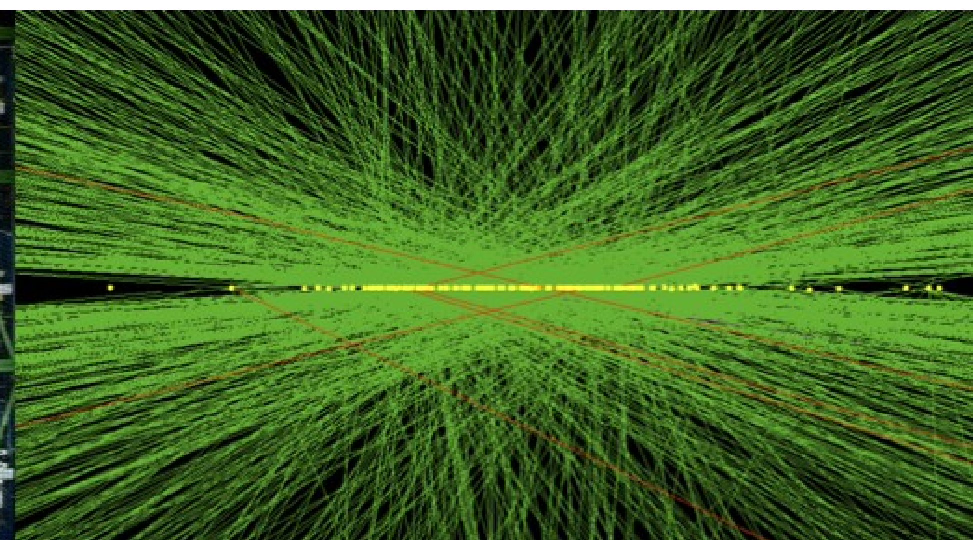
P07: 402.4 Endcap Calorimeter (CE)

Jeremiah Mans

CD1 Director's Review

March 19, 2019



Outline

- Introduction
- Design of the Endcap Calorimeter
  - Motivation, Scope, and Deliverables
- Updates since June 2018
  - Conceptual Design, Maturity
  - Organization, Cost, Schedule
  - Risks
- Response to Previous Reviews
  - June 2018 Recommendations
- Progress towards CD-3a
- ES&H / QA&QC
- Breakout Session topics
- Summary

Biographical Sketches

Charge #5

- L2 Manager: Jeremiah Mans
  - Professor (University of Minnesota)
  - L2 Manager for CMS HCAL portion of US LHC Upgrade Project (2013-2015)
    - Developed full resource-loaded schedule from the beginning of the project, led HCAL team through CD1, CD2/3 reviews
  - International Endcap Calorimeter Project Office, L2 Coordinator for scintillator system (2016-current)
  - Deputy International CMS Phase 2 Upgrade Coordinator (2013-2015)
    - Co-led preparation of CMS Phase 2 Upgrade Technical Proposal and Scoping Document, lead editor for calorimetry chapter of technical proposal
  - Physics: Search for new physics in dilepton/dijet channel, electroweak physics measurements
  - Technical work: development of HCAL Phase 1 offline electronics, evaluation of commercial solutions for on-detector radiation-tolerant FPGAs
- L2 Deputy: Harry Cheung
  - Senior Scientist (Fermilab)
  - L3 Manager/CAM for Components in CMS Forward Pixels (2013-2017)
    - Developed design and RLS from R&D through CD1, CD2/3 and CD4
  - Co-convenor of the CMS Tracker Upgrade Simulations working group (2007-2012)
  - USCMS Operations L3 Manager for Storage Manager software (2007-2009)
  - Constructed early scintillating-fiber electromagnetic calorimeter for E831 (1988-1993)

CMS HL-LHC Upgrade Overview

L1-Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193

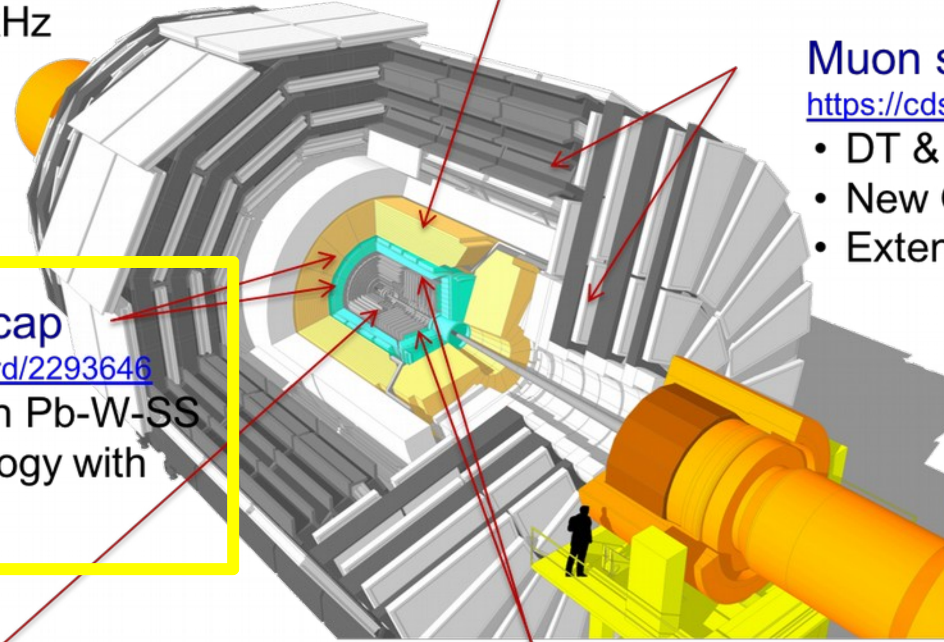
- Tracks in L1-Trigger at 40 MHz for 750 kHz PFlow-like selection rate
- HLT output 7.5 kHz

Barrel Calorimeters
https://cds.cern.ch/record/2283187

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

Muon systems
https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$



Calorimeter Endcap
https://cds.cern.ch/record/2293646

- Si, Scint+SiPM in Pb-W-SS
- 3D shower topology with precise timing

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

Tracker https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

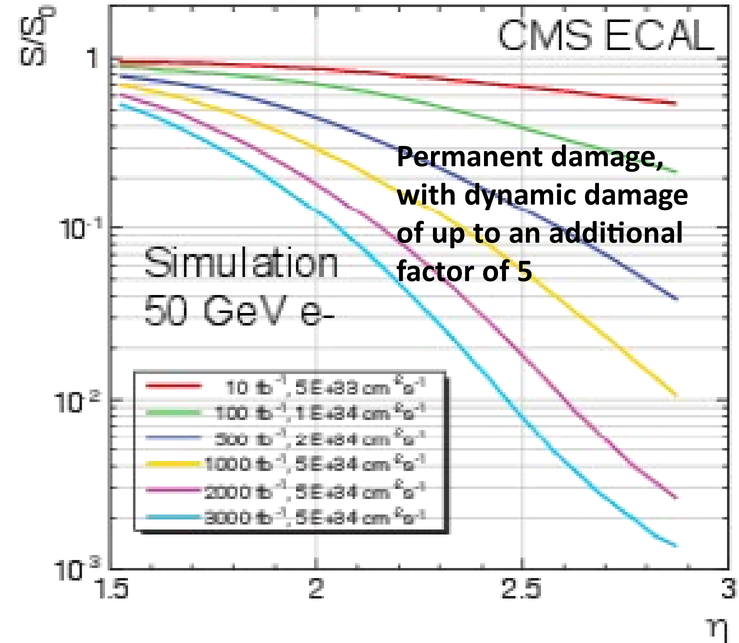
MIP Timing Detector
https://cds.cern.ch/record/2296612

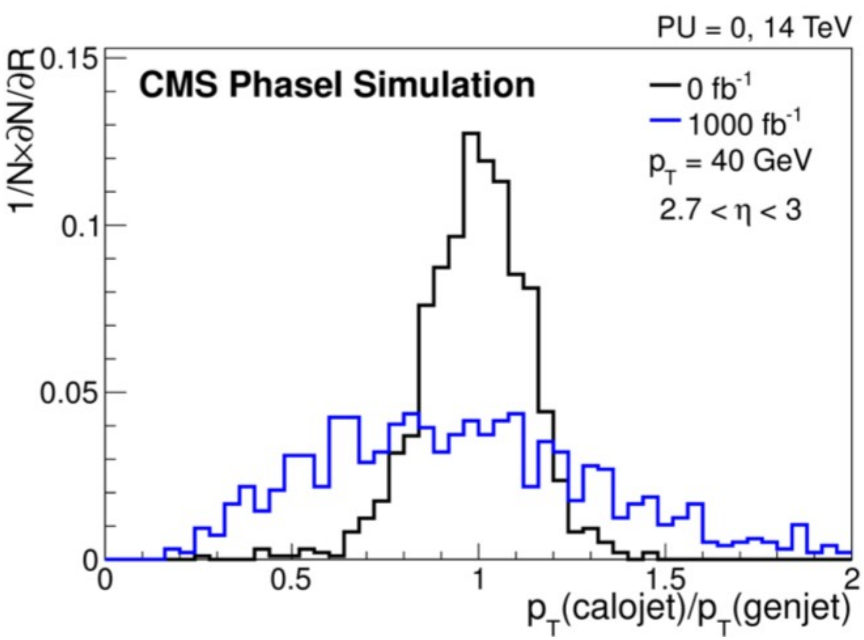
- $\simeq$ 30 ps resolution
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

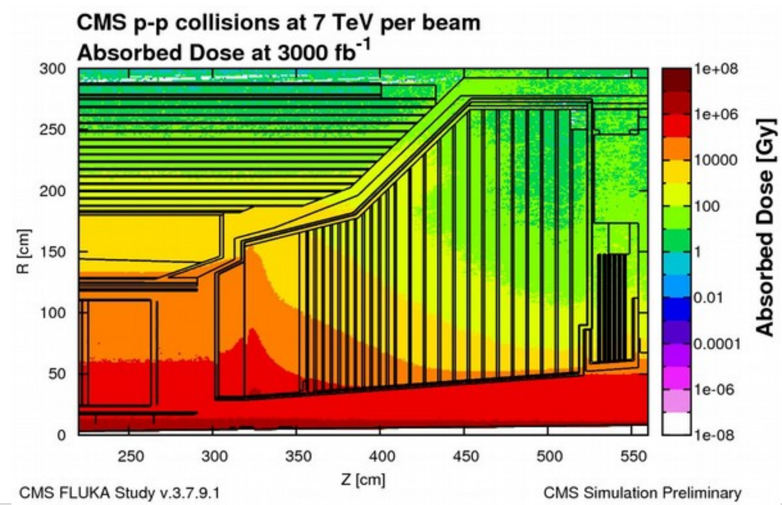
402.4 Upgrade Motivation

Charge #2

- Radiation-induced darkening is reducing the signal from the current scintillator-based endcap calorimeters
  - Up to 90% signal loss in some regions
  - HL-LHC will require good operation for radiation loads



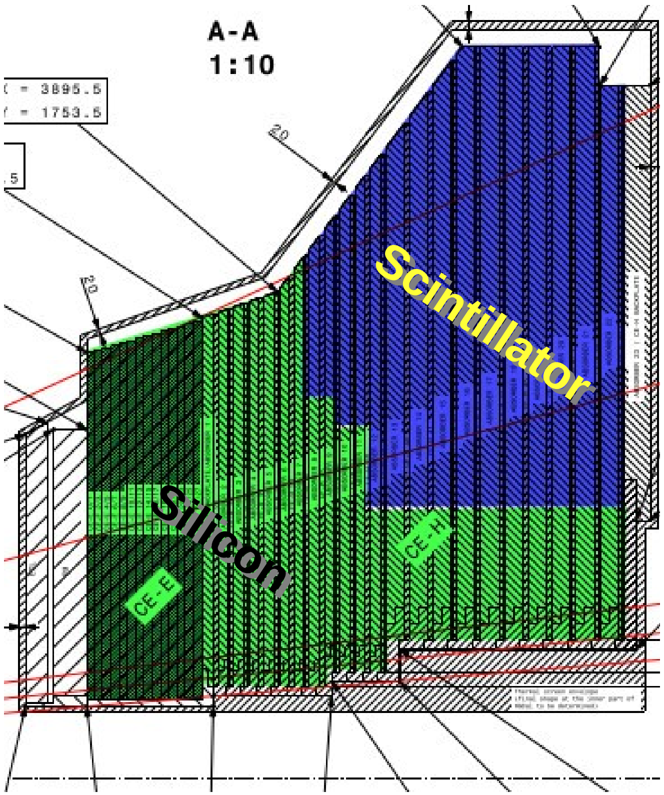




402.4 Conceptual Design

Charge #2

- High radiation zones (CE-E and portions of CE-H)
  - Silicon active material
  - EM absorber: lead+tungsten
  - HAD absorber: stainless steel
- Low radiation zones (CE-H)
  - Scintillator tile direct readout (SiPMs)
- Overall detector organized into cassettes comprised of a cooling plate with multiple silicon modules and tile-modules mounted onto it
- Full detector operated -30°C using CO_2 cooling
- Documented in approved international TDR and US CDR (cms-docdb-13151)

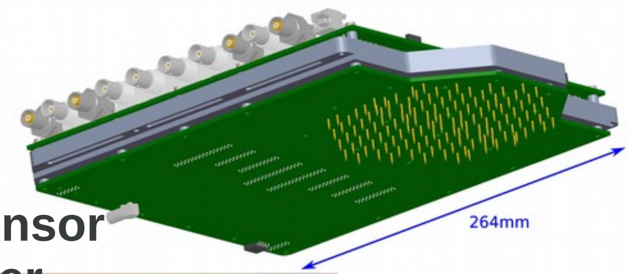


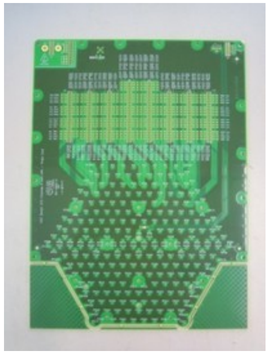
- Requirements flowdown from science goals (cms-doc-13337) to subsystem requirements (cms-doc-13447)

Pieces and Progress: Silicon

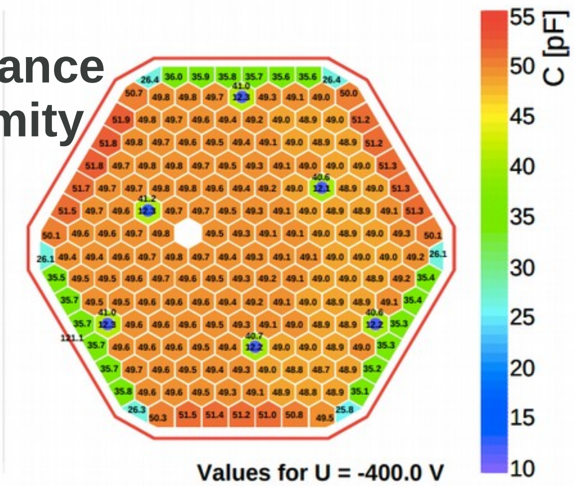
- Silicon sensors are the active element for the high-radiation portion of the calorimeter
  - Radiation tests on 6" wafers show expected performance (increase in leakage current) and no breakdowns (including on wafers with large irradiation gradients)
- Received good quality 8" sensors from HPK and the infrastructure is being commissioned at multiple sites for the necessary QC of received sensors and process-quality-control tests
- Preparing for CD-3a review of sensors

Full-Sensor Tester



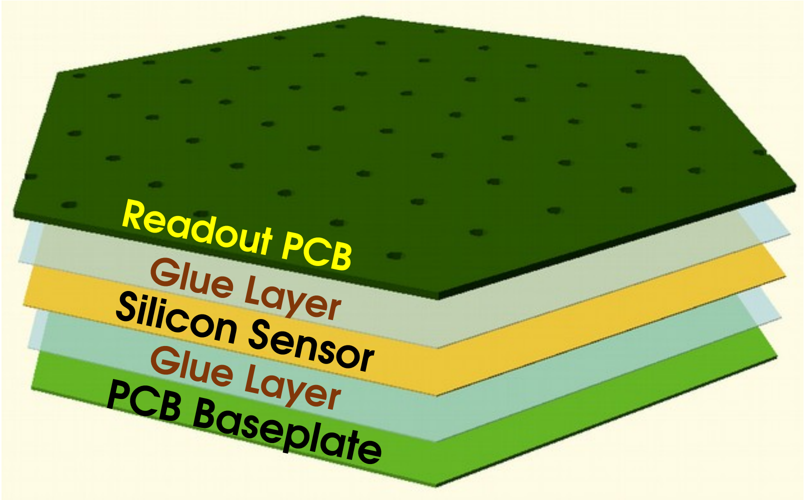


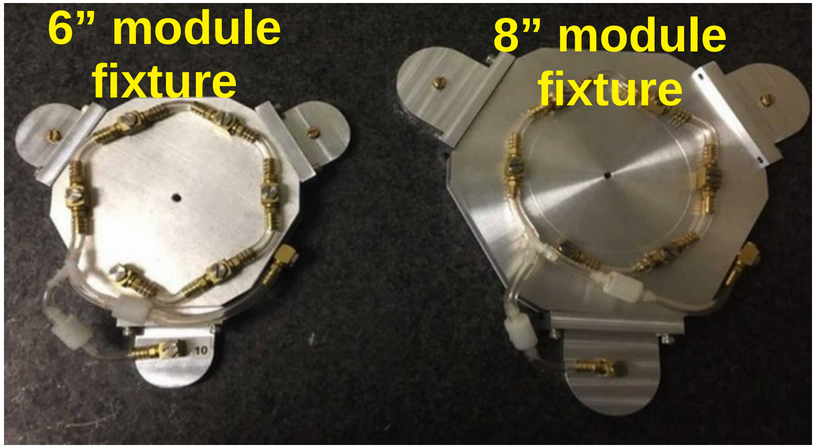
Capacitance Uniformity



Pieces and Progress: Modules

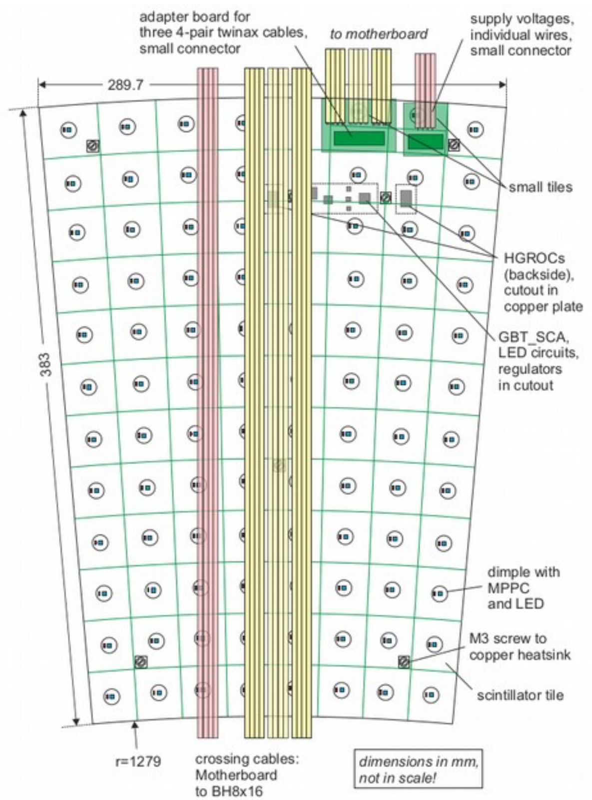
- Automation fully demonstrated with at UCSB by production run of 55 6” modules over a three week period in late summer
  - Checklists for all procedures
  - Inspection of all components, measurements of thickness and flatness for key components
  - Storage of construction and test data into local database for batch transfer to construction database
- Tooling adapted for 8” modules and preparing for a small-scale run now
- Assembly centers at TTU and CMU are beginning their setup and commissioning processes
- Design simplification for CE-H modules through use of PCB baseplate

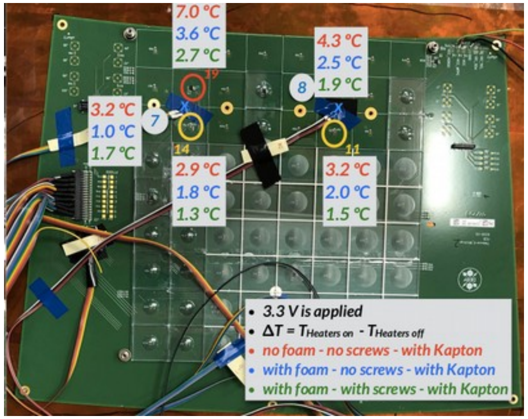


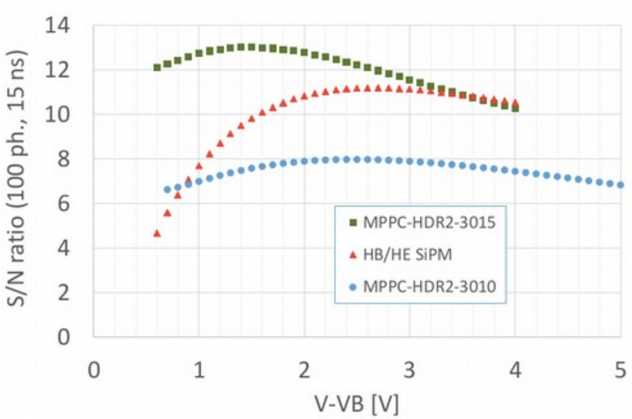


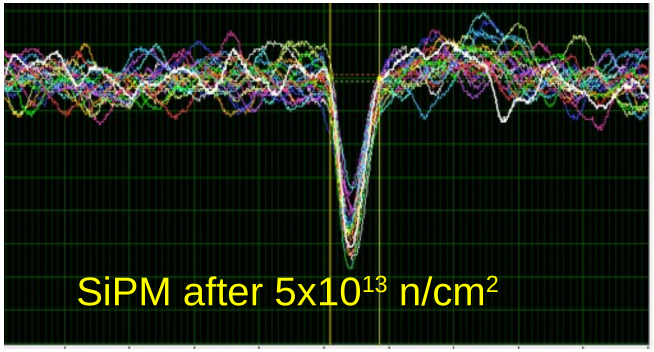
Pieces and Progress: Scintillator

- Scintillator section is based on SiPMs mounted on a common PCB with the HGCROC directly observing individual scintillator tiles
- Good progress in several areas
  - SiPM performance is established to required neutron fluence, with some recent improvements from vendor
  - Thermal performance of tileboard/cassette system has been studied in a thermal mockup
  - Detailed engineering ongoing for tileboards and associated readout/service infrastructure



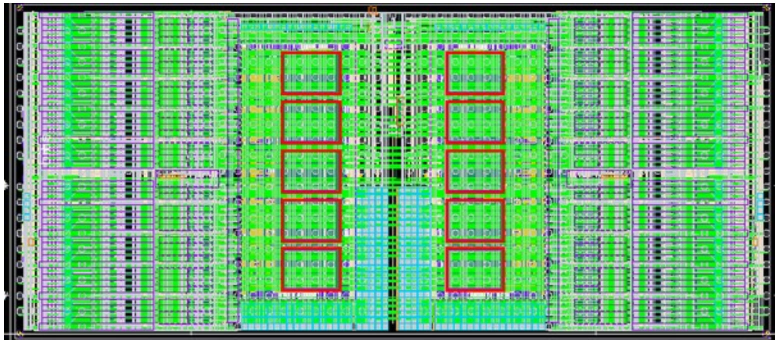


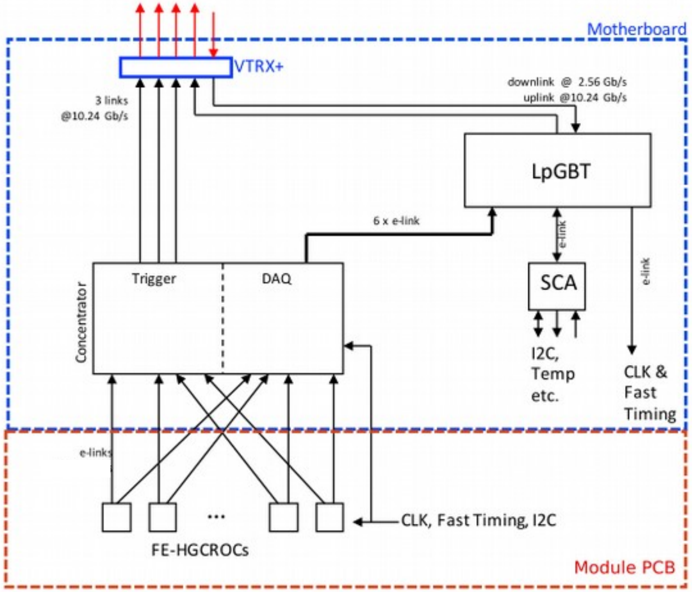




Pieces and Progress: Electronics

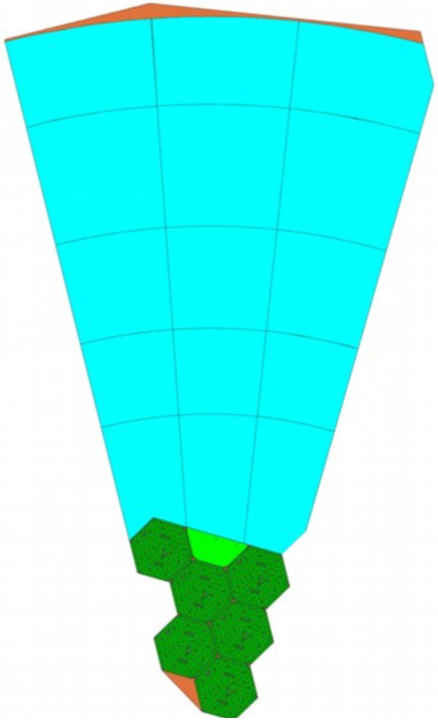
- HGCROCV2 readout ASIC sent for manufacture Feb 2019 [France/Omega]
  - Versions for both silicon and SiPM submitted together
  - Many pieces already proven in HGCROCV1
  - Changes include SEU-tolerant fast and slow control (I2C), DRAM for data pipeline (power savings), proven ADC from Krakow
  - Delay relative to June 2018 expectation: 2 months (ok)
  - Changes needed in eventual V3: DAQ derandomizer (currently limited to 1.2 us between L1A), any bug fixes identified in V2
- ECON concentrator ASIC has experienced significant delay but is now making rapid progress
  - Continuous management focus on this topic from the Fermilab, US-CMS, and International levels
  - Detailed presentation during L3 breakout
- System emulators under development to allow parallel development of testers and software/firmware required for final system

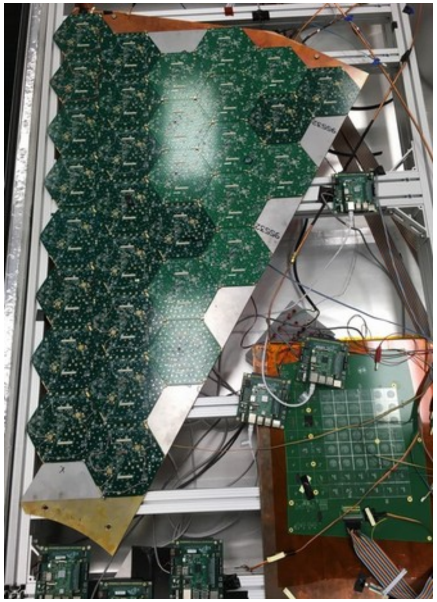


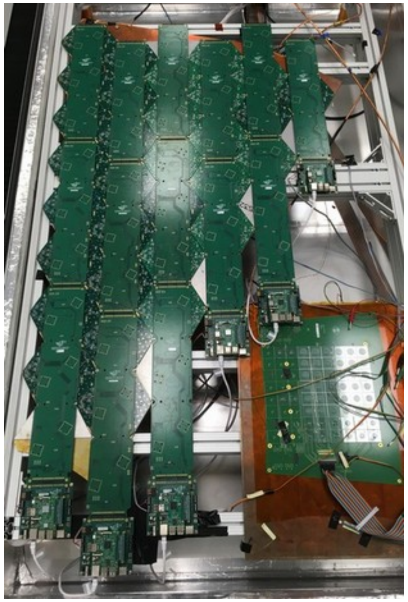


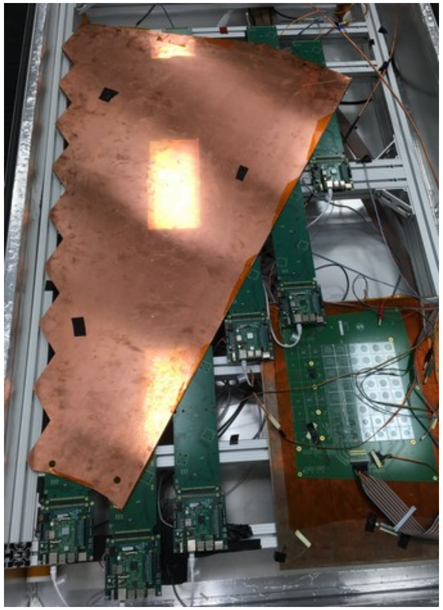
Pieces and Progress: Cassettes

- Cassette design and assembly validated through active mockup campaign
  - Included thermal loads and measurement system which validated the models of the cooling plates and helped identify good solutions for module mounting to achieve necessary thermal performance
  - Required fixturing and infrastructure has also been validated through the mockup campaign
- Current joint effort with scintillator portion of the system to complete similar tests for integrated mixed cassettes









402.4 Maturity

Charge #2

June 2018	
Silicon Sensors	36%
Silicon Modules	33%
Cassettes	30%
Scintillator Calorimetry	28%
Electronics and Services	24%
Overall	31%

March 2019	
Silicon Sensors	56%
Silicon Modules	38%
Cassettes	34%
Scintillator Calorimetry	35%
Electronics and Services	28%
Overall	38%

- Significant advance in design maturity over June 2018
  - Broadly-based advances across the endcap calorimeter project
  - Mockup effort has advanced modules, cassettes, and scintillator calorimetery
  - Silicon sensor effort is advancing rapidly in advance of CD-3a

Scope organization principle

Charge #4

- Since the original construction of CMS, the US has had a leading role in hadron calorimetry and in automated assembly of silicon detectors
  - Construction of the scintillator-based barrel hadron calorimeter, electronics for all hadron calorimeter sections (including Phase 1 Upgrade)
  - Construction of a large fraction of the tracker outer barrel, construction of the forward pixel Phase 1 Upgrade
- For the HL-LHC upgrades, the US contributions center on the production of the hadronic calorimeter silicon and scintillator modules and cassettes and aspects of the electronics and services where the US can provide particular leadership

US Construction Scope Outline

- Module Construction
  - US develops detector-wide standard procedures for silicon module construction, constructs all hadronic silicon modules and all odd-size/edge modules for the electromagnetic section
- Scintillator tilemodules
  - US wraps scintillator tiles, constructs readout PCBs, procures and mounts SiPM photodetectors, assembles and tests tile modules
- Electronics
  - US responsible for the design and development of the concentrator ASIC, development of motherboards for silicon and scintillator hadronic sections
  - Specification and procurement of LV/HV power supplies for the hadronic section
- Cassette Assembly
  - US develops cassette cooling plate design and assembly procedure, assembles cassettes of hadronic calorimeter
- Key Performance Parameters defined encapsulating the project
  - Threshold: Construction of the cassettes and delivery to CERN
  - Objective: Integration of the cassettes into the absorber and commissioning of the cassettes

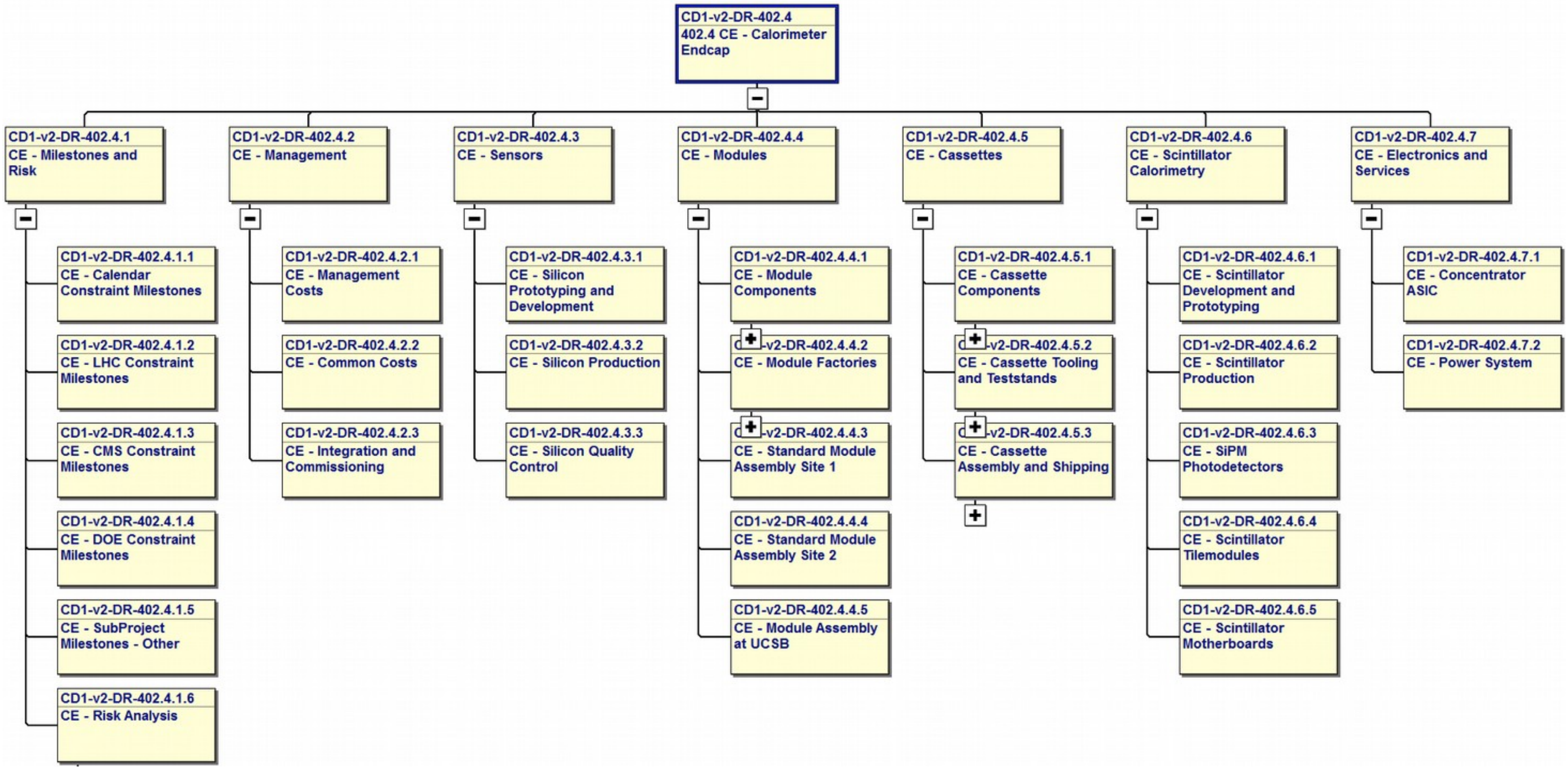
cms-docdb-13237

Changes to Scope/WBS Since June 2018

- Value Engineering
  - Concept of PCB baseplate for silicon modules eliminated the requirement to produce, QC, and process separate kapton layers for the CE-H modules
- Detector geometry updates
  - Requirement of additional volume for the tracker and additional internal space between the calorimeter layers for electronics resulted in a design update which removes the last two layers of the hadron calorimeter → 12.5% decrease in scintillator motherboards
- International scope balancing
  - Like all of the CMS upgrade, the endcap calorimeter effort involves multiple international partners with differing technical skill levels and abilities
  - Some items which have a low technical content (e.g. PCB baseplates, machining scintillator tiles) have been transferred to international partners who are capable of completing the work, to allow more resources in the US for critical tasks such as concentrator development and rapid cassette assembly
    - In every case where this has been done, the US retains the resources for reception quality control to ensure that good-quality components are always used to create larger assemblies

402.4 WBS Structure

Charge #5



402.4 Cost Summary

Charge #3

Today

WBS	Direct M&S ($)	Labor (Hours)	FTE	Direct + Indirect + Esc. ($)	Estimate Uncertainty ($)	Total Cost ($)
CD1-v2-DR-402.4 402.4 CE - Calorimeter Endcap	20,943,332	309602	175.12	39,898,172	11,010,672	50,908,844
CD1-v2-DR-402.4.2 CE - Management	1,903,843	84232	47.64	3,784,827	629,965	4,414,792
CD1-v2-DR-402.4.3 CE - Sensors	7,470,621	11110	6.28	8,239,938	2,326,482	10,566,420
CD1-v2-DR-402.4.4 CE - Modules	2,925,152	92062	52.07	8,272,878	1,488,933	9,761,812
CD1-v2-DR-402.4.5 CE - Cassettes	3,322,995	44748	25.32	9,217,378	3,225,677	12,443,055
CD1-v2-DR-402.4.6 CE - Scintillator Calorimetry	1,993,407	47998	27.15	3,790,474	1,256,122	5,046,596
CD1-v2-DR-402.4.7 CE - Electronics and Services	3,327,314	29452	16.66	6,592,676	2,083,494	8,676,170

June 2018

WBS	Direct M&S ($)	Labor (Hours)	FTE	Direct + Indirect + Esc. ($)	Estimate Uncertainty ($)	Total Cost ($)
402.4 CE - ENDCAP CALORIMETER	$21,522,856	307884	174.15	$40,937,225	$11,938,425	$52,875,650
402.4.2 CE - Management	$1,931,044	84688	47.90	$4,003,027	$748,653	$4,751,680
402.4.3 CE - Sensors	$7,412,621	9484	5.36	$8,147,707	$2,329,734	$10,477,440
402.4.4 CE - Modules	$3,377,138	96746	54.72	$9,549,106	$2,006,872	$11,555,978
402.4.5 CE - Cassettes	$3,374,244	43980	24.88	$9,027,990	$3,348,887	$12,376,877
402.4.6 CE - Scintillator Calorimetry	$2,078,576	44834	25.36	$3,827,891	$1,312,408	$5,140,299
402.4.7 CE - Electronics and Services	$3,349,233	28152	15.92	$6,381,503	$2,191,872	$8,573,375

- Module costs decreased $1.8M due to removal of kapton, PCB costs, estimate uncertainty released by order of module factory equipment
- Elsewhere: small updates in design/plan, reduction in estimate uncertainty from completed work

402.4 Cost Drivers

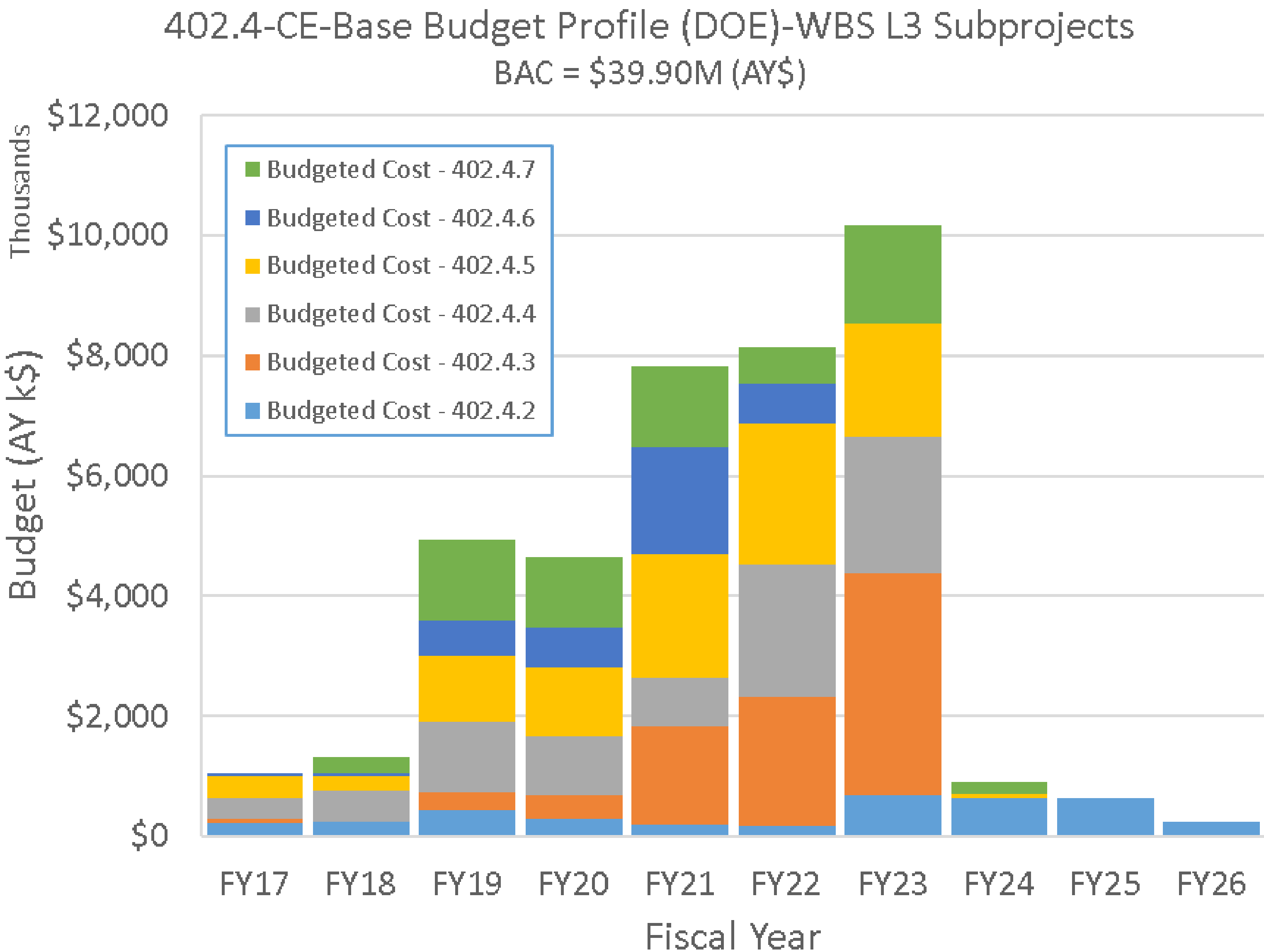
Charge #3

CMS Driver	Labor (FTE-yrs)	Labor (M$)	M&S (M$)	Labor + M&S (M$)	Estimate Uncertainty (M$)	Total (M$)
CE.3 - Si sensors purchase (M&S)	0.0	0.0	7.8	7.8	2.2	10.0
CE.5 - Cassette assembly and testing (labor)	18.3	2.7	0.1	2.7	0.8	3.5
CE.7 - Concentrator ASIC (labor)	8.6	2.4	0.0	2.4	1.0	3.4
CE - Calo Endcap integration and commissioning	5.0	0.6	1.7	2.3	0.6	2.9
CE.7 - Concentrator ASIC (M&S)	0.0	0.0	2.2	2.2	0.7	2.9
CE.4 - Module circuit boards	3.1	0.3	1.6	1.9	0.5	2.5
CE.7 - Power system	0.5	0.1	1.7	1.8	0.3	2.1
CE.5 - Silicon motherboard (M&S)	0.0	0.0	1.5	1.5	0.5	1.9
CE.6 - Scintillator panels	5.6	0.6	0.7	1.3	0.4	1.7
CE.5 - Cassette tooling and test stands	1.5	0.3	0.9	1.3	0.4	1.6
CE.4 - Module assembly and testing (UCSB)	12.5	1.3	0.1	1.4	0.2	1.6
CE.4 - Module assembly and testing (Texas Tech)	13.8	1.2	0.1	1.3	0.2	1.5
CE.5 - Silicon motherboard (labor)	4.3	1.0	0.0	1.0	0.4	1.5
CE.5 - Cassette cooling plates (M&S)	0.0	0.0	1.0	1.0	0.5	1.4
CE.4 - Module assembly and testing (CMU)	12.8	1.0	0.1	1.2	0.2	1.4
CE.6 - Scintillator motherboards	2.2	0.3	0.5	0.8	0.4	1.2
CE.6 - SiPM purchase (M&S)	0.1	0.0	0.9	0.9	0.3	1.2
CE.5 - Cassette cooling plates (labor)	3.6	0.8	0.0	0.8	0.3	1.1
CE.2 - Project engineering	2.7	0.9	0.0	0.9	0.0	1.0

- Leading cost driver is silicon sensor purchase (CD-3a Scope)
- Next tier includes engineering for the concentrator ASIC and the labor for the various subsystem assembly tasks.
- Estimate uncertainties tied to maturity of design and quality of quotes as defined by Key Assumptions document

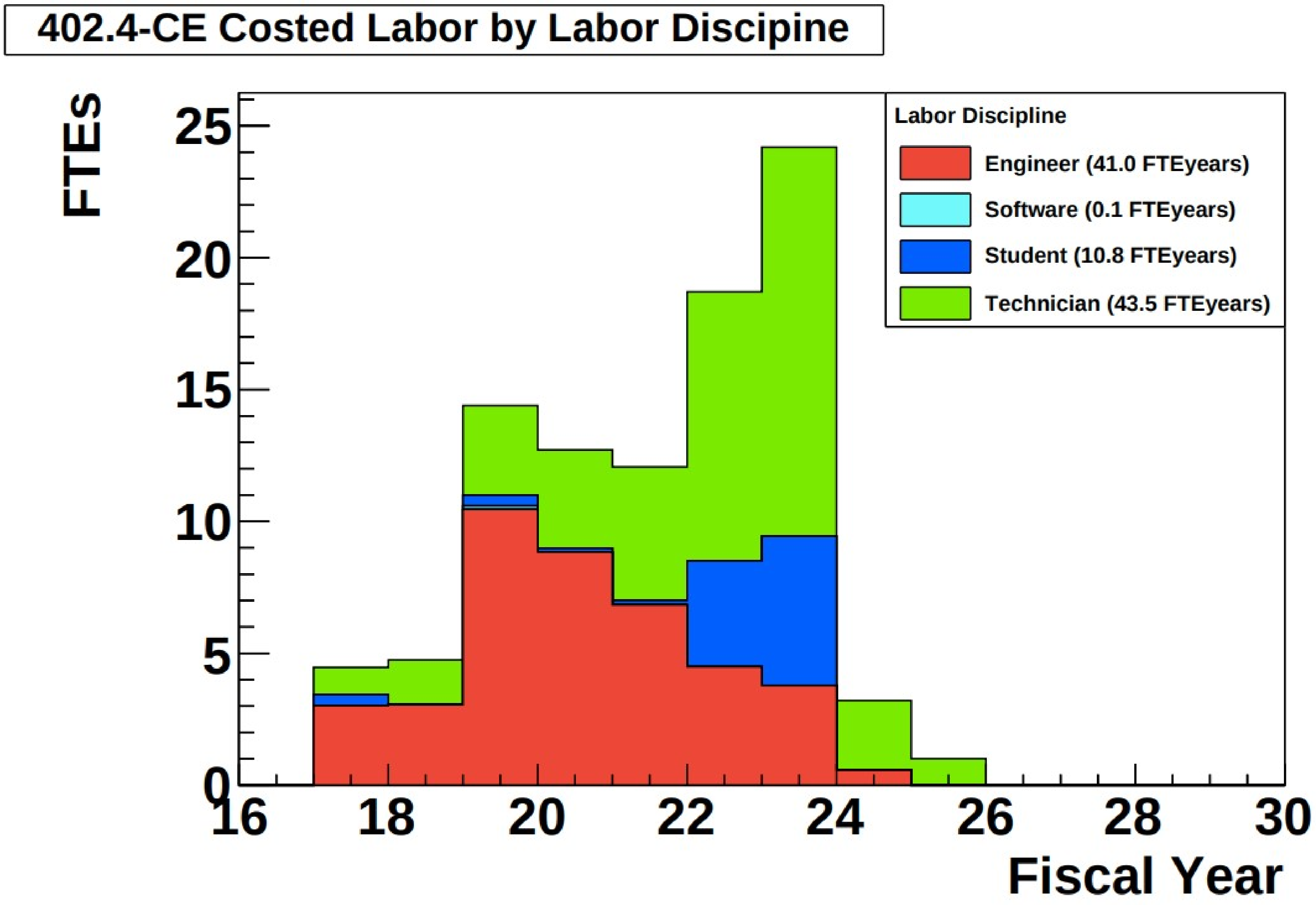
402.4 Cost Profile

Charge #3



402.4 Labor Profile

Charge #3



402.4 Labor Profile

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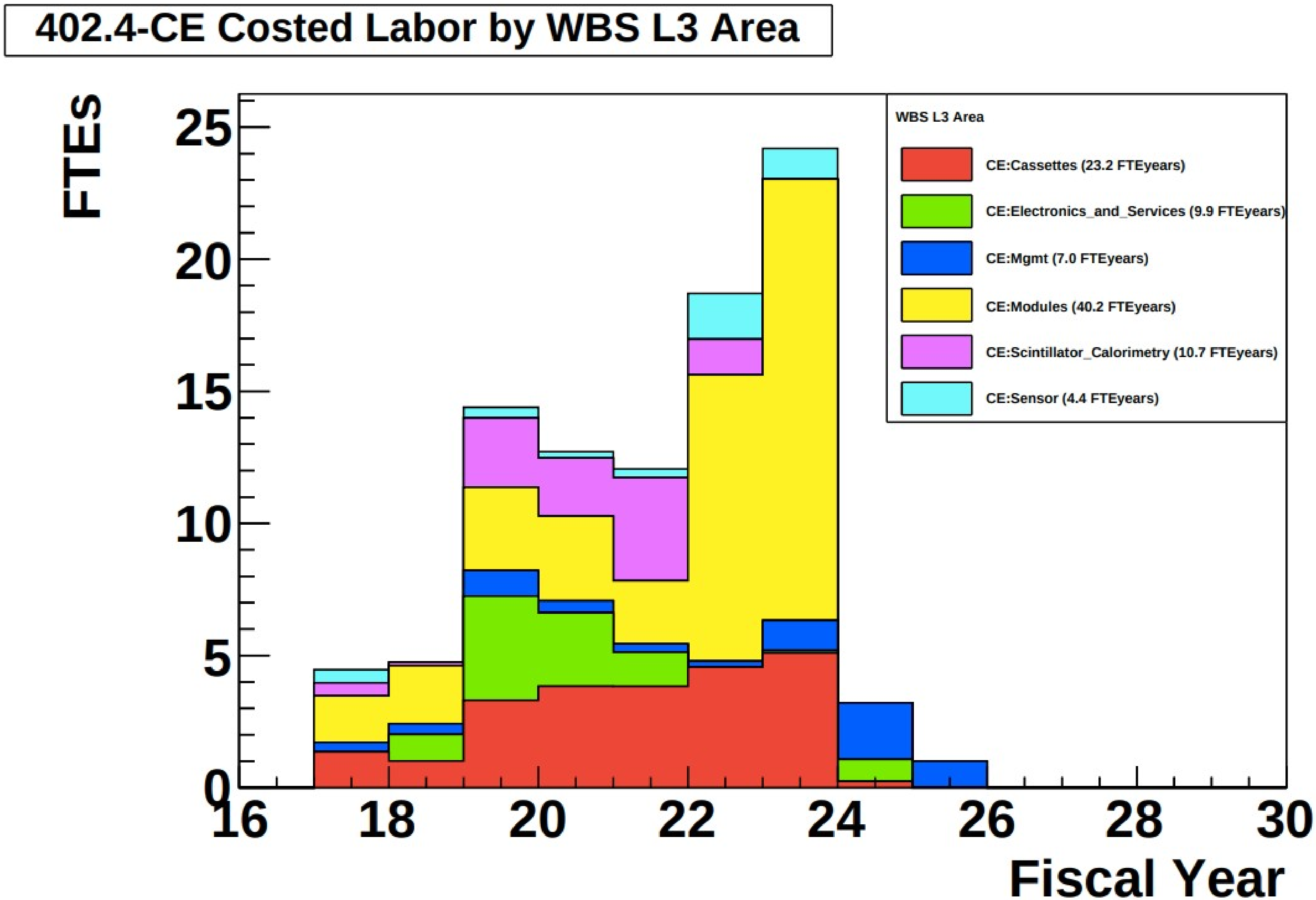
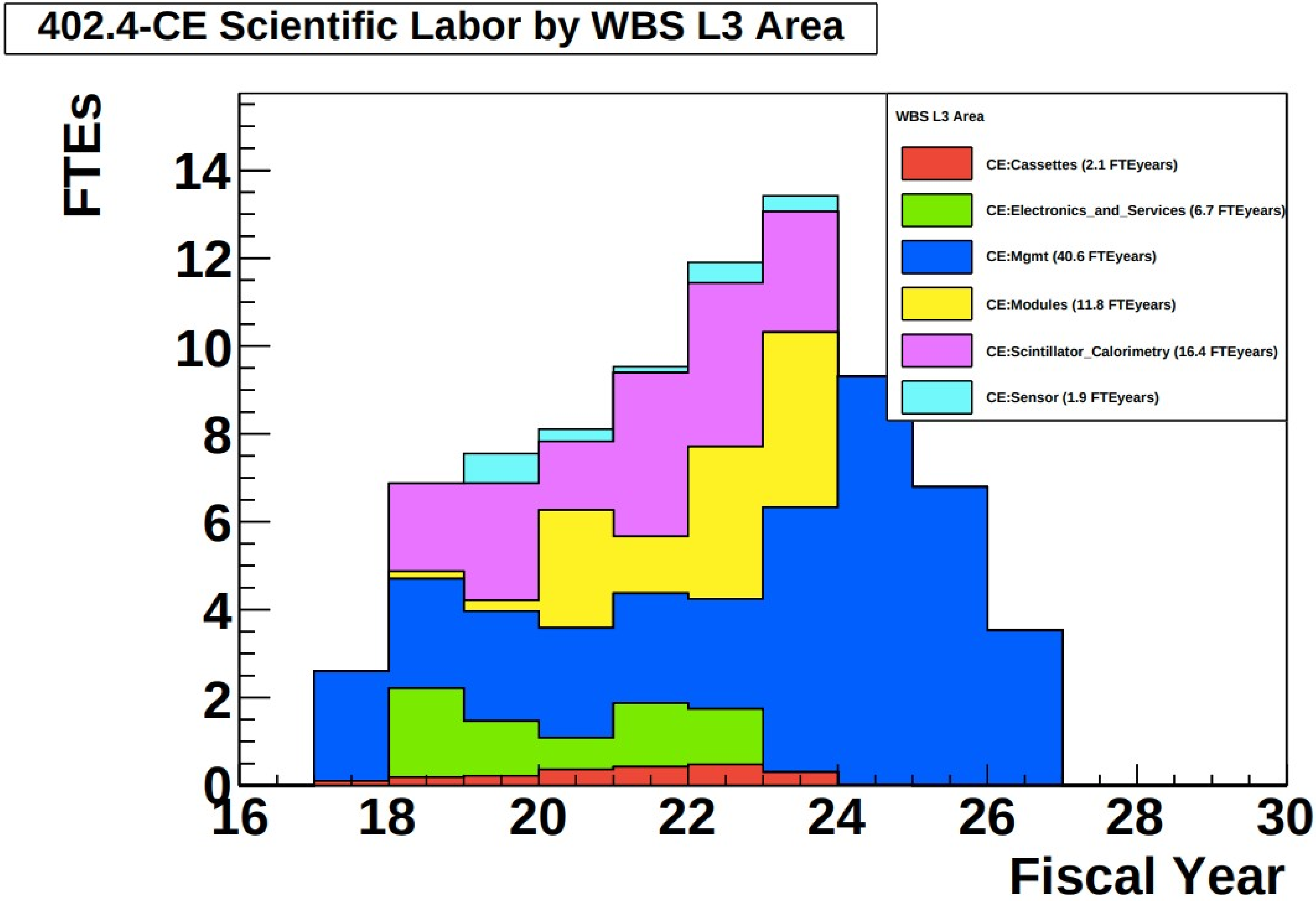


402.4 Scientific Labor

Charge #3

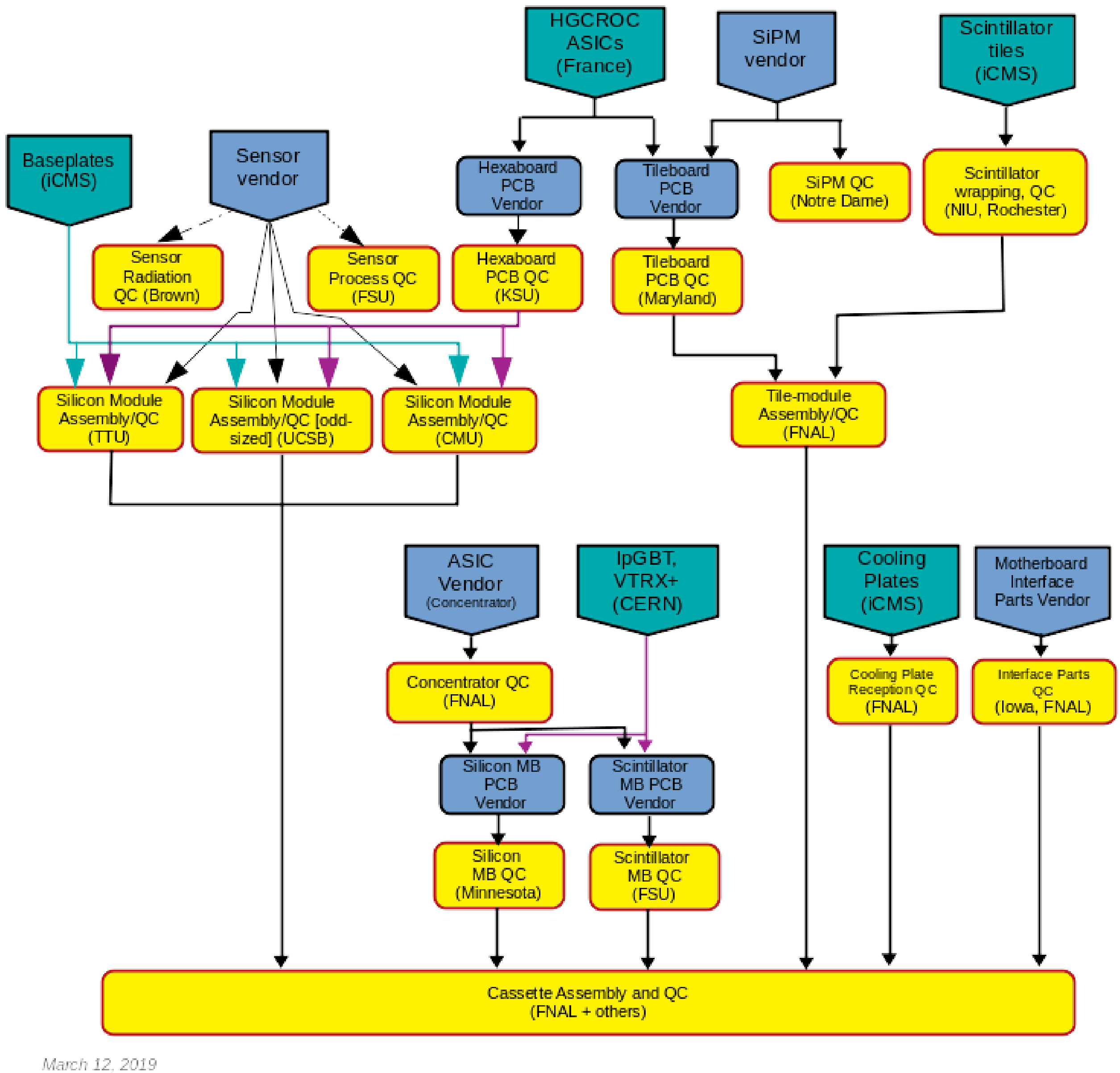


402.4 Labor Resources

Charge #4

- Assignment of R&D and production tasks arranged to take advantage of existing facilities for testing and construction, where possible, and to efficiently utilize expertise and human resources
- Institutions
  - Fermilab, Alabama, Baylor, Brown, Carnegie Mellon, Fairfield, Florida State, Florida Institute of Technology, Iowa, Kansas State, Maryland, Massachusetts Institute of Technology, Minnesota, Northern Illinois, Notre Dame, Northwestern, Rochester, Texas Tech, UC-Santa Barbara
- The set of key personnel evolves throughout the project
  - Primary criteria is ability to replace a given person with without significant disruption to schedule or cost
  - Key personnel table prepared and being tracked/updated by management quarterly
    - Currently: key engineers, developers of key processes (such as module assembly)
    - In the future: assembly site managers, QC experts

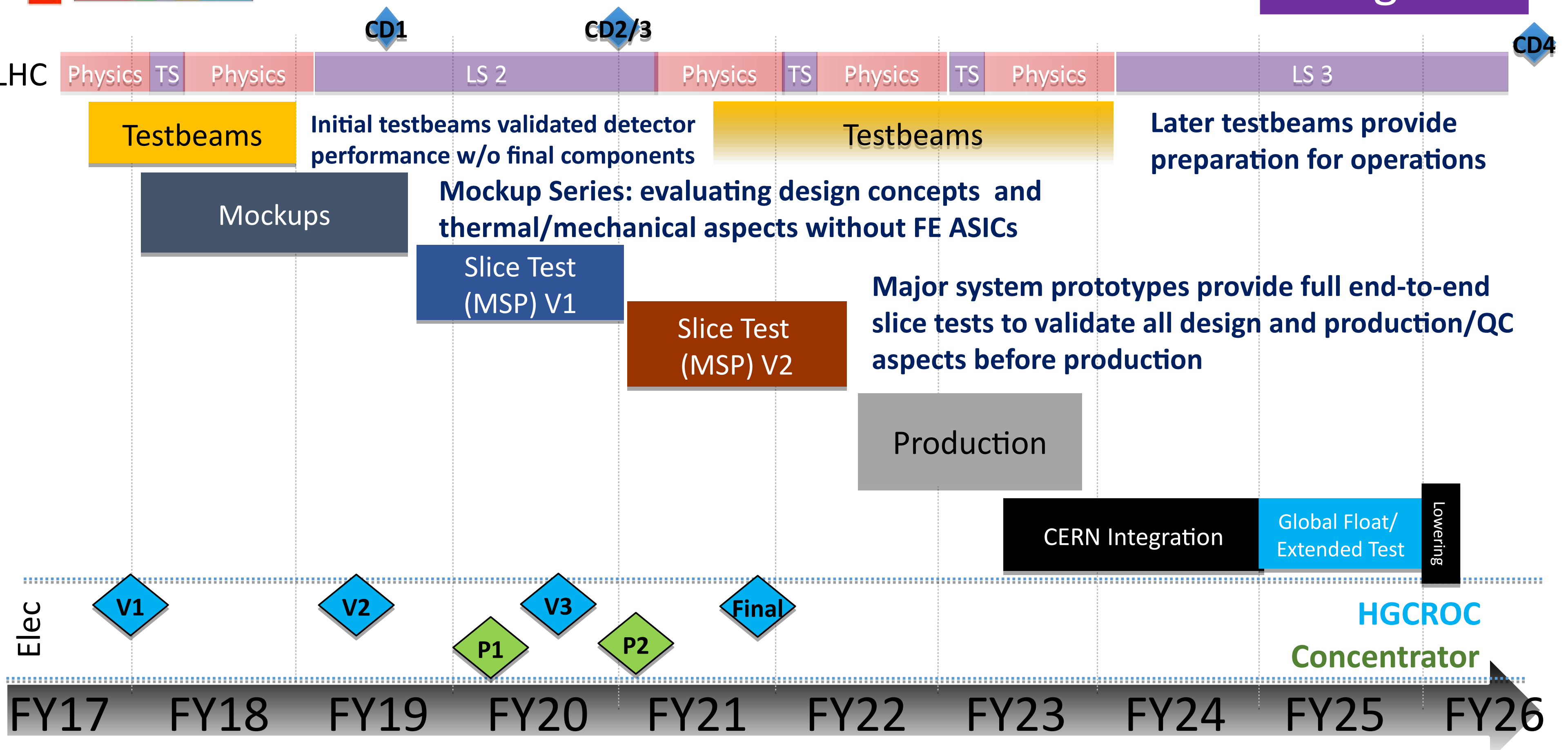
Work flow for the project



- This chart, which is part of the project QA/QC documentation outlines the flow of the project through the construction phase and can be mapped directly onto the WBS structure

402.4 Schedule Structure

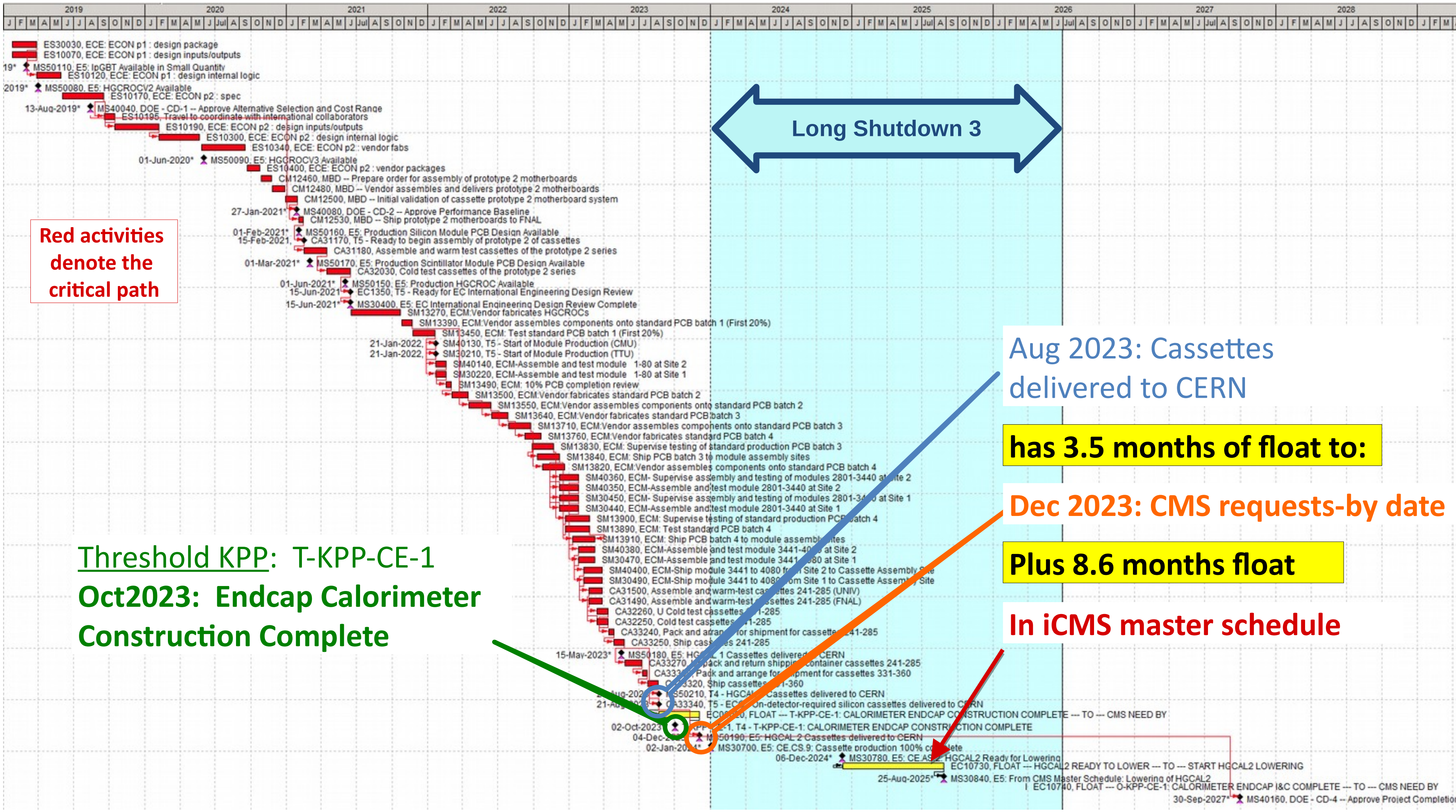
Charge #3



- Project final design and development proceeds through two major system prototypes (first under design/production now) which include full vertical slice tests of the complete system

402.4 Critical Path and Float

Charge #3



Red activities denote the critical path

Aug 2023: Cassettes delivered to CERN

has 3.5 months of float to:

Dec 2023: CMS requests-by date

Plus 8.6 months float

In iCMS master schedule

Threshold KPP: T-KPP-CE-1

Oct2023: Endcap Calorimeter Construction Complete

- Despite various schedule updates, replanning work has resulted in T-KPP-CE-1 moving by only one day (earlier)
- Float is smaller than in June 2018 due mostly to a more-accurate CMS requests-by date which became available after the freeze for the June 2018 review. International float has also become somewhat smaller due to delays affecting CE-E production

402.4 Risks

Charge #3

- Risk Changes since June 2018
  - Retire opportunity of cheaper p-on-n sensors (no vendor for 8” wafers)
  - Added risk for possible additional production acceleration requirement (P*I=$127k)
  - Added risk for possible increased engineering costs for Si motherboards (P*I=$115k)
  - Added risks for replacement/retraining of key endcap calorimeter personnel (P*I=$71k) and a shortfall in scientific labor (P*I=$98k)
- Leading risks
  - Additional concentrator MPW required (P*I=$132k) and Concentrator does not meet specifications (P*I=$97k)
    - Mitigation by proper targetting of prototype functionality and working to finalize algorithms
  - Additional production acceleration required
    - Mitigation is through successful prototype 2 series and management tracking of dependency deliveries
  - Increased engineering costs for Si motherboards
    - Mitigation by investigating modular design with a single ‘core’ motherboard design and multiple passive support motherboard designs

402.4 Response to June 2018 Review Items

- *4. The aggregator ASIC, the ECON, is a critical U.S. deliverable and a potential schedule driver for cassette production. Maintain close interaction with FNAL management to ensure the necessary access to ASIC designers and engineers*
  - The PM, L2, and L3 have worked through the FNAL ASIC PMG and direct communication with FNAL management to obtain the necessary access to ASIC engineers. There have been delays in the process, but the ECON is making rapid progress now with substantial engineering resources active on the effort.
- *5. For CD-2, develop simulation tools to determine the dependence of HGCAL performance on the assumed level and distribution of dead and noisy cells.*
  - Such a simulation tool has been developed and is in use to validate the detailed specifications, such as those being provided to the silicon sensor vendor. (Noisy cells can be suppressed in HGCROC, so they behave as dead cells)
- *6. For CD-2, develop the combined tracker-HGCAL simulation to provide an expectation of the physics performance of the upgraded calorimeter using the full particle flow technology. A suitable physics process to consider is VBF Higgs production with invisible Higgs decay.*
  - The study of physics objects and their reconstruction with full particle flow is underway at the international level. The completion and approval of a formal physics analysis study is not part of the US project scope. The existing simulation as documented in the Endcap Calorimeter TDR demonstrates that the design will achieve the physics goals of the project.

Charge #8

402.4 Response to June 2018 Review Items

- *7. By third-quarter CY 2018 define the goals and schedule for the cassette prototype P1 to ensure that the feedback which is necessary for CD-2 is obtained.*
  - The goals and schedule for cassette P1 were re-evaluated in light of the ASIC schedule and the schedule for CD-2. The prototype efforts have been scheduled along with system emulators which will guarantee the necessary information for CD-2 is obtained in a timely manner.
- *8. For CD-2 develop a strategy to deal with the variation of gain stability of the SiPMs against temperature variations across the active layers.*
  - A strategy which includes the use of RTD sensors and a software loop to adjust SiPM bias voltages has been developed and will be validated using the P1 prototype in advance of CD-2
- *9. By third-quarter CY 2018 establish a high-level schedule of external dependencies and associated milestones defined by suppliers and/or international CMS. Review these dependencies and schedule regularly with the integrated project team.*
  - Such a high-level schedule of external dependencies has been developed. It is reviewed quarterly for any schedule implications, additions, or deletions.
- *10. Proceed to CD-1*

Charge #8

402.4 Progress towards CD-3a

- CD-3a Scope
  - Production and QC of sensors (full and odd-sized)
  - CD-3a required for placement of contracts to begin delivery process on time
- Progress
  - Sample 8" sensors have been received and basic performance has been validated
  - Radiation tests and inclusion into modules are planned for the late spring
  - Detailed specification prepared and under review by international CMS, negotiations with vendor on likely impact of specific requirements
- Efforts are on-schedule for CD-3a review in the Fall

WBS	Direct M&S ($)	Labor (Hours)	Direct, Indirect + Esc. ($)	Estimate Uncertainty ($)	Total Cost ($)
Production Silicon	6,853,236	0	7,171,912	2,151,573	9,323,485
Silicon QC	0	5830	171,291	51,388	222,679
CD-3a Scope Total	6,853,236	5830	7,343,203	2,202,961	9,546,164

402.4 Progress towards CD-2

- Silicon Motherboard design concepts will be validated through major system prototype 1 efforts which are ramping up now and will continue through early FY20
  - Affects both cost and schedule
- ECON ASIC, while making rapid progress, has some significant schedule uncertainty due to the short experience with the effort
  - By CD-2, the first prototype will have been evaluated and the engineering requirements for the final chip will be quite clear
- Overall: the process of carrying out major system prototype will allow a further detailed refinement of all BOE documentation with final or near-final designs

ES&H

Charge #6

- ES&H aspects are guided by the Fermilab Integrated Safety Management approach, with rules and procedures laid out in the Fermilab ES&H Manual
- Careful analysis of safety and production risks has been carried out, with updates made in the case of any relevant design evolution in pHAR (cms-doc-13394)
  - SiDet has Operational Readiness Clearance for required CO2-based cooling (cryogenic, oxygen-deficiency, and CO2 toxicity risks)
  - Items comply with local safety standards in site of fabrication and operation
  - Connection to individual institutes established through L2/L3 Managers to institute Pis. Safety contacts specified/updated as part of annual SOW process with institutes
- Endcap Calorimeter participated in the Nov 29 2018 ESH&Q review

QA/QC

Charge #6

- QA/QC aspects are guided by the Fermilab Integrated Quality Management approach, with rules and procedures laid out in the Fermilab Integrated Quality Assurance Manual
  - Project overall strategy defined by project in the QAP (cms-doc-13093)
- Quality assurance
  - Prototype sequence to validate vendors and procedures, requires sufficient quantity in prototypes
  - Stress-testing of design using radiation (total dose/fluence), beams (single-event effects), thermal cycling, shipping tests
  - International CMS approval for the prototype plan and international coordination of testing strategies, equipment
- Quality control
  - Combine known-good sub-assemblies when constructing more complex objects (silicon sensors are the most-expensive single input)
  - Use databases to track all components through the assembly and testing procedures (development of databases has started)

Breakout Session

- Concentrator ASIC (40')
  - Speaker: James Hirschauer (Fermilab)
- Planning for CD-3a (30')
  - Speaker: Harry Cheung (Fermilab)
- Recent Progress Summary (25')
  - Speaker: Jeremiah Mans (University of Minnesota)
- Cassette R&D Progress and Production Plans (Site Visit) (50’ + 20’)
  - Speaker: Zoltan Gesce (Fermilab)

Summary

- Endcap Calorimeter Project has made strong progress in multiple areas since June 2018
  - 8” sensors produced by HPK, initial results are good
  - Automated module assembly demonstrated at full scale for 6” modules
  - Cassette integration and thermal performance validated with mockup
  - SiPM R&D converging on an excellent candidate device and package
- Some areas have experienced challenges, but are now making progress
  - ECON ASIC had some delays due to resource availability, now proceeding strongly
  - Management tracking issues actively and seeking both technical and planning possibilities to maintain project schedule float
- We have a plan to converge on necessary technical and cost/schedule input for both CD-3a (sensors) and CD-2/3 as envisioned by the project
- Ready for CD1!

Additional Material

402.4 Labor Resources

Charge #4

- Assignment of R&D and production tasks arranged to take advantage of existing facilities for testing and construction, where possible, and to efficiently utilize expertise and human resources
  - FNAL : ASIC design (experience from previous concentrators, high-speed links), cassette assembly and test leverage existing CO_2 infrastructure and expertise at SiDet
  - UCSB, TTU, CMU: module assembly centers with experience and equipment from previous detector construction projects, access to pool of lower-cost undergraduate technicians, significant setup cost-contributions from institutional resources.
    - UCSB: Worldwide module assembly oversight, specialized module construction, and reserve capacity
    - Distributed capacity provides risk mitigation flexibility against problems during production and possible schedule delays leading up to module assembly
  - NIU: Leading institution in scintillator technology and development of SiPM-on-tile technology, existing infrastructure for evaluating different designs for SiPM-on-tile readout
  - Notre Dame: strong expertise on SiPM technology, existing test infrastructure
  - Minnesota: experience with high-speed PCB technology from CMS Phase 1 HCAL electronics
  - Institutions with strong experience with detector construction and/or testing during the original CMS construction or the Phase 1 Upgrade: Alabama, Baylor, Brown, Fairfield, FSU, FIT, Iowa, KSU, Northwestern, Rochester

Current Risk Register Snapshot

Risk Rank	RI-ID	Title	Probability	Schedule Impact	Cost Impact	P * Impact (k$)
WBS / Ops Lab Activity : 402.4 CE - Calorimeter Endcap (16)						
Risk Type : Threat (16)						
3 (High)	RT-402-4-18-D	CE - Additional concentrator ASIC engineering (MPW) run is required	50 %	6 -- 7.5 -- 9 months	164 -- 241 -- 385 k$	132
3 (High)	RT-402-4-01-D	CE - Additional FE ASIC engineering run required	25 %	8 months	336 k$	84
2 (Medium)	RT-402-4-22-D	CE - Additional production acceleration required	20 %	1 months	564 -- 564 -- 777 k$	127
2 (Medium)	RT-402-4-23-D	CE - Si Motherboard complexity is much higher than expected	20 %	0 months	383 -- 575 -- 767 k$	115
2 (Medium)	RT-402-4-91-D	CE - Shortfall in Calorimeter Endcap scientific labor	30 %	0 months	0 -- 0 -- 982 k$	98
2 (Medium)	RT-402-4-04-D	CE - Concentrator does not meet specifications	10 %	6 -- 7.5 -- 9 months	907 -- 971 -- 1035 k$	97
2 (Medium)	RT-402-4-90-D	CE - Key Calorimeter Endcap personnel need to be replaced	25 %	0 -- 0 -- 3 months	75 -- 225 -- 555 k$	71
2 (Medium)	RT-402-4-02-D	CE - Infrastructure failure at module assembly facility	30 %	1 -- 4 months	100 -- 336 k$	65
2 (Medium)	RT-402-4-13-D	CE - HGCROC front end chip is delayed	20 %	1 -- 6 -- 12 months	21 -- 126 -- 252 k$	27
2 (Medium)	RT-402-4-20-D	CE - Boundary between Si and scintillator sections is moved	10 %	0 months	252 k$	25
1 (Low)	RT-402-4-16-D	CE - Cassettes damaged or lost in assembly, testing or shipping	5 %	3 months	100 -- 1000 k$	28
1 (Low)	RT-402-4-14-D	CE - Cassette cooling plate fabrication failure	10 %	3 months	73 -- 213 k$	14
1 (Low)	RT-402-4-15-D	CE - Motherboard and interface board fabrication failure	10 %	3 months	73 -- 193 k$	13
1 (Low)	RT-402-4-17-D	CE - Cassette assembly site failure	10 %	3 months	73 -- 163 k$	12
1 (Low)	RT-402-4-09-D	CE - Module PCB batch failure	5 %	2 -- 4 months	144 -- 186 k$	8
1 (Low)	RT-402-4-10-D	CE - Silicon sensor has low yield	1 %	2 -- 4 months	542 -- 784 k$	7