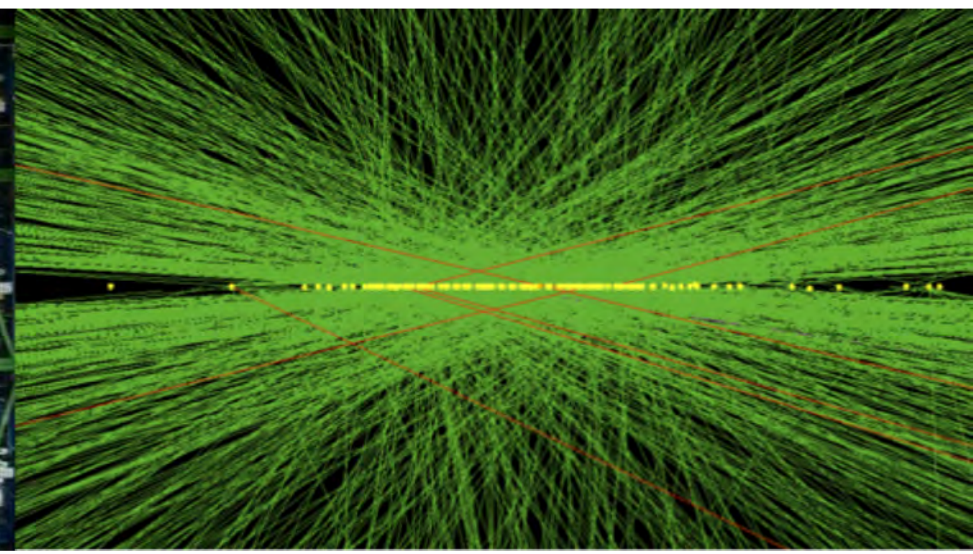
402.6.3 Calorimeter Trigger Cost and Schedule

Wesley H. Smith, U. Wisconsin

HL LHC CMS Detector Upgrade CD-1 Review

June 5-7, 2018

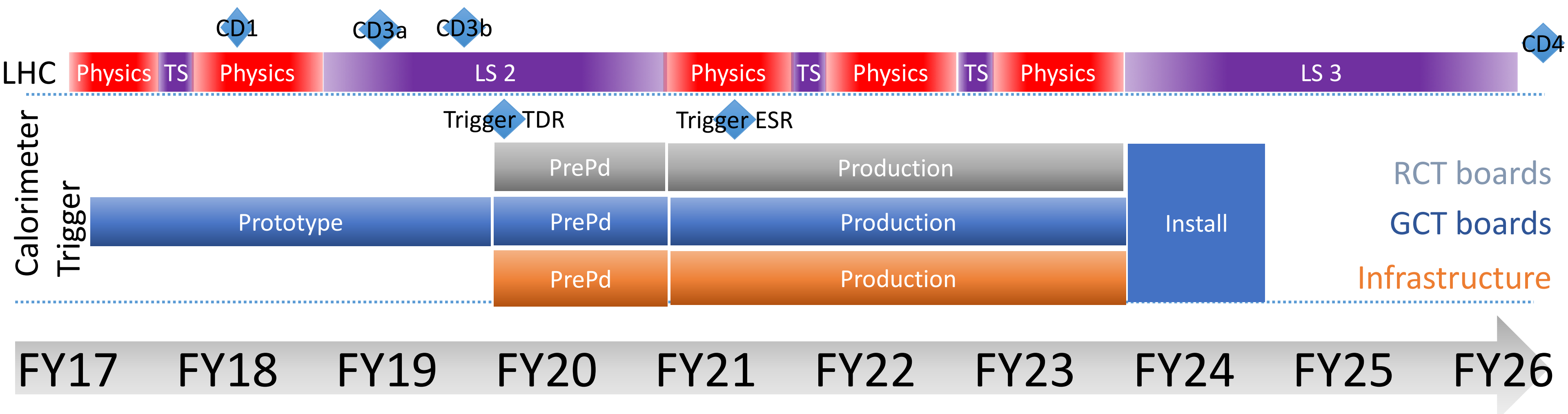


Outline

- Cost and Schedule
- Calorimeter Trigger Organizational aspects
- Contributing Institutions
- Optimization
- ES&H
- QA/QC
- Summary

Schedule Overview

- L1 Prototyping/R&D phase 2017-2019, for Trigger TDR at end of 2019 (FDR/CD2)
- L1 Preproduction phase 2020, for Trigger ESR
- L1 Production phase 2021-2023
- L1 Installation phase 2024



Schedule Overview

Charge #3

- Schedule Basis
  - Phase-1 Construction and Installation schedule experience
    - Next slides
- R&D program concludes with subsystem interconnect test at the end of CY19:
  - Calorimeter BE → Calorimeter Trigger → Correlator
  - Test provides input for Trigger TDR
- Pre-production testing concludes at end of CY20
- Production starts with a pilot run of a few cards with card tests complete by end of CY21
  - CY22 uses pilot and pre-production cards for final system integration tests
- Full production starts with funding for parts procurement at beginning of CY23
  - Production testing complete and system shipped by end of CY23
- Testing, installation and integration at CERN in FY24

Construction Schedule Planning

- Input: U. Wisc. CTP 7 MicroTCA Card for Phase 1 Cal. Trig.
  - 12 MGT MicroTCA backplane links
  - 67 Rx and 48 Tx 10G optical links
  - Virtex-7 690T FPGA
    - Data Processor
  - ZYNQ `045 System-on-Chip (SoC)
    - embedded Linux control platform

- Phase 1 Production Experience:
  - 1st Proto: Q4/CY13
  - 6 Pre. Prod. Proto: Q2-3/CY14
  - 1st Production Board: Q1/CY15
  - 50 Board Production Complete Q2CY15
  - Installation Complete: Q2/CY15
  - Commissioned, Operations start: Q3/CY15
    - Layer-1 Calorimeter Trigger since 2016
  - ⇒ 21 Months: 1st prototype to pp operations
    - On schedule and on budget (performance in backup)

Construction Schedule Milestones

- FY21
  - 2020Q4 preproduction test
  - 2021Q1 final production design optimization
  - 2021Q2 pilot production procure
  - 2021Q3 pilot production manufacture
- FY22
  - 2021Q4 pilot test
  - 2022Q1 system integration assembly
  - 2022Q2 system integration test
  - 2022Q3 system integration test
- FY23
  - 2022Q4 final procurement
  - 2023Q1 final manufacture
  - 2023Q2 final test batch 1
  - 2023Q3 final test batch 2, ship batch 1
- FY24
  - 2023Q4 ship batch 2
  - 2024Q1-Q3 installation and integration at P5

External Dependencies

- Minimal
- Since calorimeter trigger has full self-test capabilities, both threshold and objective KPP are satisfied w/o requiring connected inputs or outputs.
- Trigger electronics can store up sequences of test patterns and inject them into the front end of the trigger electronics at speed
- Trigger electronics can receive its output, process and record this at speed for subsequent readout by DAQ.
- Because of exhaustive self-test capabilities, we can flexibly install and commission the calorimeter trigger system independently from CMS completion status

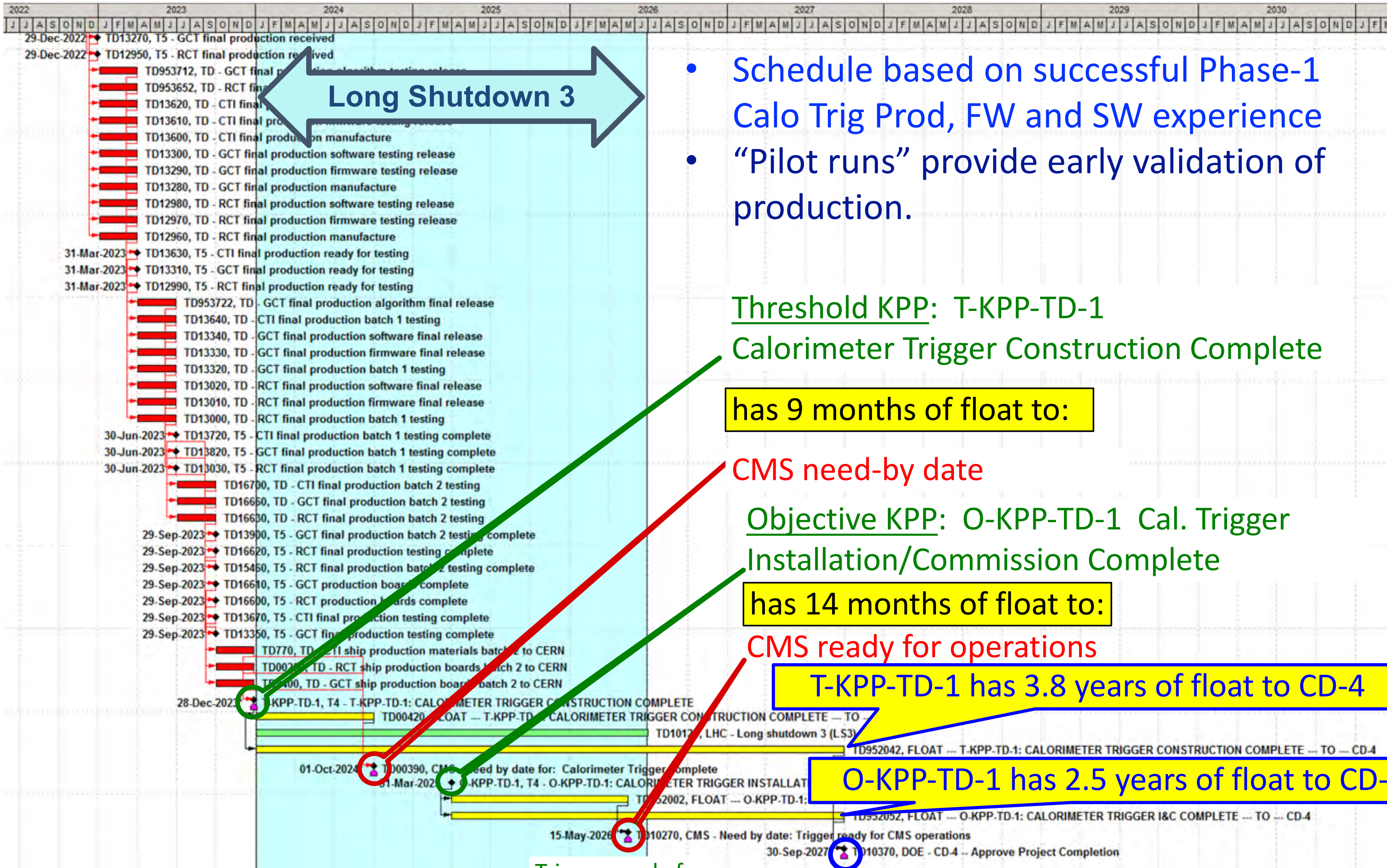
Threshold and Objective KPPs

CMS-doc-13237

WBS	Threshold KPP	Objective KPP
402.6 Trigger and DAQ	T-KPP-TD-1: CALORIMETER TRIGGER CONSTRUCTION COMPLETE The project shall design, produce, and test the electronics required for receiving data from the barrel calorimeter, processing them for L1 trigger reconstruction, and transmitting output to the Correlator Trigger and DAQ. The Calorimeter trigger shall be validated, based on simulated test data patterns from MC verified against detector readout data, to give an average factor of four reduction of electron, photon and tau trigger object rates, after combination with track trigger simulated data, with respect to the Run-2 system with less than 20% efficiency loss.	O-KPP-TD-1: CALORIMETER TRIGGER INSTALLATION AND COMMISSIONING COMPLETE The project shall design, produce, and test the electronics required for receiving data from the barrel calorimeter, processing them for L1 trigger reconstruction, and transmitting output to the Correlator Trigger and DAQ. The Calorimeter trigger shall be validated, based on simulated test data patterns from MC verified against detector readout data, to give an average factor of four reduction of electron, photon and tau trigger object rates, after combination with track trigger simulated data, with respect to the Run-2 system with less than 20% efficiency loss. The Calorimeter trigger shall be installed, commissioned, and calibrated, with the overall CMS upgraded trigger.
402.6 Trigger and DAQ	T-KPP-TD-2: CORRELATOR TRIGGER CONSTRUCTION COMPLETE The project shall design, produce, and test the electronics required for receiving data from the barrel calorimeter, barrel muon, and track trigger systems, processing them for L1 trigger reconstruction, and transmitting output to the DAQ and downstream trigger components. The Correlator trigger shall be validated, based on simulated test data patterns from MC verified against detector readout data, to give an average factor of four reduction of electron, photon, tau and muon trigger object rates using validated calorimeter, muon and track trigger simulated data, with respect to the Run-2 system with less than 20% efficiency loss.	O-KPP-TD-2: CORRELATOR TRIGGER INSTALLATION AND COMMISSIONING COMPLETE The project shall design, produce, and test the electronics required for receiving data from the barrel calorimeter, barrel muon, and track trigger systems, processing them for L1 trigger reconstruction, and transmitting output to the DAQ and downstream trigger components. The Correlator trigger shall be validated, based on simulated test data patterns from MC verified against detector readout data, to give an average factor of four reduction of electron, photon, tau and muon trigger object rates using validated calorimeter, muon and track trigger simulated data, with respect to the Run-2 system with less than 20% efficiency loss. The Correlator trigger shall be installed and commissioned with the overall CMS upgraded trigger.
402.6 Trigger and DAQ	T-KPP-TD-3: DAQ CONSTRUCTION COMPLETE The project shall specify, procure, and test the equipment needed for the startup online Storage Manager and Transfer System. Deliverables are the storage-system hardware and the software used for collecting, aggregating and distributing events accepted by the high-level trigger. The Storage Manager startup hardware shall be sized to support data buffering of at least 1 day of data from the HLT at a minimum of 31 GB/s, concurrently transferring data to CERN central computing and transferring monitoring data to the online monitoring system.	O-KPP-TD-3: DAQ INSTALLATION AND COMMISSIONING COMPLETE The project shall specify, procure, and test the equipment needed for the startup online Storage Manager and Transfer System. Deliverables are the storage-system hardware and the software used for collecting, aggregating and distributing events accepted by the high-level trigger. The Storage Manager startup hardware shall be sized to support data buffering of at least 1 day of data from the HLT at a minimum of 31 GB/s, concurrently transferring data to CERN central computing and transferring monitoring data to the online monitoring system. The project shall install and commission the new storage manager hardware and software.

Critical Path and Float

Charge #3



- Schedule based on successful Phase-1 Calo Trig Prod, FW and SW experience
- "Pilot runs" provide early validation of production.

Threshold KPP: T-KPP-TD-1 Calorimeter Trigger Construction Complete

has 9 months of float to:

CMS need-by date

Objective KPP: O-KPP-TD-1 Cal. Trigger Installation/Commission Complete

has 14 months of float to:

CMS ready for operations

T-KPP-TD-1 has 3.8 years of float to CD-4

O-KPP-TD-1 has 2.5 years of float to CD-4

Trigger ready for CMS operations

CD-4

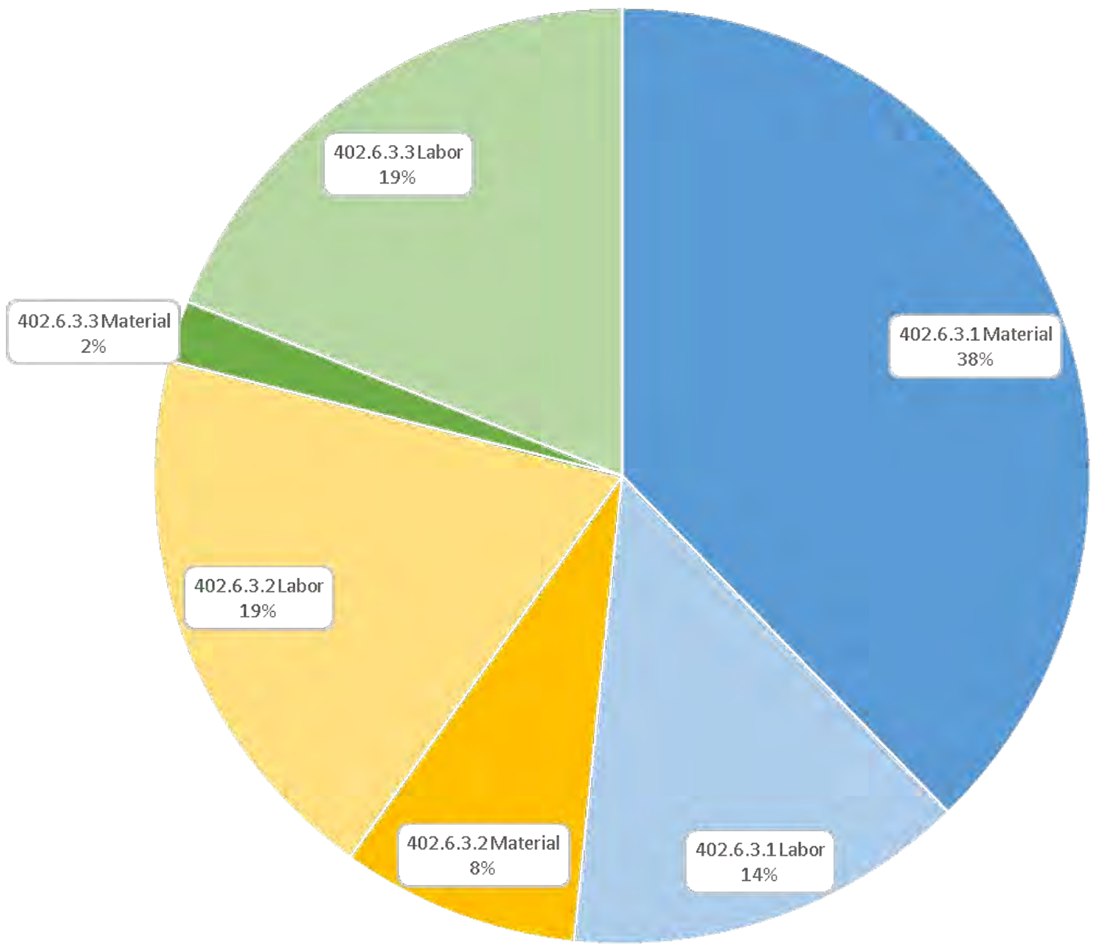
Costs: Calorimeter Trigger

CMS-doc-13215

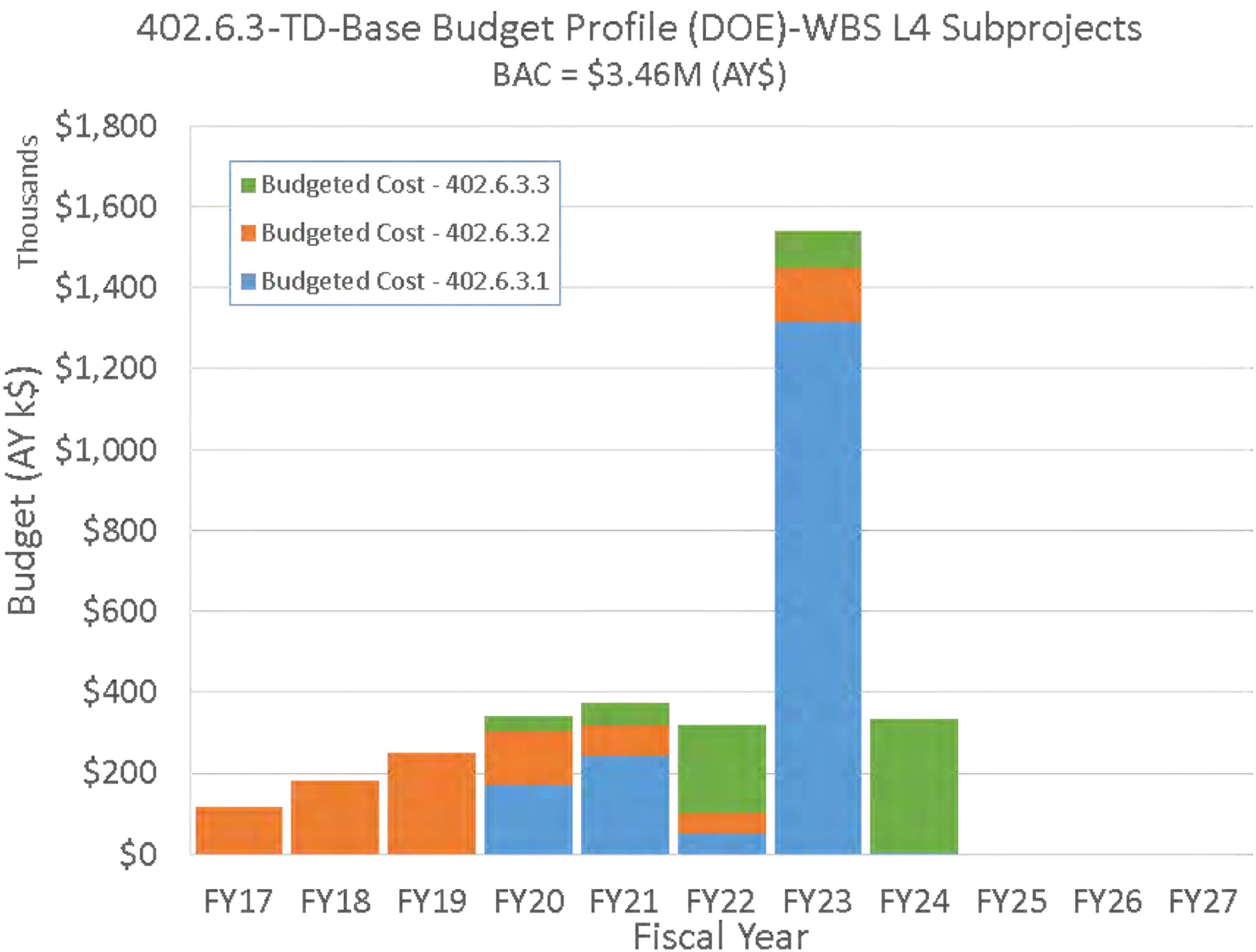
WBS	Direct M&S ($)	Labor (Hours)	FTE	Direct + Indirect + Esc. ($)	Estimate Uncertainty ($)	Total Cost ($)
402.6 TD - TRIGGER AND DAQ	$3,662,994	111126	62.85	$9,155,653	$2,777,343	$11,932,996
402.6.2 TD - Management	$162,000	26133	14.78	$213,104	$21,310	$234,414
402.6.3 TD - Calorimeter Trigger	$1,426,855	31043	17.56	$3,461,136	$958,265	$4,419,400
402.6.3.1 TD - Regional Calorimeter Trigger	$1,113,846	9737	5.51	$1,787,436	$524,468	$2,311,904
402.6.3.2 TD - Global Calorimeter Trigger	$253,609	11689	6.61	$945,416	$229,986	$1,175,401
402.6.3.3 TD - Calorimeter Trigger Infrastructure	$59,400	9617	5.44	$728,284	$203,810	$932,095
402.6.4 TD - Muon Trigger	$9,594	0	0.00	$10,001	$0	$10,001
402.6.5 TD - Correlator Trigger	$1,296,545	53950	30.51	$4,530,645	$1,327,385	$5,858,030
402.6.6 TD - Data Acquisition (DAQ)	$768,000	0	0.00	$940,767	$470,384	$1,411,151

Budget Breakdown by Labor & Material

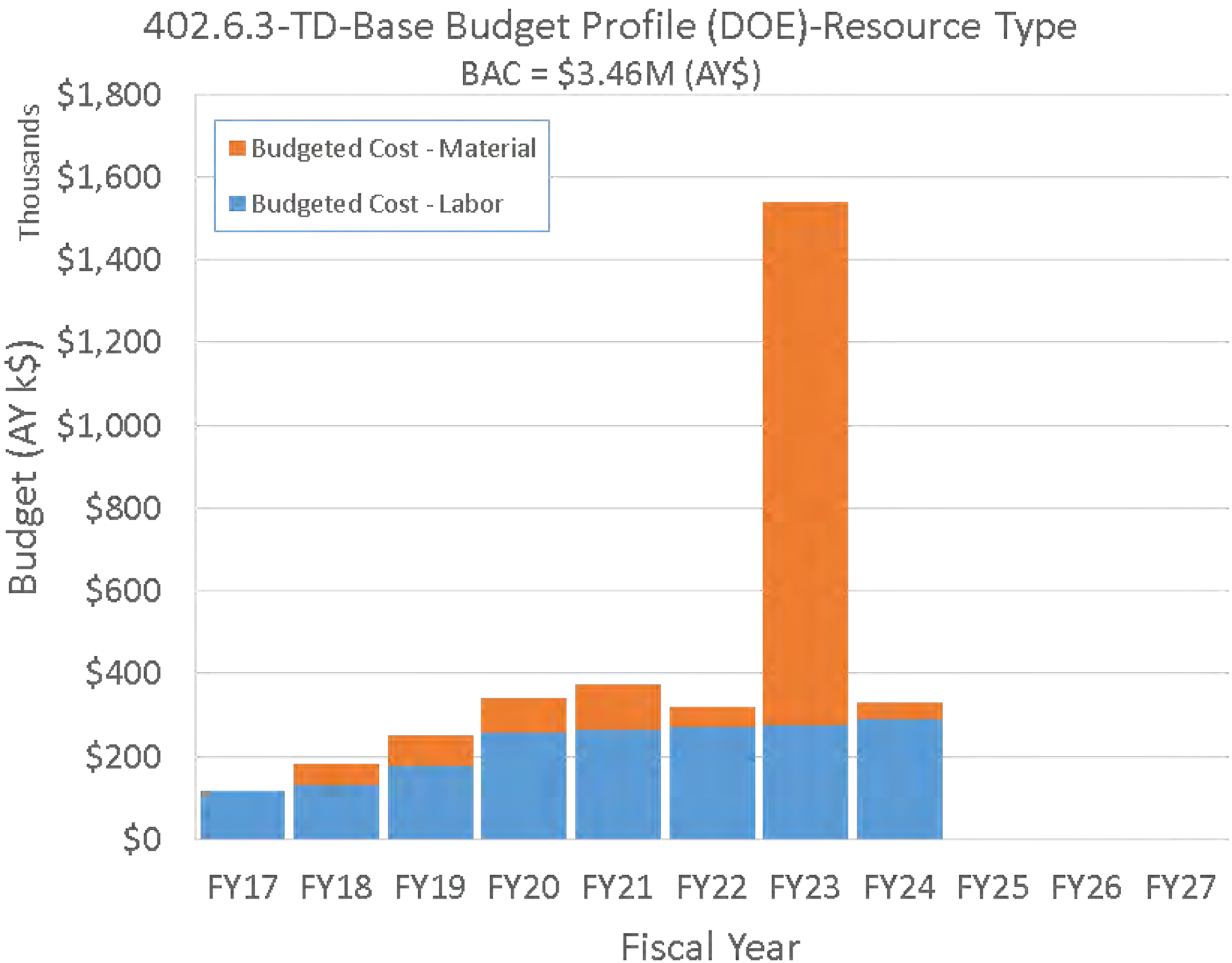
402.6.3-EC-WBS L4 Base Budget Breakdown (DOE)
BAC = $3.46M (AY$)



Base Budget Profile By WBS



Base Budget Profile By Resource



Cost Drivers: Calorimeter Trigger

CMS Driver	Labor (FTE-years)	Labor (M$)	M&S (M$)	Labor + M&S (M$)	Estimate Uncertainty (M$)	Total (M$)
TD.3 - Calorimeter Trigger delivery (M&S)	0.0	0.0	1.5	1.5	0.4	1.9
TD.5 - Correlator Trigger firmware	7.8	1.4	0.0	1.4	0.4	1.8
TD.5 - Correlator Trigger delivery (M&S)	0.0	0.0	1.4	1.4	0.4	1.8
TD.6 - Data Acquisition	0.0	0.0	0.9	0.9	0.5	1.4
TD.3 - Calorimeter Trigger delivery (labor)	6.1	0.9	0.1	1.0	0.3	1.2
TD.5 - Correlator Trigger delivery (labor)	5.5	0.8	0.1	0.9	0.3	1.2
TD - Trigger/DAQ installation and commissioning	5.0	0.7	0.1	0.8	0.2	1.1
TD.3 - Calorimeter Trigger firmware and software	7.2	0.6	0.0	0.6	0.2	0.8
TD.5 - Correlator Trigger software	2.9	0.3	0.0	0.3	0.1	0.4
TD.2 - Travel	0.0	0.0	0.3	0.3	0.0	0.4
TD.4 - Muon Track Finder R&D	0.0	0.0	0.0	0.0	0.0	0.0

M&S Cost Driver: APT

- RCT: 48 Total: 36 production boards, 4 test stand boards, and 6 spare boards.
  - 2 pre-production boards repurposed for a third test stand.
  - Estimated number of boards assumes 16 bits of trigger primitive data from each calorimeter cell being processed by the trigger processor boards. These boards have 96 16-Gbit input links, running 352 bits at 40 MHz. The total number of 70.4K channels is composed from 61.2K actual EB channels and 9.2K actual HB channels.
- GCT: 3 production boards and 1 spare board.
  - Number of boards is based on processing RCT output
- Cost per board: $21.19K
  - Prototype and Pre-production cost: $22.94K
  - Detail on next slide

Details of APT Cost – BoE: cmsdoc-13102

Primary Item	Subitem	Ext. Cost	Qty	Unit Cost	Comments
APT (Advanced Processor--Trigger) Fully Assembled Board		$23,374			
	PCB Fabrication	$1,800	1.0	$1,800	Ultra-low loss material used
	Heat Exchanger Assembly	$750	1.0	$750	Custom design likely copper with embedded fans
	Contract Assembly Solder Reflow	$900	1.0	$900	
	Power Subsystem Components	$420	1.0	$420	48V input modules, secondary converters
	Timing Subsystem Components	$120	1.0	$120	Clock circuitry
	Miscellaneous Components	$300	1.0	$300	Resistors, capacitors, connectors smaller ICs, etc.
	Panel Hardware	$75	1.0	$75	Hardware including panels and handles/ejectors
(Prototype built)	Mezzanine: ELM	$1,250	1.0	$1,250	ZYNQ-based, use Ultrascale+ family to reduce board unit cost
(Prototype built)	Mezzanine: IPMC	$360	1.0	$360	IPMI Controller for ATCA blades per the ATCA specification
	Mezzanine: PT LUT		0.0	$2,430	Required for Corl Trigger
	Processing FPGA	$12,774	1.0	$17,783	Virtex device in C2104 Package for 100 active links. XCVU9P-1FLGC2104E quantity: 3 and more, price: $12774, XCVU9P-2FLGC2104E quantity: 3 and more, price: $17783; -2 device is costed.
	Optical Modules--16G	$3,120	12.0	$260	Assuming either 12 RX or 12 TX @16G. Use present average 14G price. 16G available soon
	Optical Modules--25G		0.0	$375	assuming 1 device = 4TX+4RX
	RTM Board	$1,505	1.0	$1,505	See itemization below
	Remove 1.9% for FY17 vs FY18	$22,938			used for prototypes and preproduction
	Remove following 2%/yr escalation rate	$21,191			used for pilot and final production
RTM Optical Board		$1,505			
	PCB Fabrication	$160	1.0	$160	Assumes ultra low loss dielectric, layer count sufficient for high quality routing solution between optical modules and RTM connector
	Contract Asssembly Solder Reflow	$100	1.0	$100	
	Interface logic (power, IPMI)	$85	1.0	$85	
	Optical components	$1,040	4.0	$260	Assuming either 12 RX or 12 TX @16G. Use present average 14G price. 16G available soon
	Panel Hardware	$75	1.0	$75	Rear face panel
	Misc electrical components	$45	1.0	$45	Includes connector

Calorimeter Trigger Labor Costs

- Electronics Engineering and Technical work to design, produce, and test the calorimeter trigger electronics
- Software Engineering to produce the software to program, test, operate, diagnose, configure, validate and read out the calorimeter L1 trigger upgrade electronics.
  - This includes software to interface with the Trigger Online System
- Firmware Engineering to implement the full functionality of the calorimeter L1 trigger upgrade electronics
  - Including implementing the trigger algorithms, diagnostics, data acquisition and readout.
- SW and FW produced in validated releases for testing cards individually, integrated into a test system, integrated into the final test system, full production tests, and system installation and commissioning.
- All labor costs based on actual costs for corresponding tasks for the Phase 1 Trigger Upgrade
  - In most cases by the same people

Calorimeter Trigger Costed Labor

- Determined from Resource Loaded Schedule with durations and levels of effort informed by analogous activities in the Phase-1 calorimeter trigger project and Phase-2 R&D experience thus far
  - Phase-1 project did not break down technical project labor associated with crates, fibers other and infrastructure vs. cards and the project covered a single layer.
  - Review of Phase-1 project resulted in estimate of effort used for Phase 2 apportioned as 60% Regional (402.6.3.1), 20% Global (402.6.3.2) and 20% Infrastructure (402.6.3.3).
- Effort is mapped onto 5 cycles:
  - 2 R&D cycles: APD1 and APD2
  - 3 construction cycles: 1 preproduction cycle and 2 production cycles (pilot and final).
- A typical cycle involves:
  - Design, procurement, manufacturing, and testing, as well as required firmware and software releases for development, initial, testing, and operational.

Calorimeter Trigger Scientific Labor
(a.k.a. contributed labor)

- Personnel:
  - Wisconsin Scientist, Postdocs and Graduate Students
- Tasks:
  - Testing and Operational Software
    - For RCT, GCT and Infrastructure
    - For Prototype, Pre-production and Production phases.
    - Framework and basic software system by software engineer professional
- Total Level of Effort
  - 406.3.1 (RCT): 2.1 FTE-years
  - 406.3.2 (GCT): 1.8 FTE-years
  - 406.3.3 (Infrastructure): 1.0 FTE-years

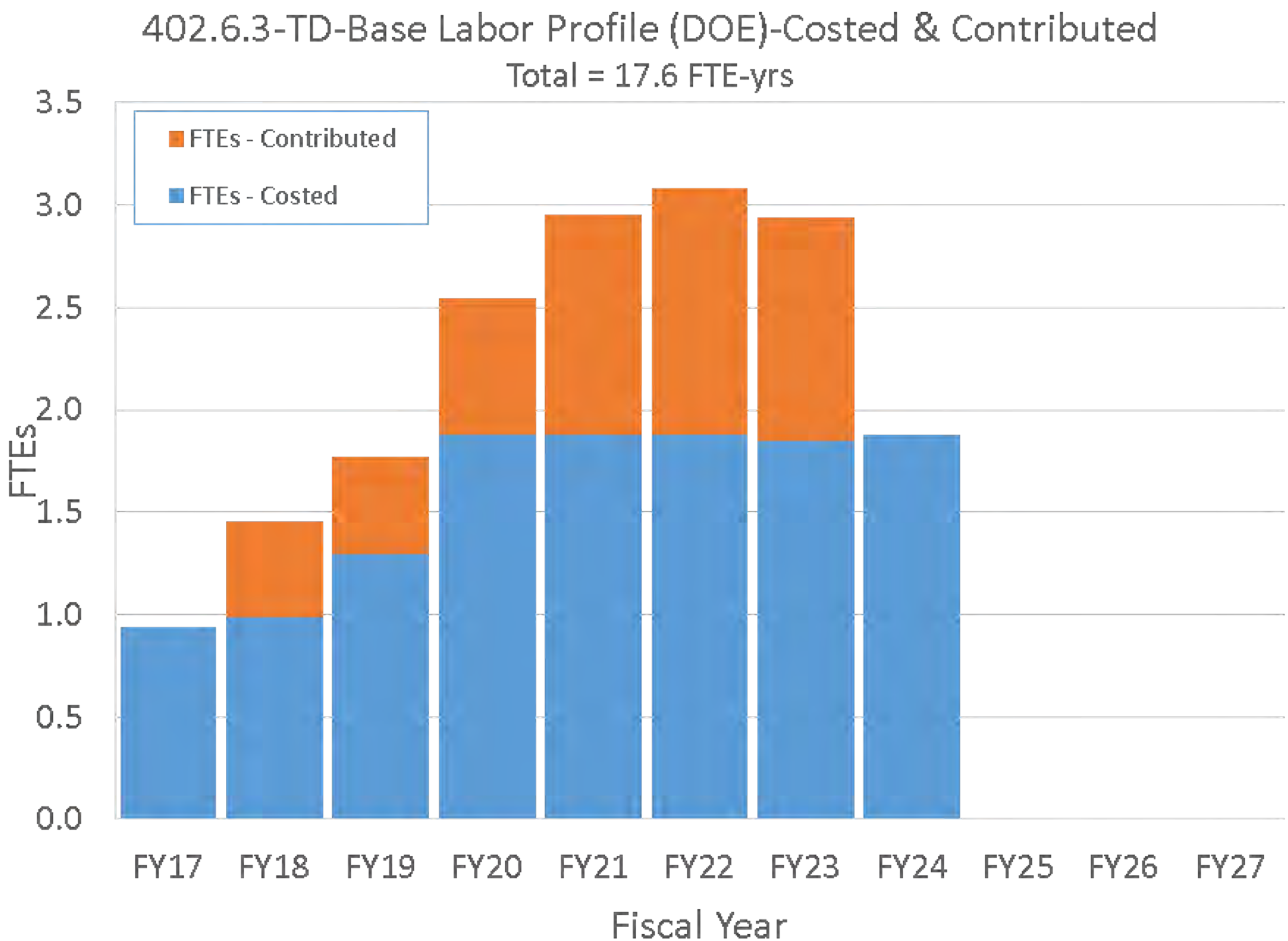
Labor: Calorimeter Trigger

WBS	Labor hours	FTE-years	Direct + Indirect + Escalation ($)	Estimate Uncertainty ($)	Total Labor Cost ($)
Total	111126	62.85	$4,810,749	$1,396,708	$6,207,457
402.6 TD - TRIGGER AND DAQ	111126	62.85	$4,810,749	$1,396,708	$6,207,457
402.6.2 TD - Management	26133	14.78	$0	$0	$0
Uncosted	26133	14.78	$0	$0	$0
402.6.3 TD - Calorimeter Trigger	31043	17.56	$1,796,717	$492,498	$2,289,215
Uncosted (contributed)	8784	4.97	$0	$0	$0
Costed	22259	12.59	$1,796,717	$492,498	$2,289,215
402.6.5 TD - Correlator Trigger	53950	30.51	$3,014,032	$904,210	$3,918,241
Uncosted	21107	11.94	$0	$0	$0
Costed	32843	18.58	$3,014,032	$904,210	$3,918,241

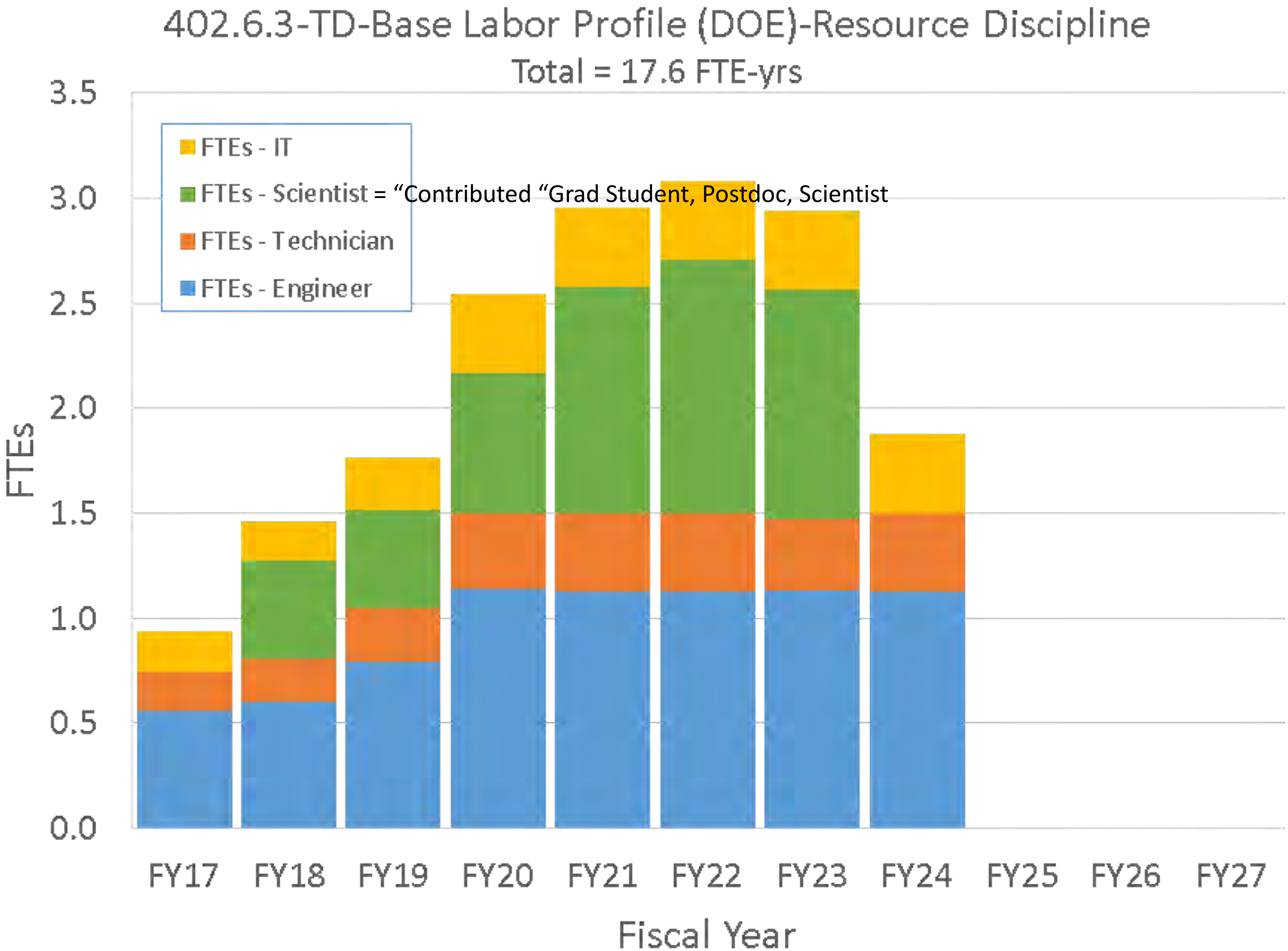
Breakdown of calorimeter trigger contributed labor:

402.6.3 TD - Calorimeter Trigger (University of Wisconsin)	8784
Graduate student— contributed (uncosted) labor at Average University	4392
Postdoc — contributed (uncosted) labor at Average University (Incl. Scientist)	4392

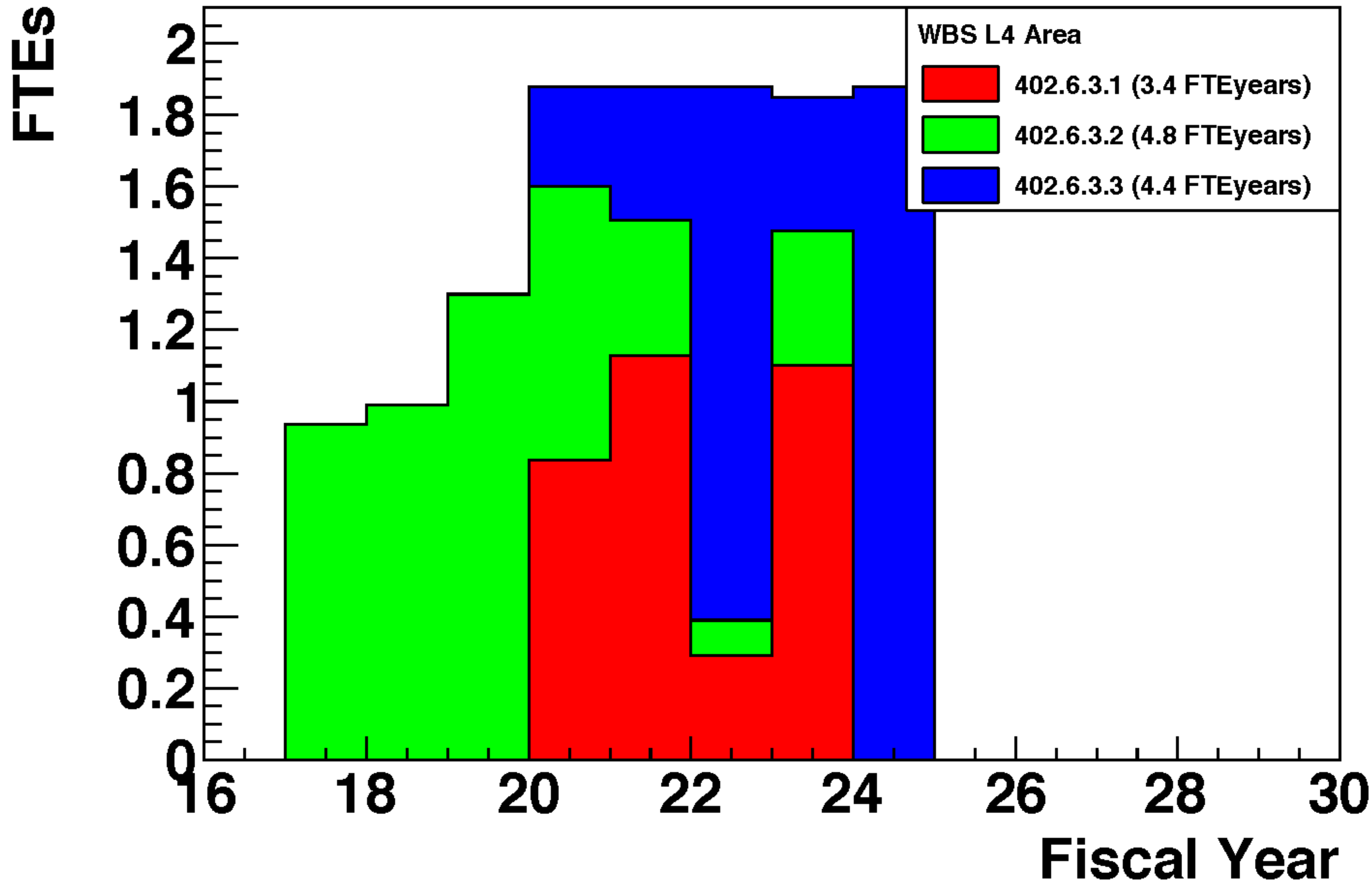
Labor Profile (FTEs): Costed & Contributed



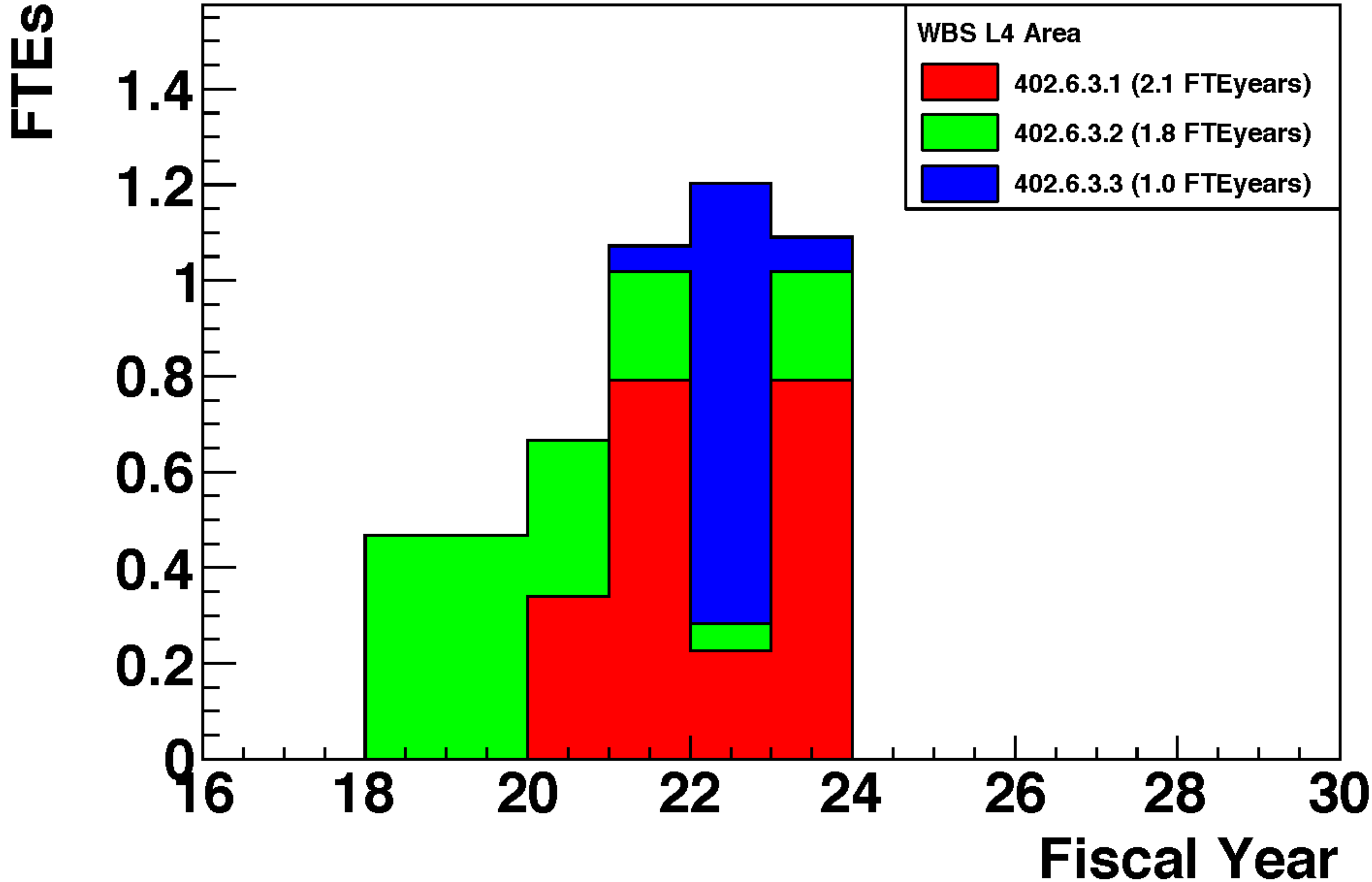
Labor Profile By Resource Discipline



Calorimeter Trigger Labor Profile
(costed)



Cal. Trig. Contributed Labor Profile



Value Engineering

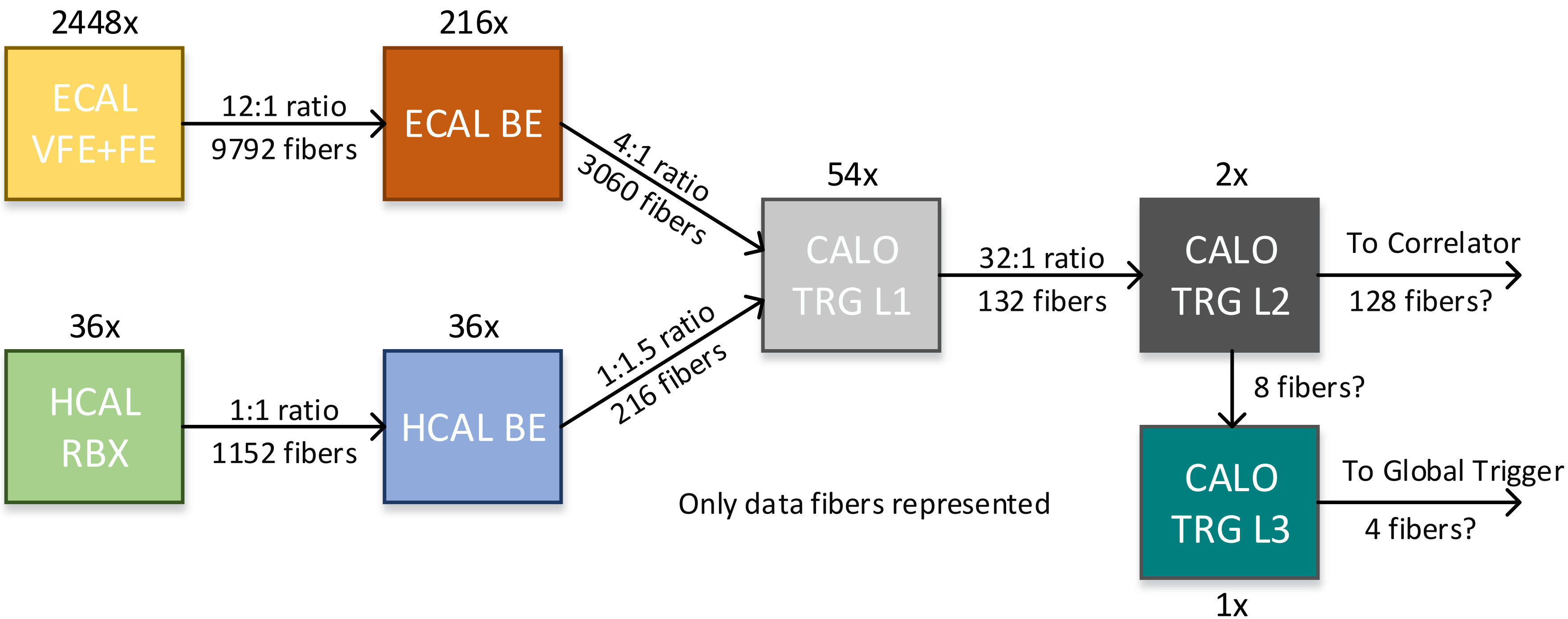
Charge #1

- Standardize within US CMS Trigger Project
  - Use of a single FPGA family: Xilinx Ultrascale/+
    - Also used across CMS upgrade and other CERN projects
  - Allows negotiation of discounts through CERN and US distributor (Avnet) – as was done in Phase-1.
- Standardize across US CMS Upgrade Project
  - Use of a common crate/backplane infrastructure
    - Use same ATCA architecture as is being used by other CMS and ATLAS subsystems
    - Built to similar specifications by common vendors.
    - Opportunities for pooling spares and cooperation on engineering.
    - This allows use of common components such as:
  - Use of standard DAQ/Trigger/Clock Interface: DTH
    - Common connection to CMS data acquisition, trigger timing and control systems.
    - Developed by CMS CERN CDAQ group
- Explore alternative architectures (next slide)

Alternative Architecture Studies

- Example: Use a smaller and less expensive FPGA (below)
  - Fewer links per card → more cards, more layers (latency), awkward geometry, more complexity, more cost
- Example: Use two cheaper FPGAs per card
  - Large usage of links and circuitry for data exchange, dividing logic leads to inefficiencies, complex clocking to synchronize, more cost

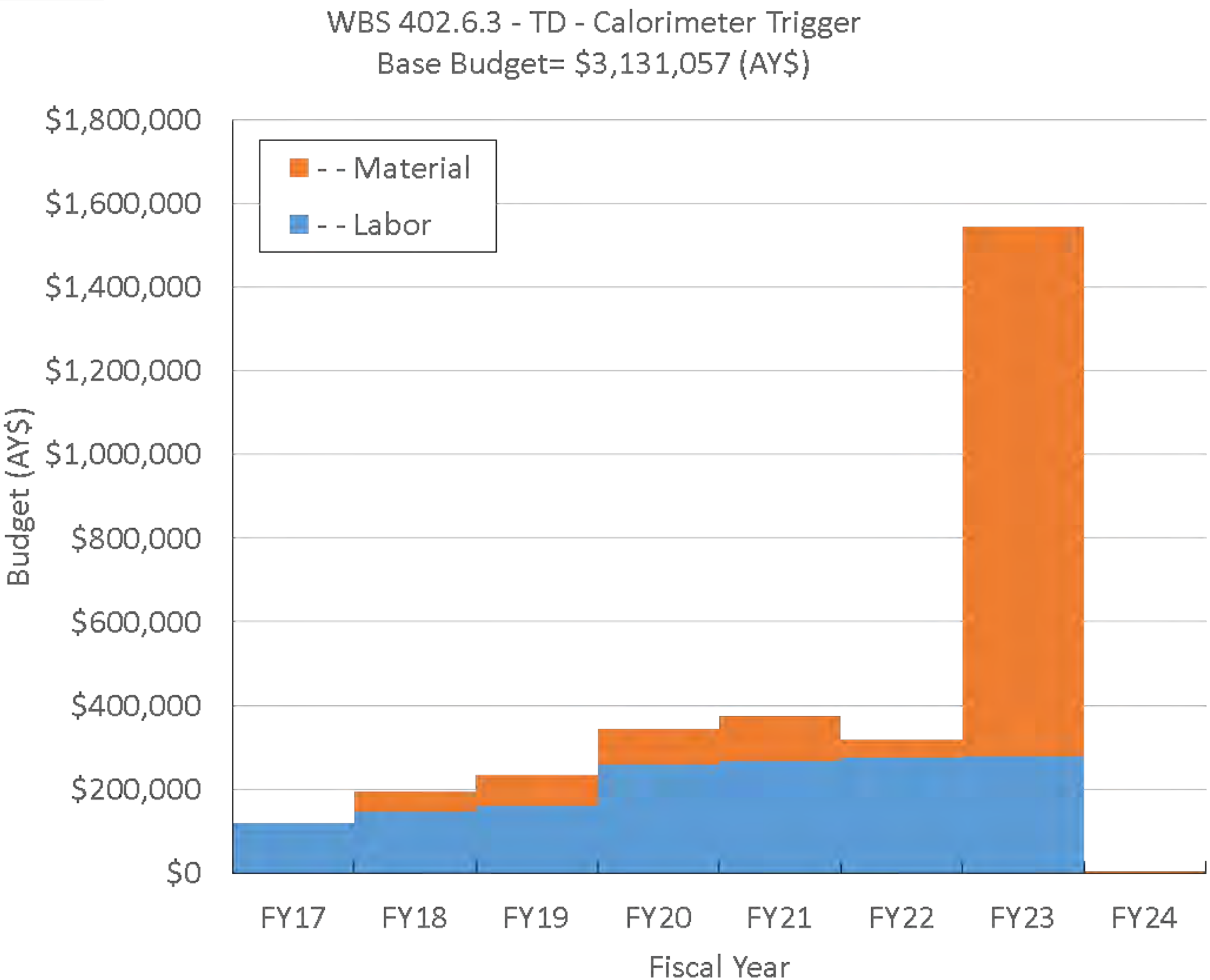
Charge #1



Ratios reflect ηxϕ input regions to output regions

Fiscal Year Cost Profile

Charge #3



Maturity of Design

- ATCA hardware is similar to μTCA Phase-1 System
- Prototype Cards already made capture ATCA interface
  - IPMC, ELM1: control interfaces, CDB: Ethernet and physical interfaces
- Phase-2 system is based on same classes of components as Phase-1
- Hardware, Firmware and Software based on experience of the same team that built and wrote hardware, software and firmware for Phase-1 trigger system
- Hardware is based upon common ATCA hardware platform also to be used by other CMS subsystems
- Same team wrote software and firmware for Phase-1 trigger system → scope and requirements well understood
- Requirements are detailed in Trigger Interim Document
- Schedule is designed based upon experience of Phase-1 system.

Contingency Breakdown

Charge #3

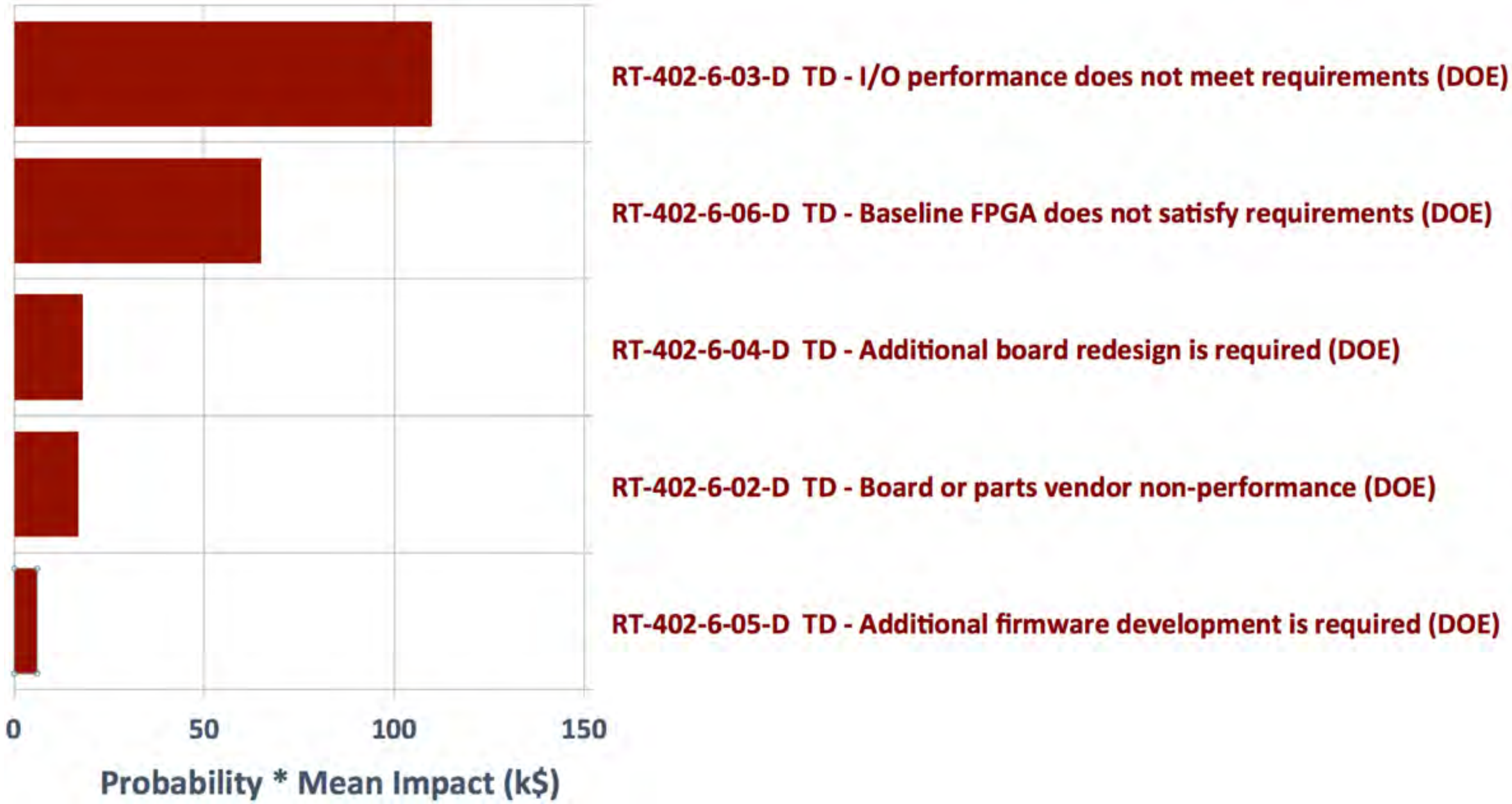
- Most M&S contingency set per OPSS rules at M4: 30%, since the same team has just built a similar technology µTCA calorimeter trigger for Phase 1 and the dominant costs (FPGAs, Optical components, memories) are based on quotes.
  - Exception for travel, COLA and shipping at M2: 10%.
- Most Labor contingency set per OPSS rules at L4: 30% since the since the same team has just built a similar technology µTCA calorimeter trigger along with Firmware and Software for Phase 1 and the various labor activities are based on this experience.
- Experience with Phase 2 R&D and prototyping thus far bears this out.

Risk Register: CMS-doc-13480

Risk Rank	RI-ID	Title	Probability	Schedule Impact	Cost Impact	P * Impact (k$)
WBS / Ops Lab Activity : 402.6 TD - Trigger and DAQ (5)						
Risk Type : Threat (5)						
2 (Medium)	RT-402-6-03-D	TD - I/O performance does not meet requirements (DOE)	20 %	3 -- 5 -- 7 months	280 -- 550 -- 820 k$	110
2 (Medium)	RT-402-6-06-D	TD - Baseline FPGA does not satisfy requirements (DOE)	20 %	1 -- 3 -- 6 months	136 -- 282 -- 564 k$	65
2 (Medium)	RT-402-6-04-D	TD - Additional board redesign is required (DOE)	10 %	1 -- 3 -- 6 months	60 -- 155 -- 310 k$	18
2 (Medium)	RT-402-6-02-D	TD - Board or parts vendor non-performance (DOE)	10 %	1 -- 3 -- 6 months	35 -- 155 -- 310 k$	17
1 (Low)	RT-402-6-05-D	TD - Additional firmware development is required (DOE)	20 %	1 -- 2 -- 3 months	12 -- 25 -- 50 k$	6

These are risks remaining after completion of R&D program which results in a successful demonstrator

Probability-weighted Mean Cost Impact



Trigger and DAQ risk threats:
Approx. share of total contingency at
90% C.L. = $0.5M (5% of total)

Managed Trigger Risks & Mitigation

Charge #3

- Senior Engineer becomes unavailable (Low Risk)
  - Hire new engineer, subcontract to consulting firm, use FNAL engineer
- Funding is delayed (Low Risk)
  - Commission with prototypes and/or fewer production boards
- Software or Firmware does not meet requirements (Low Risk)
  - Hire extra expert effort to recover schedule and help personnel
- Boards are delayed (design, manufacture or testing) (Low Risk)
  - Hire extra effort to speed up testing schedule
- Vendor non-performance (Low Risk)
  - Acquire spending authority to use alternative vendors (while original funds are being unencumbered).
- Input or output electronics (non-trigger) delayed (Low Risk)
  - Built in capabilities of trigger electronics provide signals for their own inputs & outputs

R&D Program and Risk Reduction

- R&D is well underway for some of the key technologies to be used (optical links at >10Gbps, Ultrascale FPGAs, large LUTs)
- Completion of the design and manufacture of the Advanced Processor prototype (APd1), and the demonstrator will validate the technology by end of 2019
- R&D program of realistic firmware to demonstrate that FPGA resource usage and latency are within specs by time of demonstrator
- The Advanced Processor is modular with mezzanines and RTMs for optical links, memory, control, etc.
  - Limits risk impact during production

Contributing Institutions and Resource Optimization

Contributing Institute

Charge #4,5

- University of Wisconsin – Madison
- CMS Regional Calorimeter Trigger
  - Operated from 2007 – 2015
  - 22 (18 + spare/test) 9U-crate 1800-card system based on 5 distinct custom (UW-designed) high-speed ASICs and including 28 high-speed 160 MHz backplanes, 154 Receiver Cards 154 Electron ID Cards, 25 Jet Summary Cards, 25 Clock Cards and a 1400 card 4 Gbit/s copper serial data link mezzanine card system with associated testing cards.
- CMS Stage 1 and Stage 2 Layer-1 Calorimeter Triggers
  - 22 CTP7's including hot spares
  - Stage-1 was main calorimeter trigger for 2015 – integrated w/RCT
  - Stage-2 operating in parallel since 2015 – main cal. Trig. for 2016 onward.
  - 26 CTP7's used in Phase 2 Trigger R&D Program (see Tech. Overview)

Key Personnel

Charge #5

- Wesley Smith (U. Wisconsin) - Professor
  - CMS Trigger Project Manager 1994 – 2007, CMS Trigger Coordinator, 2007 - 2012
  - Co-chair, CMS Trigger Performance & Strategy Working Group, 2012 – 2015 (Trigger Chapter of CMS HL-LHC Technical Proposal)
  - US CMS Trigger L2 Project Manager 1997 – present,
  - US CMS Phase 1 Trigger L2 Upgrade Project Manager, 2013-2017
- Sridhara Dasu (U. Wisconsin) - Professor
  - US CMS L3 Manager Calorimeter Trigger (construction & operations) 1998 – present
  - US CMS L3 Manager Phase 1 Calorimeter Trigger Upgrade 2013 – 2017
- Sascha Savin (U. Wisconsin) – Senior Scientist
  - 4 years of HL-LHC Trigger Studies, CMS Future Standard Model Physics Group Co-Convener.
  - CMS Standard Model Physics Convener, Trigger Studies Group Trigger Performance Convener
- Tom Gorski (U. Wisconsin) – Electrical Engineer
  - Over a decade of engineering on the CMS Calorimeter Trigger
  - Delivered final phase of original Regional CMS Calorimeter Trigger
  - Delivered Phase 1 Layer-1 Calorimeter Trigger Upgrade Electronics
- Ales Svetek (U. Wisconsin) – Firmware Engineer
  - 4 yrs on Phase 1 Calorimeter Trigger Upgrade Firmware
  - (4 yrs ATLAS Beam Conditions Monitor FW, DAQ, Commissioning, Det. Ops.)
- Marcelo Vicente (U. Wisconsin) – Firmware Engineer
  - 4 yrs on Phase 1 Calorimeter Trigger Upgrade Firmware + HCAL Firmware
  - 2 yrs on ECAL Phase 1 Upgrade Trigger Primitive Generation Electronics
- Jes Tikalski (U. Wisconsin) – Software Engineer
  - 4 yrs on Phase 1 Calorimeter Trigger Upgrade Software and embedded systems

Resource Optimization

Charge #4

- University Resources
  - U. Wisconsin has an experienced electronics engineering, technical, firmware and software team that has delivered two successful CMS calorimeter trigger electronics systems on schedule and on budget using U. Wisconsin Physics Dept. lab facilities for final assembly and testing.
    - Provided additional systems for Phase 2 R&D effort
  - Mutual support and task sharing through APx consortium members
    - Fermilab, U. Florida, Notre Dame, U. I. Chicago, U. Virginia
- Vendor Resources
  - The Wisconsin team works with experienced vendors regularly qualified through R&D, pre-production and production orders for board manufacture, parts ordering and board assembly.
    - Only non-vendor assembly are final parts needing installation after initial testing (e.g. heat-sink, surface connection cables).
  - Where possible, State of Wisconsin purchasing is leveraged with placement of major parts orders through State Contract Vendors, including AVNET (Xilinx partner).

ES&H

Charge #6

- All ES&H aspects of the HL LHC CMS Detector Upgrade Project will be handled in accordance with the Fermilab Integrated Safety Management approach, and the rules and procedures laid out in the Fermilab ES&H Manual (FESHM)
- We are following our Integrated Safety Management Plan (cms-doc-13395) and have documented our hazards in the preliminary Hazard Awareness Report (cms-doc-13394)
- In General Safety is achieved through standard Lab/Institute practices
  - No construction, accelerator operation, or exotic fabrication
  - No imminent peril situations or unusual hazards
  - Items comply with local safety standards in site of fabrication and operation
  - Site Safety officers at Institutes identified in the SOW
- Specific Safety for this WBS
  - Modules similar to others built before, of medium size and no high voltage
  - Integrated into existing well-tested and long-term performing safety system
  - All activities and personnel at CERN regulated by CERN Safety Rules
  - e.g. safety training courses required of all personnel

Quality Assurance and Quality Control

Charge #4

- QA/QC for hardware: follows cms-doc-13093
  - QA: All boards are designed for manufacturability, evaluated through prototyping
  - QC: Full testing at the institute before shipping to CERN.
    - All tests are recorded (of all types) for individual boards in the database.
    - The tests use and validate the software and firmware test releases.
  - QC: After shipment and receipt at CERN there is acceptance testing in the individual testing labs in the Electronics Integration Center (EIC) at CERN, where the boards are retested to validate the institute test results. These tests use the same software and firmware test releases as used in the institute testing. (Trigger boards also have Built In Self Test usable at power-up)
- QA/QC for Firmware, Online and Offline Software
  - Produced in a sequence of releases with specific functionality requirements for each release to be demonstrated with specific tests defined to validate each release.
  - Requirements will include performance metrics by which the software and firmware can be verified to satisfy the system requirements.
  - Specific testing procedures will be established to certify that the software emulation of the hardware meets requirements by specifying specific tests with specific input and output data files.
  - The releases will comply with the Software Quality Assurance procedures of the Fermilab Software Quality Assurance Program specified in QAM 12003 and the Software Assurance Grading and Inventory Procedure specified in QAM 12090.

Production and Design QA/QC

- Design
  - Design reviews
  - Engineering analysis
  - Engineering demonstration (with prototypes)
- Production
  - Qualification testing
  - Inspection
  - Partial construction of initial boards – “pilot run”
  - Thorough suite of tests at institute before shipment
  - Tests duplicated when boards arrive at CERN

Major System Tests

- Subsystem interconnect test at the end of CY19:
  - Prototypes used
  - Calorimeter BE → Calorimeter Trigger → Correlator
    - AP Consortium boards have same link technologies so Calorimeter trigger cards can temporarily serve as substitutes for Calorimeter BE to decouple schedules.
    - Correlator is identical board to Calorimeter Trigger.
  - Test provides input for Trigger TDR
- System integration test Mid-CY22
  - Production Pilot Boards used
  - Calorimeter BE → Calorimeter Trigger → Correlator
  - Final Test before production starts
  - Final Major System test before shipment to CERN.

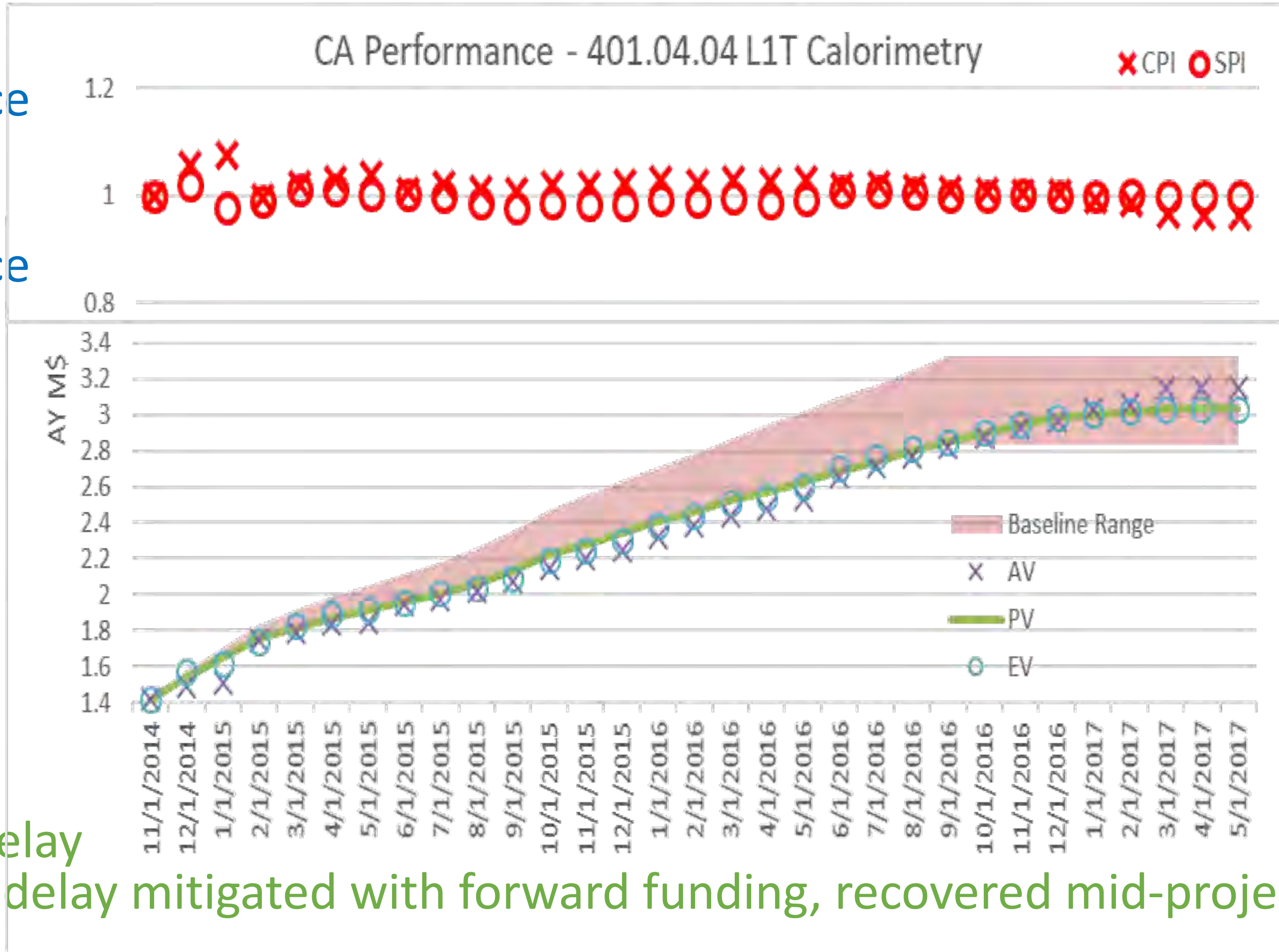
Summary

- Project costs for M&S and Labor based on Phase-1 experience, reinforced by R&D program.
  - M&S Costs validated with quotes for major parts costs
- ES&H, QA/QC plans, C&S based on experience with Phase-1 Upgrade
- Management and Engineering teams are experienced with sufficient design skills, having designed and built original CMS trigger and Phase-1 upgrade.
- Firmware and software tasks based on Phase-1 models and experience.
  - Firmware development will exploit new High Level Synthesis tools

Backup

Phase-1 Project Performance

- L1 Calorimeter Trigger Control Account History superb
- Excellent performance on:
  - Cost Performance Index
  - Schedule Performance Index
  - Actual Value
  - Planned Value
  - Earned Value



Early minor delay
from funding delay mitigated with forward funding, recovered mid-project

Risk Register: CMS-doc-13480

ID / Title: RT-402-6-02-D TD - Board or parts vendor non-performance (DOE)

Summary: If the vendor has intermittent problems during the production causing sub-standard batches to be delivered then parts from batch N do not meet electrical specs causing a delay of order one batch length or another vendor is sought. Similarly if there is significant vendor delay to due to internal technical or inventory problems. The risk is repeated per L3 area.

Explanation of estimate: Based on previous dealings with similar vendors. Possible cost increases due to new vendor choice: Min/likely/max cost = 25/125/250k$. Min/likely/max delay = 1/3/6 months for another production batch or vendor selection.

The average L3 burn rate due to the delay of downstream activities is $10k/month (CMS-doc-13481).

Min cost = $25k + 1 month * $10k burn rate = $35k.

Likely cost = $125k + 3 months * $10k burn rate = $155k.

Max cost = $250k + 6 months * $10k burn rate = $310k.

Risk mitigations (in base plan):

Risk responses (if risk should occur): Diagnose the problem. If a simple technical fix is available, consider reordering. If not, find another vendor.

Risk Type:	Threat
Project:	CMS HL-LHC
WBS:	402.6 TD - Trigger and DAQ
Risk Area:	External Risk / Vendors
Owner:	Jeffrey W Berryhill
Risk Status:	Open
Probability (P):	10%
Technical Impact:	2 (M) - significantly substandard
Cost impact	
-- **P.D.F.:**	3-point - triangular
-- **Minimum:**	35 k$
-- **Most likely:**	155 k$
-- **Maximum:**	310 k$
-- **Mean:**	167 k$
-- **P * <Impact>**	17 k$
Schedule impact:	
-- **P.D.F.:**	3-point - triangular
-- **Minimum:**	1 months
-- **Most likely:**	3 months
-- **Maximum:**	3.336 months
-- **Mean:**	3.33 months
-- **P * <Impact>**	0.3 months
Risk Scores:	Probability : 2 (L) Cost: 2 (M) Schedule: 2 (M)
Risk Rank:	2 (Medium)
Start date:	1/Jan/2021
Expiry date:	1/Jan/2024
More Information:	CMS-doc-13481

Risk Register: CMS-doc-13480

ID / Title: RT-402-6-03-D TD - I/O performance does not meet requirements (DOE)

Summary: I/O requirements of a trigger subsystem change

Explanation of estimate: 10-30% upscope of a 100-board production to meet changed requirements, with min/likely/max cost of 250/500/750k$.

Schedule delaysof 3/5/7 months due to the acquisition of more batches.

The average L3 burn rate due to the delay of downstream activities is $10k/month (CMS-doc-13481).

Min cost = $250k + 3 month * $10k burn rate = $280k.

Likely cost = $500k + 5 months * $10k burn rate = $550k.

Max cost = $750k + 7 months * $10k burn rate = $820k.

Risk mitigations (in base plan):

Risk responses (if risk should occur):

Risk Type:	Threat
Project:	CMS HL-LHC
WBS:	402.6 TD - Trigger and DAQ
Risk Area:	Technical Risk / Requirements
Owner:	Jeffrey W Berryhill
Risk Status:	Open
Probability (P):	20%
Technical Impact:	2 (M) - significantly substandard
Cost impact	
-- **P.D.F.:**	3-point - triangular
-- **Minimum:**	280 k$
-- **Most likely:**	550 k$
-- **Maximum:**	820 k$
-- **Mean:**	550 k$
-- **P * <Impact>**	110 k$
Schedule impact:	
-- **P.D.F.:**	3-point - triangular
-- **Minimum:**	3 months
-- **Most likely:**	5 months
-- **Maximum:**	57 months
-- **Mean:**	5 months
-- **P * <Impact>**	1.0 months
Risk Scores:	Probability : 2 (L) Cost: 2 (M) Schedule: 3 (H)
Risk Rank:	2 (Medium)
Start date:	1/Jan/2021
Expiry date:	1/Jan/2024
More Information:	CMS-doc-13481

Risk Register: CMS-doc-13480

ID / Title: RT-402-6-04-D TD - Additional board redesign is required (DOE)

Summary: A prototype or production batch has technical flaws.

Explanation of estimate: 2-10 boards at 25k each are found to require a technical redesign. Min/likely/max cost = 50/125/250k$. Min/likely/max delay = 1/3/6 months for redesign and procurement.

The average L3 burn rate due to the delay of downstream activities is $10k/month (CMS-doc-13481).

Min cost = $50k + 1 month * $10k burn rate = $60k.

Likely cost = $125k + 3 months * $10k burn rate = $155k.

Max cost = $250k + 6 months * $10k burn rate = $310k.

Risk mitigations (in base plan):

Risk responses (if risk should occur):

Risk Type:	Threat
Project:	CMS HL-LHC
WBS:	402.6 TD - Trigger and DAQ
Risk Area:	Technical Risk / Reliability or Performance
Owner:	Jeffrey W Berryhill
Risk Status:	Open
Probability (P):	10%
Technical Impact:	2 (M) - significantly substandard
Cost impact	
-- P.D.F.:	3-point - triangular
-- Minimum:	60 k$
-- Most likely:	155 k$
-- Maximum:	310 k$
-- Mean:	175 k$
-- P * <Impact>	18 k$
Schedule impact:	
-- P.D.F.:	3-point - triangular
-- Minimum:	1 months
-- Most likely:	3 months
-- Maximum:	3.336 months
-- Mean:	3.33 months
-- P * <Impact>	0.3 months
Risk Scores:	Probability : 2 (L) Cost: 2 (M) Schedule: 2 (M)
Risk Rank:	2 (Medium)
Start date:	1/Jul/2017
Expiry date:	1/Jan/2024
More Information:	CMS-doc-13481

Risk Register: CMS-doc-13480

ID / Title: **RT-402-6-05-D TD - Additional firmware development is required (DOE)**

Summary: Firmware does not meet technical or scientific requirements at time of milestoned releases.

Explanation of estimate: New firmware requires 1-3 months of rework, with a firmware engineer at 0.1-0.5 FTE.

No standing army cost (there is no idle workforce in the event of a delay).

Risk mitigations (in base plan):

Risk responses (if risk should occur):

Risk Type:	Threat
Project:	CMS HL-LHC
WBS:	402.6 TD - Trigger and DAQ
Risk Area:	Technical Risk / Reliability or Performance
Owner:	Jeffrey W Berryhill
Risk Status:	Open
Probability (P):	20%
Technical Impact:	1 (L) - somewhat substandard
Cost impact	
-- **P.D.F.:**	3-point - triangular
-- **Minimum:**	12 k$
-- **Most likely:**	25 k$
-- **Maximum:**	50 k$
-- **Mean:**	29 k$
-- **P * <Impact>**	6 k$
Schedule impact:	
-- **P.D.F.:**	3-point - triangular
-- **Minimum:**	1 months
-- **Most likely:**	2 months
-- **Maximum:**	23 months
-- **Mean:**	2 months
-- **P * <Impact>**	0.4 months
Risk Scores:	Probability : 2 (L) Cost: 1 (L) Schedule: 1 (L)
Risk Rank:	1 (Low)
Start date:	1/Jul/2017
Expiry date:	1/Jan/2024
More Information:	

Risk Register: CMS-doc-13480

ID / Title: **RT-402-6-06-D TD - Baseline FPGA does not satisfy requirements (DOE)**

Summary: Computation requirements of calorimeter trigger and correlator are not satisfied by the baseline FPGA.

Explanation of estimate: 12.5/25/50% FPGA cost increase on (36+48=) 84 FPGAs at 12k/chip base cost.. Min/likely/max cost = 126/252/504k$.

1/3/6 months delay for procurement.

The average L3 burn rate due to the delay of downstream activities is $10k/month (CMS-doc-13481).

Min cost = $126k + 1 month * $10k burn rate = $136k.

Likely cost = $252k + 3 months * $10k burn rate = $282k.

Max cost = $504k + 6 months * $10k burn rate = $564k.

Risk mitigations (in base plan):

Risk responses (if risk should occur):

Risk Type:	Threat
Project:	CMS HL-LHC
WBS:	402.6 TD - Trigger and DAQ
Risk Area:	Technical Risk / Reliability or Performance
Owner:	Jeffrey W Berryhill
Risk Status:	Open
Probability (P):	20%
Technical Impact:	2 (M) - significantly substandard
Cost impact	
-- **P.D.F.:**	3-point - triangular
-- **Minimum:**	136 k$
-- **Most likely:**	282 k$
-- **Maximum:**	564 k$
-- **Mean:**	327 k$
-- **P * <Impact>**	65 k$
Schedule impact:	
-- **P.D.F.:**	3-point - triangular
-- **Minimum:**	1 months
-- **Most likely:**	3 months
-- **Maximum:**	3.336 months
-- **Mean:**	3.33 months
-- **P * <Impact>**	0.7 months
Risk Scores:	Probability : 2 (L) Cost: 2 (M) Schedule: 2 (M)
Risk Rank:	2 (Medium)
Start date:	1/Jan/2020
Expiry date:	1/Jan/2024
More Information:	CMS-doc-13481

Labor Estimation Sanity Check

Phase 1 Actuals for Calorimeter Trigger (Pre-prod. to end of construction):				Predict HL-LHC from Phase 1:		Difference	Proposed HL-LHC: BOE Sum of Preproduction through Construction		
Title	Hourly Cost (*)	Hours (**) Total	Total Cost		Hours		Title	Hours	
Wisc. El. Eng.	$ 89.71	4325	$ 388,000	****Split part with correlator	2475	98.19%	U_Eng_EL_Wisc	2521	
Wisc. FW Eng. CERN	$ 57.10	5079	$ 290,000	*****Scale Ph.1 Stage-2, Correl Split	5294	98.03%	U_Eng_FW_Wisc	5400	
Wisc. FW. Consult	$ 65.74	167	$ 11,000						Note: Summed into above
Wisc. FW. Eng.	$ 44.29	5689	$ 252,000						Note: Summed into above
Wisc. On Site FW Eng. CERN	$ 50.30	1948	$ 98,000						Note: Summed into above
Wisc. SW. Eng.	$ 44.29	5689	$ 252,000	Split effort with correlator	2505	100.59%	U_Eng_SW_Wisc	2490	
Wisc. Tech.	$ 42.70	4356	$ 186,000	Split effort with correlator	2404	103.53%	U_Tech_EL_Wisc	2322	
Wisc. Tech. Asst.******	$ 34.77	1841	$ 64,000						Note: Summed into above
			TOTAL		12678	hours (***)		12733	hours (***)

(*) Labor rates shown above were the rates for the Phase-1 Upgrade Project, and are not those for the HL-LHC Proposal

(**) The Phase 1 Project assumed 2008 hours in one FTE year.

(***) The HL-LHC Proposal assumes 1768 hours in one FTE year. Because all labor is calculated in FTE units from Phase-1 actuals, the labor hours for the HL-LHC proposal have been scaled by 1768/2008

(****) For work related to the Calorimeter Trigger, there is a 50-50 split of the enginneering labor for design and prototyping between Calorimeter (402.06.03) and Correlator (402.06.05) Trigger Projects, but this does not include production and testing (30% of engineering) so scaling is ((0.3) +(1/2)(0.7))

(*****)Phase-1 included two different Stages with different Firmware. Only scale the Stage-2 Final System FW (2/3). Adjust for common FW framework between Cal. + Correl. Trig (70%)

(******)Tech Asst. was occasional labor needing training so hours derated by 60%.

WARNING: This is not the calculation of the Labor in the BOE, which was calculated for each task based on Phase-1 experience.

This is a sanity check of the overall hours resulting from this calculation.