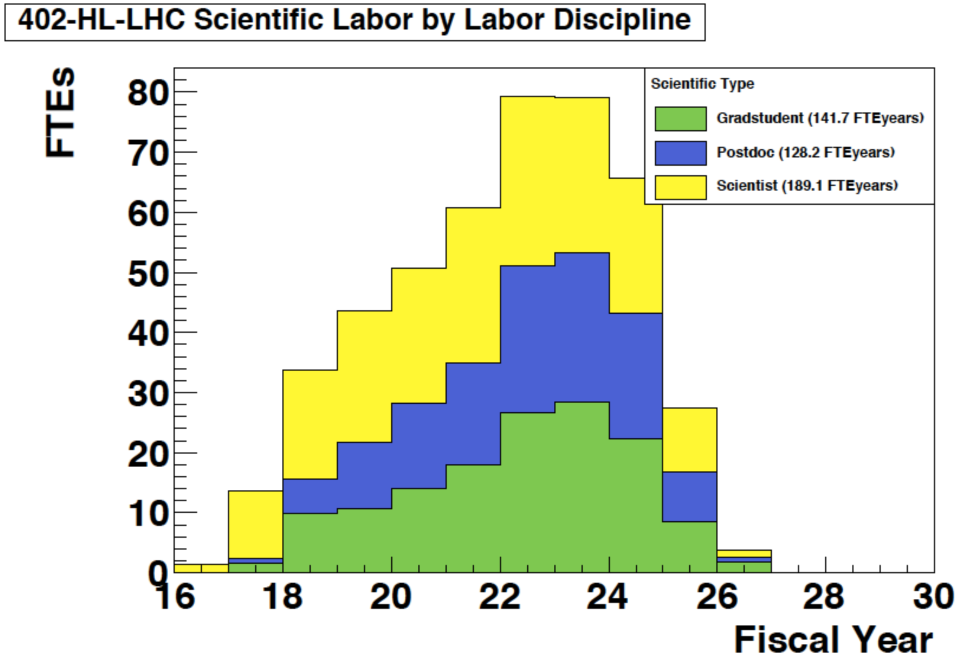
Scientific Labor

- 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

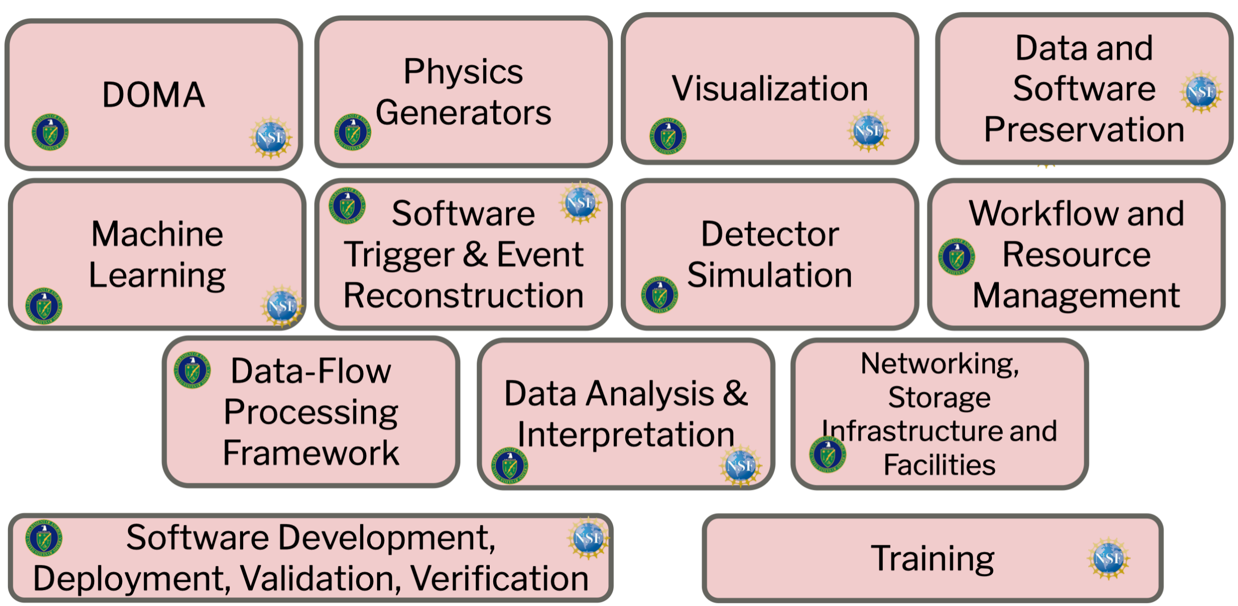
We also have 94 FTE years of costed undergraduate effort



- With the tight funding for research the availability of the scientific labor is a concern for the upgrade project

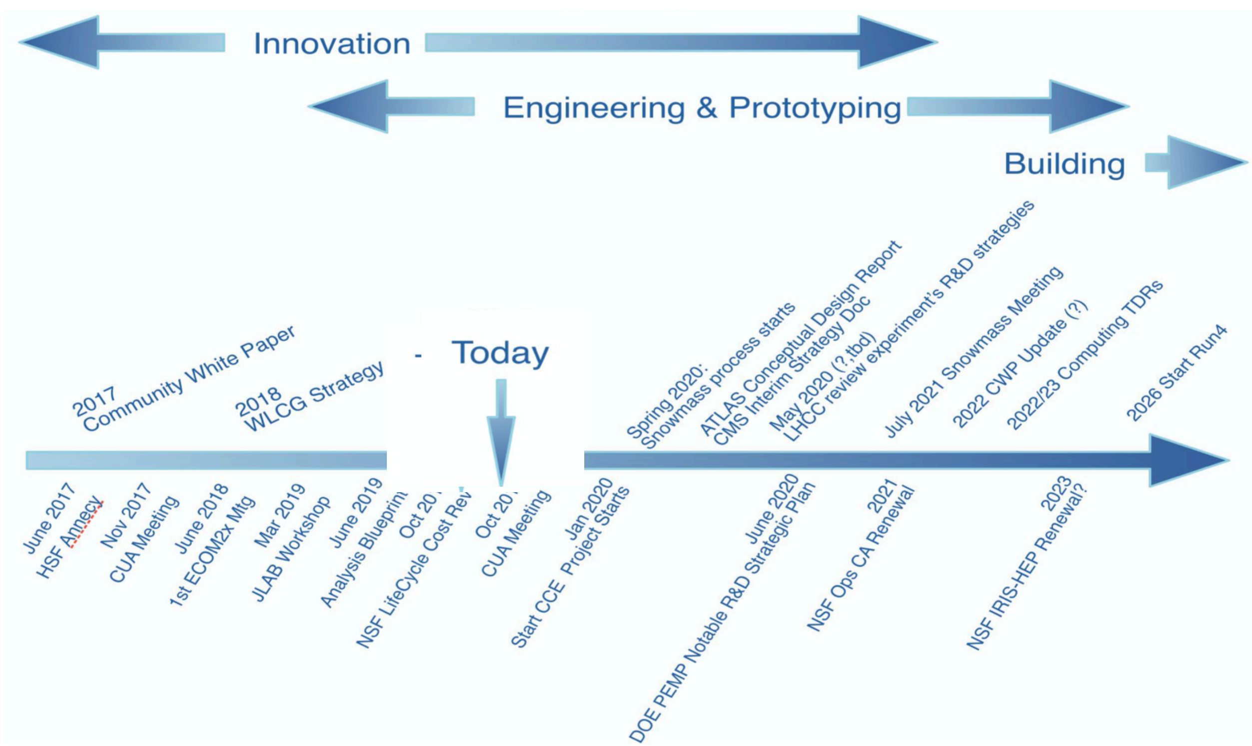
HL-LHC: Unprecedented Computing Challenges

- 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



HL-LHC Computing R&D Timeline

- 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

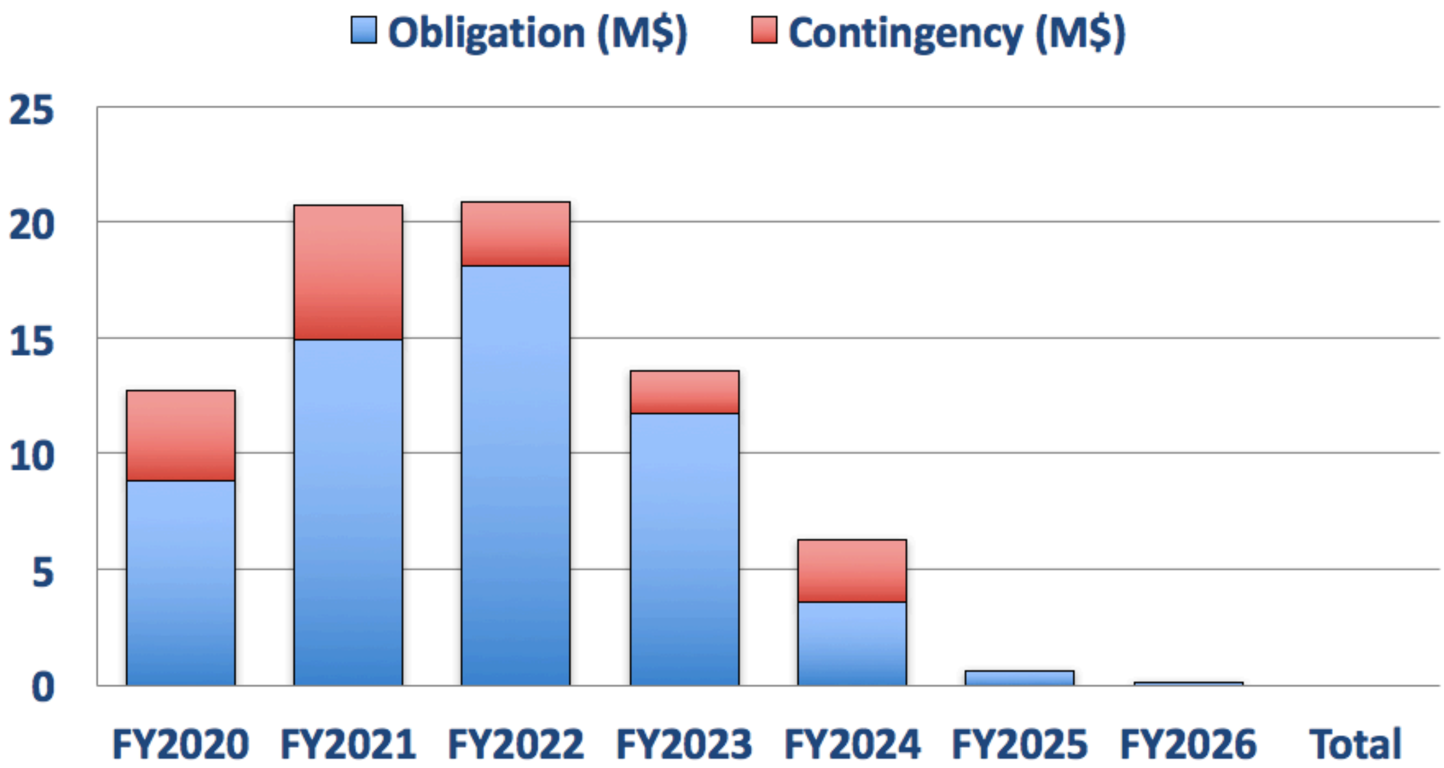


Summary

- 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
  - DOE CD-1 Review held Oct. 2012
    - CD-2 expected Nov. 2020
- U.S. CMS collaboration enthusiastically engaged

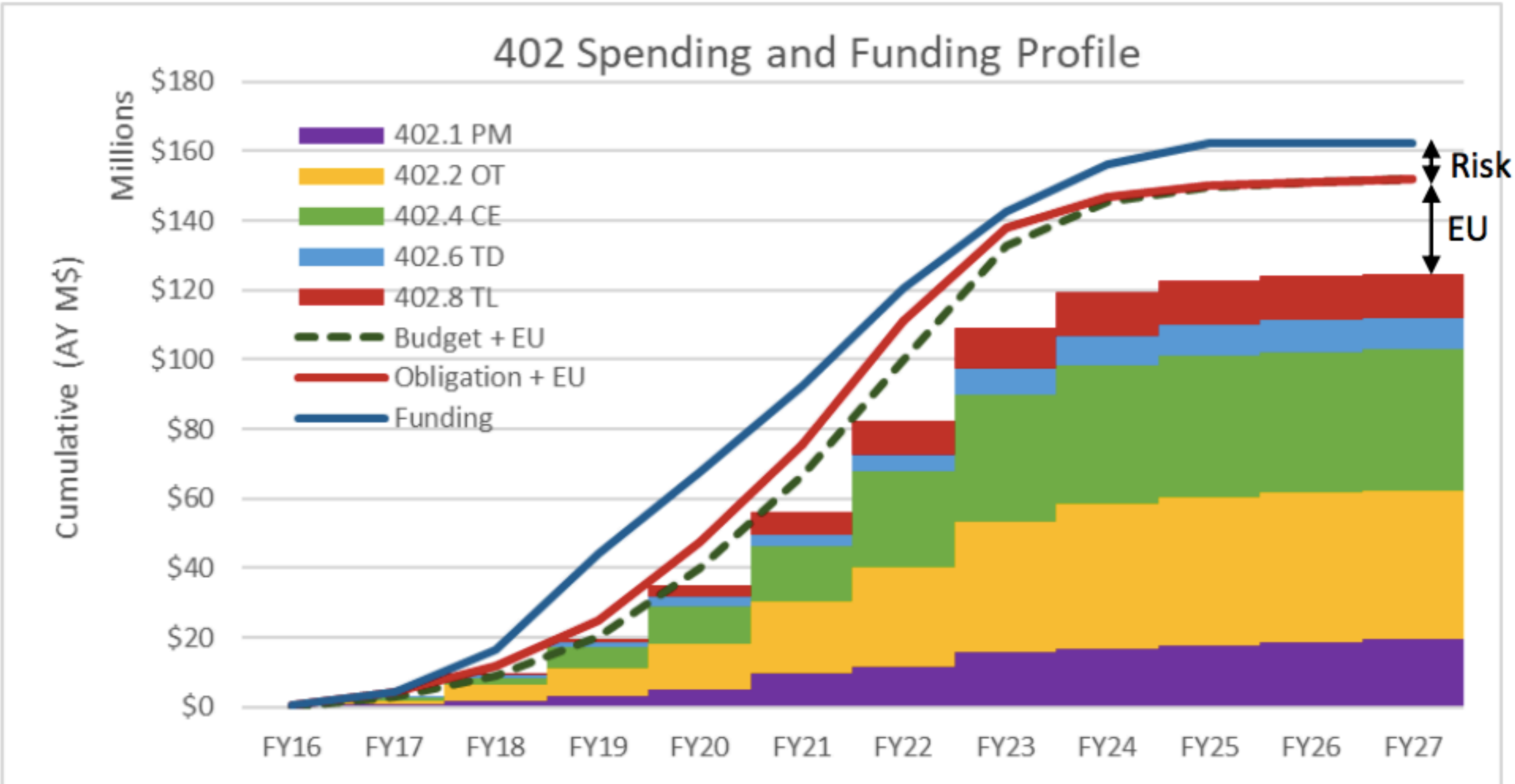
BACKUP

NSF Scope Budget Profile at FDR

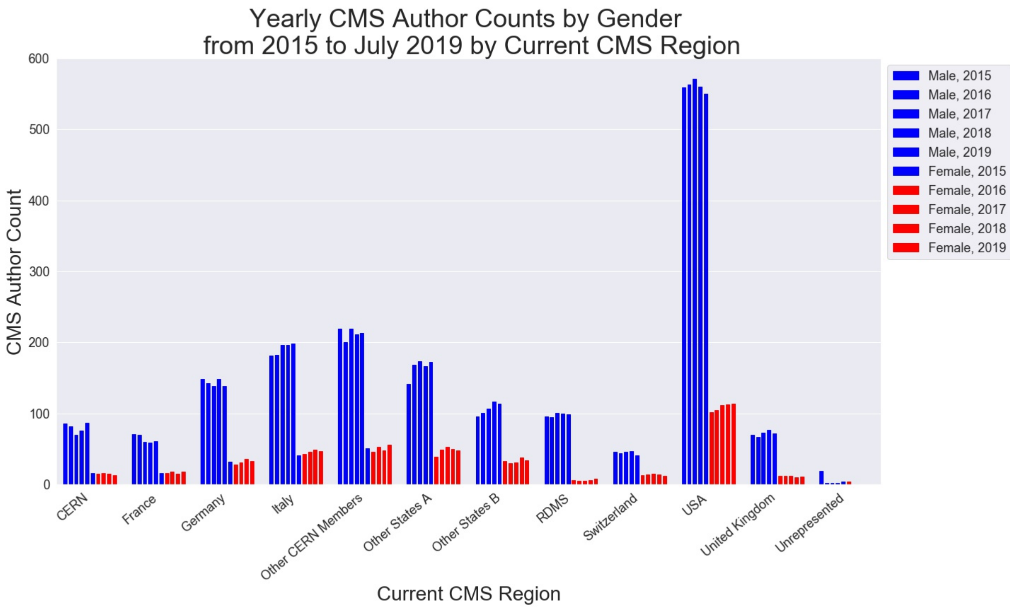


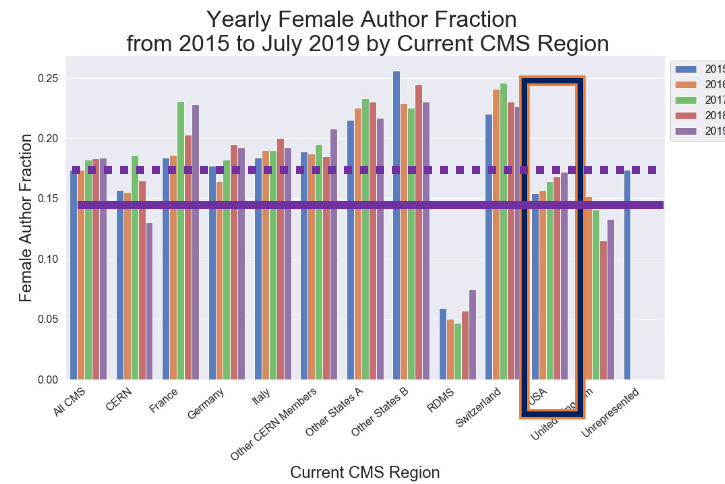
Contingency (M$)	3.9	5.8	2.8	1.9	2.7	0.0	0.0	17.1
Obligation (M$)	8.8	14.9	18.1	11.7	3.6	0.6	0.1	57.9
Total (M$)	12.7	20.7	20.9	13.6	6.3	0.6	0.1	75.0

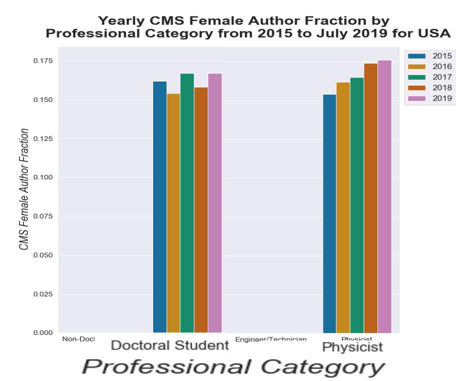
DOE Funding Profile



Trends in CMS, USCMS authors by region & gender



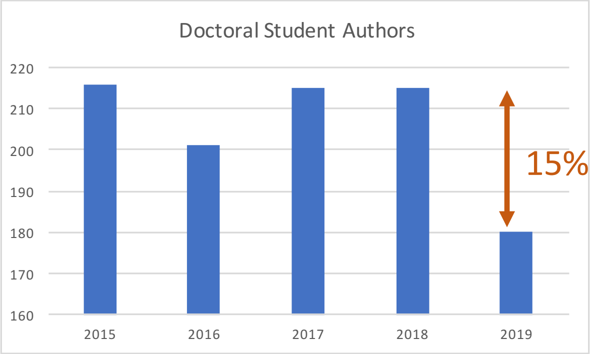




Female author fraction U.S. CMS Physicists:
Postdocs: 23±4%
(faculty + researchers):
Junior: 35±10%
Senior: 12±2%

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-HC 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.