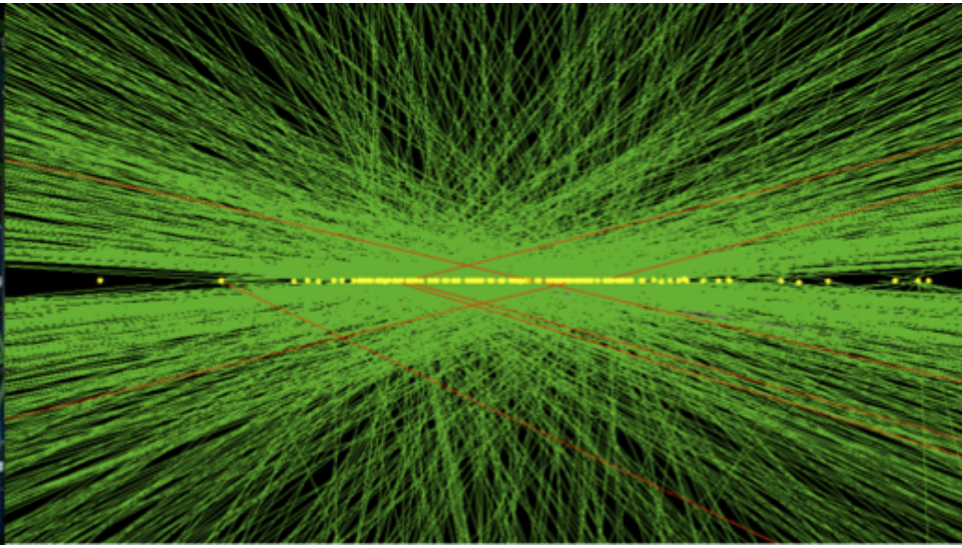
P04 - L2 Overview: MIP Timing Detector - 402.8

Chris Neu, MTD L2 Manager

DOE CD-1 Review

22-24 October 2019



Outline

- Introduction and Motivation
- The MIP Timing Detector
  - System Requirements
  - Conceptual Design
  - US Scope and Deliverables
- Project Organization
  - WBS and Organization
  - Resource Optimization and Value Engineering
  - Interfaces
- Technical Progress and Maturity ← Also covered in BO session talks
- Cost, Schedule, Risk ← Covered in Frank's BO session talk
- Response to Previous Reviews
- Plan for CD-2/Preliminary Design ← Covered in David's BO session talk
- ESH&Q
- Breakout Session topics
- Summary

Biographical Sketch

- Chris Neu
  - L2 manager for US MTD
  - Associate Professor, University of Virginia (2008-present)
  - Member of the MTD Steering Group
  - Served as co-convener of the MTD Simulation and Performance group through June 2018
  - Previously served as co-convener in CMS subgroups associated with top-Higgs and top quark physics
  - Formerly a member of CDF working on the L2 trigger upgrade for Run IIb, XFT track trigger for Run II, CMU/P upgrade, COT wire planes
  - Physics interests: top-Higgs coupling, Higgs characterization, top quark measurements, dark matter

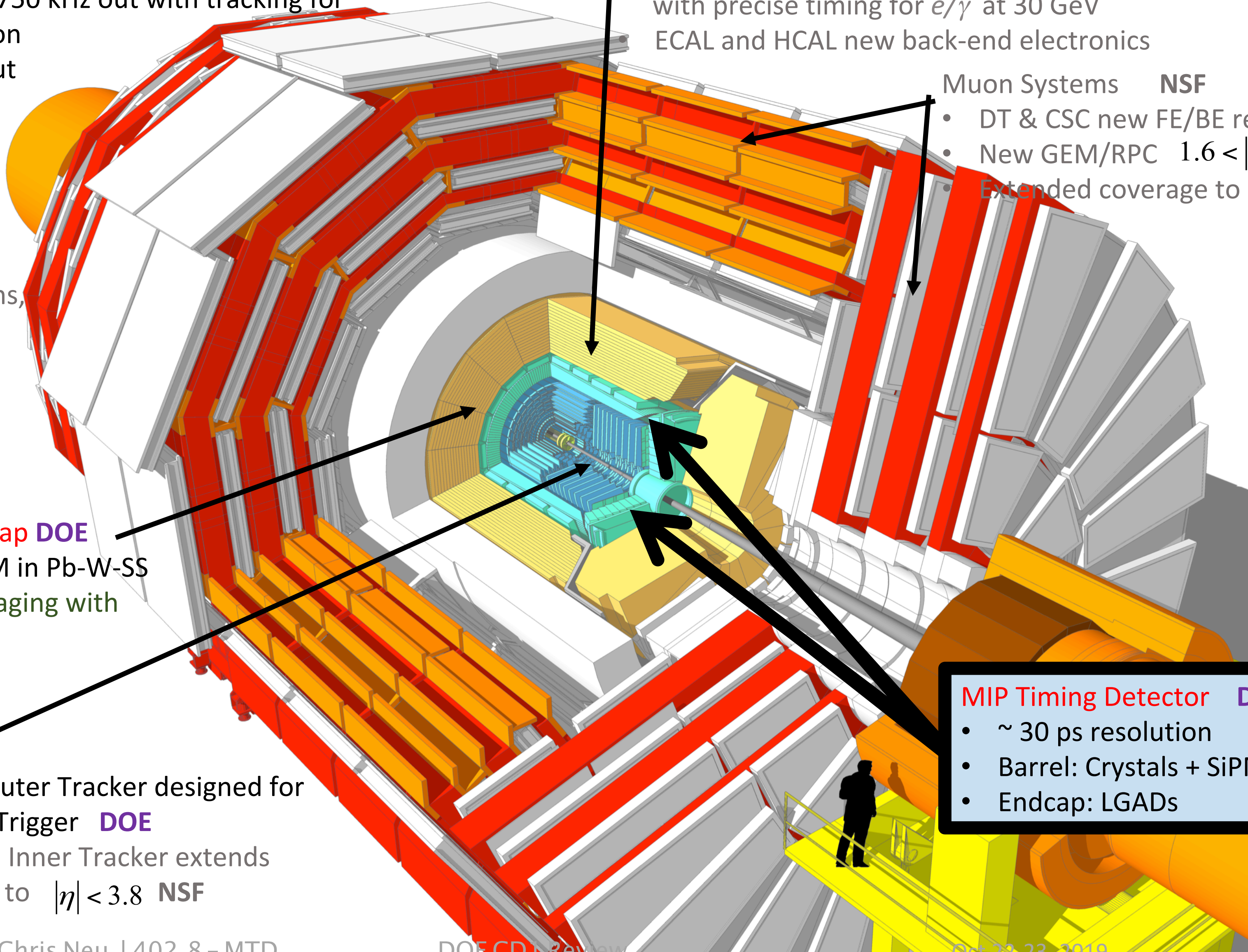
CMS Upgrade Scope

L1 Trigger/HLT/DAQ **NSF** and **DOE**
- L1 40 MHz in/750 kHz out with tracking for PF-like selection
- HLT 7.5 kHz out

Barrel Calorimeters **NSF**
- ECAL single crystal granularity in L1 Trigger with precise timing for e/γ at 30 GeV
- ECAL and HCAL new back-end electronics

Muon Systems **NSF**
- DT & CSC new FE/BE readout
- New GEM/RPC $1.6 < |\eta| < 2.4$
- Extended coverage to $|\eta| < 3.0$

Beam Radiation and Luminosity, Common Systems, Infrastructure

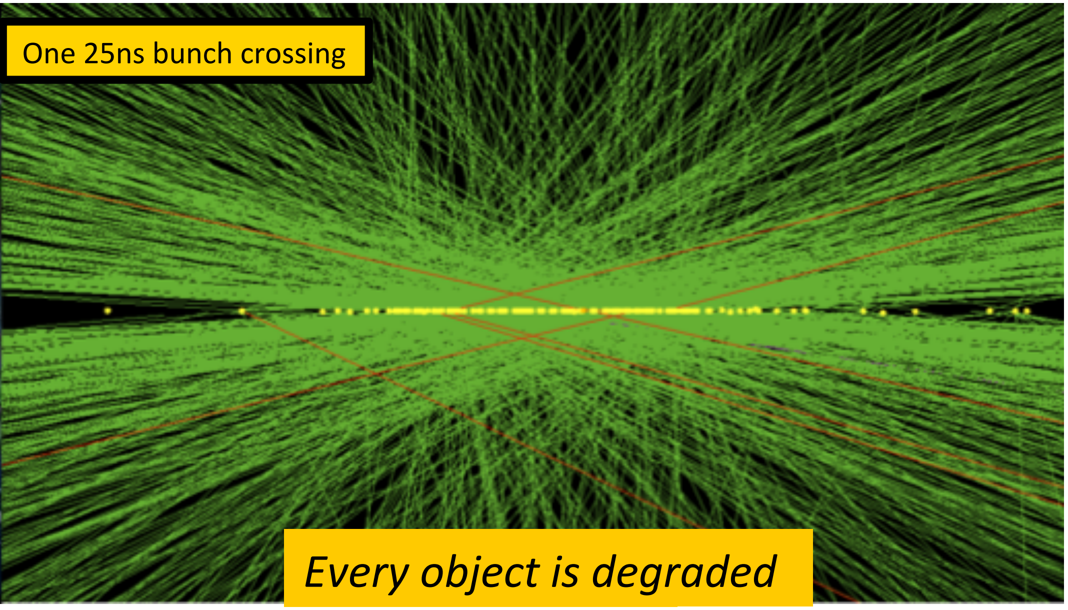


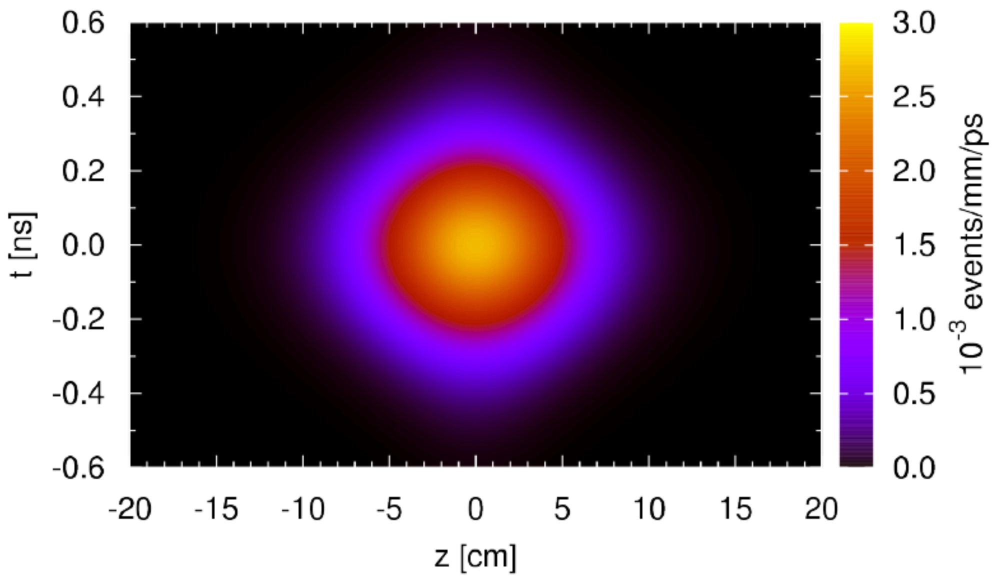
Calorimeter Endcap **DOE**
- Si, Scint + SiPM in Pb-W-SS
- 3D shower imaging with precise timing

MIP Timing Detector **DOE**
- ~ 30 ps resolution
- Barrel: Crystals + SiPMs
- Endcap: LGADs

Tracker
- Si Strip Outer Tracker designed for L1 Track Trigger **DOE**
- Pixelated Inner Tracker extends coverage to $|\eta| < 3.8$ **NSF**

The Challenge of the HL-LHC era



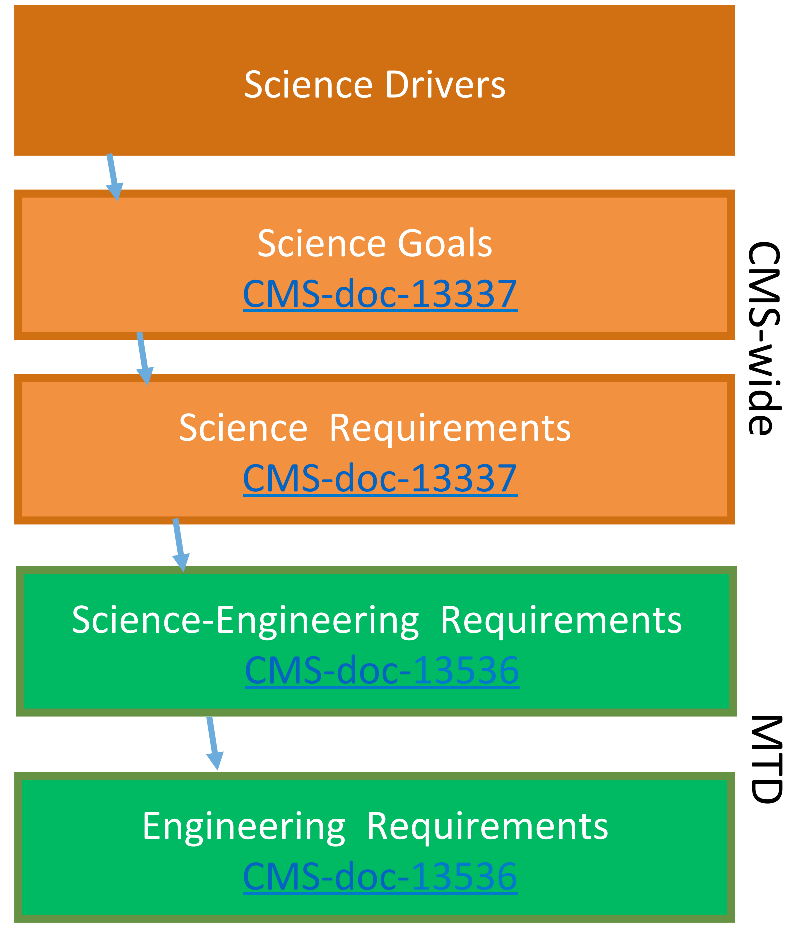


- Dealing with the effects of pileup interactions will be a major challenge of the HL-LHC era
- Although PU interactions significantly overlap in space, they are **more separable in space + time.**
- Imagine separating the 25ns beam crossing into consecutive time slices
  - **Each exposure has far fewer vertices** than when integrating over an event's complete time profile.
- Per-particle timing provided by the **MIP Timing Detector (MTD)** allows 4D track and vertex reconstruction
  - PU reduced in each time slice
  - Every object is improved
  - **Significant benefit to CMS physics program**

Charge #2

Science Flowdown

- Start from **Science Drivers** for U.S. particle physics from P5
- Science Drivers inform **Science Goals**
  - Examples:
    - Precision Higgs coupling measurements
    - Search for BSM Physics
    - Several others
- Science Goals inform **Science Requirements**
  - Primary Vertex reconstruction
  - Pileup mitigation
  - b-tag efficiency and purity
  - MET resolution
  - etc
- Science Requirements inform **MTD Science-Engineering Requirements**
  - These define the MTD design principles
- MTD Science-Engineering Requirements inform **MTD Engineering Requirements**
  - These define MTD design specifications



Charge #2

MTD Science Engineering Requirements

Title	ID	Requirement	Rationale
MIP Timing	01	The MTD shall provide time-of-arrival information for minimum ionizing particles (MIP) with **resolution of <60ps** while accumulating up to 3000/fb in nominal fluence, sufficient to disambiguate spatially-coincident vertices	Improve the particle-flow performance at high pileup (PU) to a level comparable to the Phase-1 CMS detector. Extend the CMS physics reach in a broad class of new physics searches with long-lived particles
Material budget	02	MTD shall have **low material density** (<0.4X0 and <0.2X0 in the barrel and endcap regions, respectively) to reduce multiple scattering and to avoid EM showers ahead of calorimetry	Energy measurements are performed by the calorimeters, and therefore particle energy losses and changes in their trajectory before calorimeter surface must be minimized.
Reliability and maintainability	03	The MTD shall operate within the CMS detector for **a minimum of 10 years** within the access and maintenance constraints of CMS	Barrel section of the MTD will be installed within the tracker support tube (TST), which will be inaccessible for repairs once installed. The endcap section will be accessible for repairs during extended technical stops and long shutdowns.
Integration	04	The MTD **shall fit within the envelope and parameters** to conform to in situ CMS detector and other HL-LHC systems under concurrent development.	The overall geometric envelope and certain other infrastructure and services are not subject to upgrade, and the MTD must maintain compatibility with these pre-existing constraints.
Data Throughput	05	The MTD data **readout shall have sufficient bandwidth** (up to 10.24 Gb/s in the barrel, and 5.12 Gb/s in the endcap) to accommodate the expected hit rates for up to 200 PU	Maintain bandwidth compatibility with the backend electronics constraints.
Occupancy	06	The MTD **shall not exceed 10% occupancy per readout channel** at 200 PU interactions	Multiple hits per channel would cause an ambiguous assignment of the time information per charged particle, and would also distort the pulse shape which would complicate time-stamp reconstruction.
Coverage	07	MTD shall **cover the range |eta|<3.0** in order to provide precision timing information in the region covered by the precision calorimetry, muons, and tracker	Improve charged lepton isolation measurements, b-tag and PU jet identification efficiencies, and MET resolution in the regions of highest sensitivity for Higgs boson measurements and new physics searches.

CMS-doc-13536

MTD Engineering Requirements

Charge #2

- The MTD Science-Engineering Requirements inform the MTD Engineering Requirements
  - MTD has 37 Engineering Requirements in total
  - Categorized under different headings: *General engineering*, *Logistics*, *Cooling*, *Sensor*, *Integration*, *Electronics*, *ES&H*, *Modules & Components*
  - Example:
    - MTD Sci-Eng Requirement 01 informs MTD Engineering Requirement 001:

MTD Science Engineering Requirement 01:

Title	ID	Type	Requirement	Rationale	Parents
MIP timing	MTD-sci-engr-01	requirement	The MTD shall provide time-of-arrival information for minimum ionizing particles (MIP) with resolution of <60ps while accumulating up to 3000/fb in nominal fluence, sufficient to disambiguate spatially-coincident vertices	Improve the particle-flow performance at high pileup (PU) to a level comparable to the Phase-1 CMS detector. Extend the CMS physics reach in a broad class of new physics searches with long-lived particles	sci-req-7, sci-req-8,sci-req-9,sci-req-10,sci-req-11,sci-req-12,sci-req-13,sci-req-14

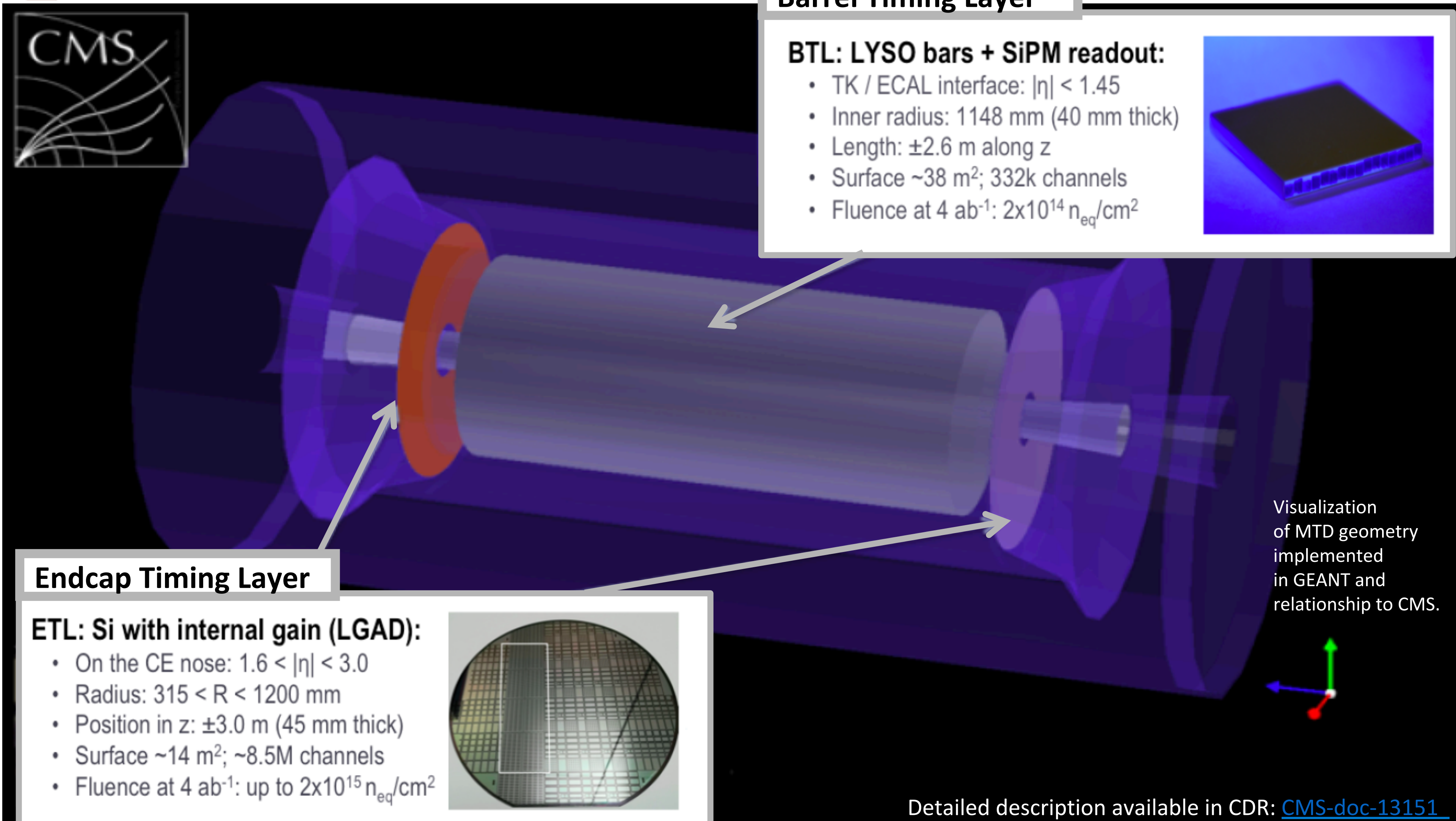
MTD Engineering Requirement 001:

Title	ID	Type	Requirement Text	Rationale/Notes	Parents	QA Activities	QC Activities
Survive Radiation	MTD-engr-001	requirement	The MTD must be able to operate efficiently up to an integrated luminosity of 4000 fb−1, without any maintenance intervention for the barrel detector, whereas the endcap detector may be accessible during the HL-LHC era.	The MTD is expected to experience in the highest radiation region of ionizing radiation dose of up to 38 kGy and a hadron fluence of up to 3x10^14 neq/cm^2 in the barrel, and 1,035 kGy and 3x10^15 neq/cm2 in the endcap at the end of lifetime.	MTD-sci-engr-01, MTD-sci-engr-02, MTD-sci-engr-06	MT-QA-001, 005	MT-QC-001, 005

- All details are ready for inspection in [CMS-doc-13536]
- **Summary**: Requirements are well defined and verifiable via QA/QC activities

Charge #2

MTD Conceptual Design



Barrel Timing Layer

BTL: LYSO bars + SiPM readout:
- TK / ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: $2 \times 10^{14}\ n_{eq}/cm^2$

Endcap Timing Layer

ETL: Si with internal gain (LGAD):
- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to $2 \times 10^{15}\ n_{eq}/cm^2$

Visualization of MTD geometry implemented in GEANT and relationship to CMS.

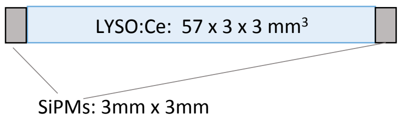
Detailed description available in CDR: CMS-doc-13151

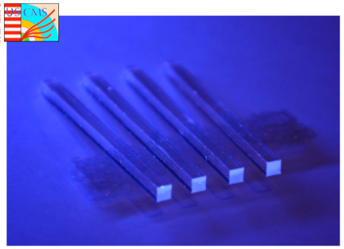
MTD provides precision time measurement for MIPs with σ_t=30-40ps with sufficient radiation tolerance to maintain σ_t<60ps up to 3000/fb.

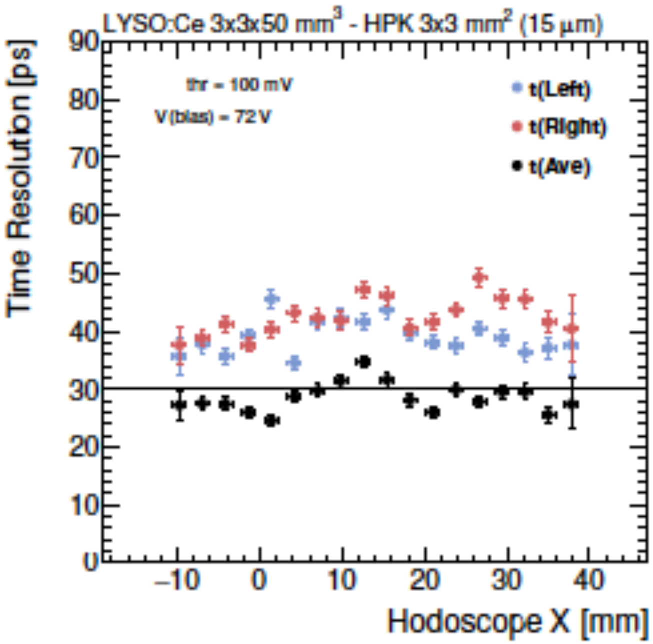
BTL Overview

= USCMS area of activity

Active elements:

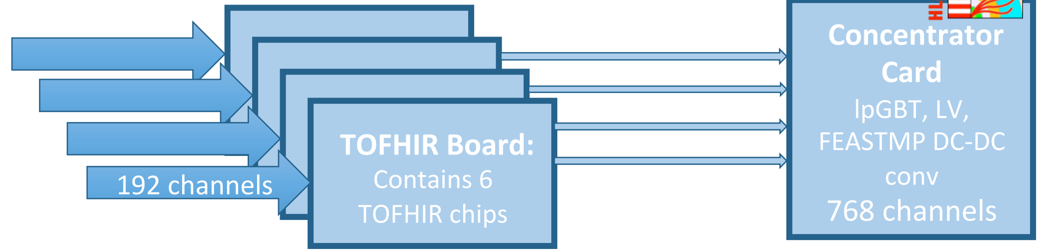






- LYSO:Ce bar glued to SiPMs on each end
  - Fast and bright crystal
  - Radiation tolerant
  - Well-understood commodities

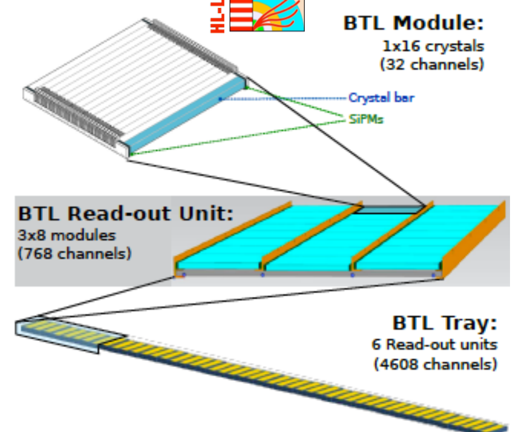
Readout Unit:

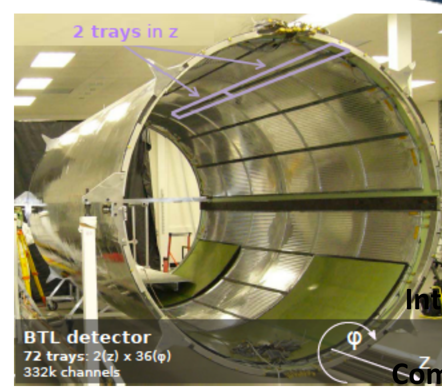


Mechanics and integration:

Construction

- BTL will reside in the Tracker Support Tube (TST)
- Modules and Readout Units are assembled onto aluminum cooling trays
- Trays are a deliverable of the BTL assembly project – sent to CERN for integration
- 332k total channels
  - Compare to 215M for Outer Tracker – relative 0.2% in number of channels



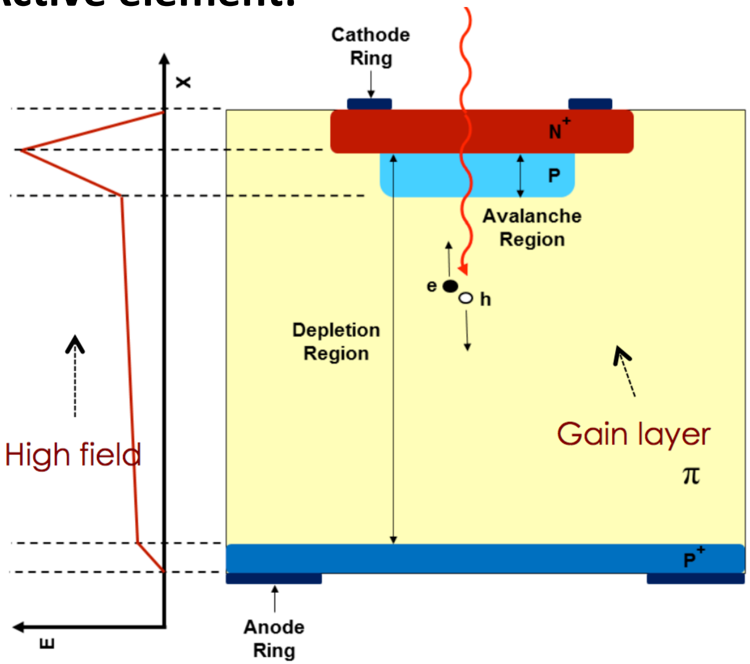


Integration & Commissioning

More in BTL talks in MTD breakout

ETL Overview

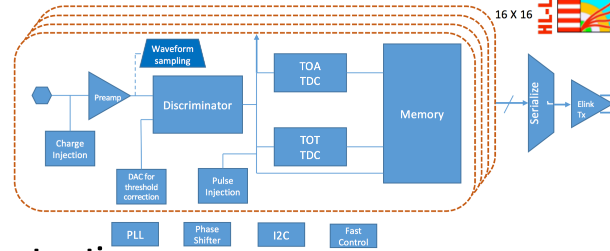
Active element:



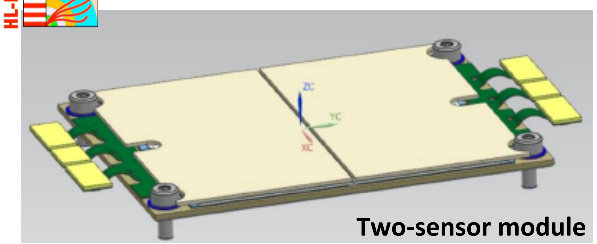
- **"Low-Gain Avalanche Detector" (LGAD)**
  - Large signal, large slew-rate ⇒rapid electrical response
  - More signal in less material ⇒ short drift time, better timing resolution
  - Low gain ⇒ low shot noise, below electronics pedestal

Sensors, ASICs and Modules:

- Each sensor: 2x4 cm^2 array of 512 1.3x1.3 mm^2 pixels
- Module is an sub-assembly of sensor + ASICs
- One or two sensors per module, ~9000 total modules ➔ ~9M pixels
  - Relative 4% in number of channels wrt OT

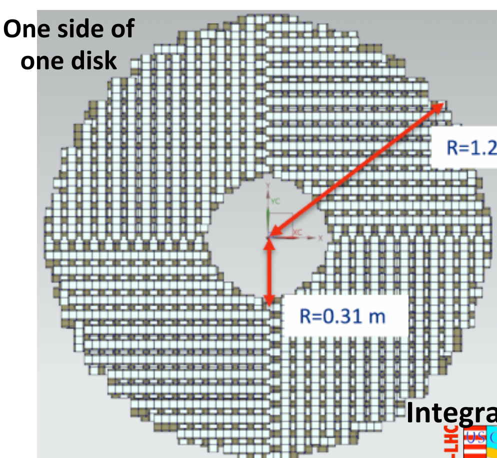


Construction



Mechanics and Integration:

- Two double-sided disks on each endcap
- Each disk has 85% coverage
- Allows two time meas per track
- Stageable, serviceable, maintainable



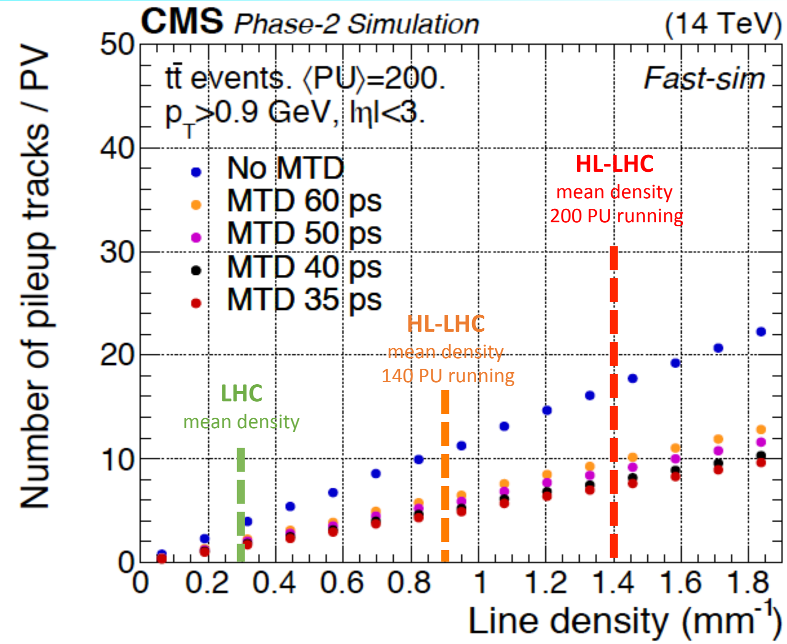
Integration & Commissioning

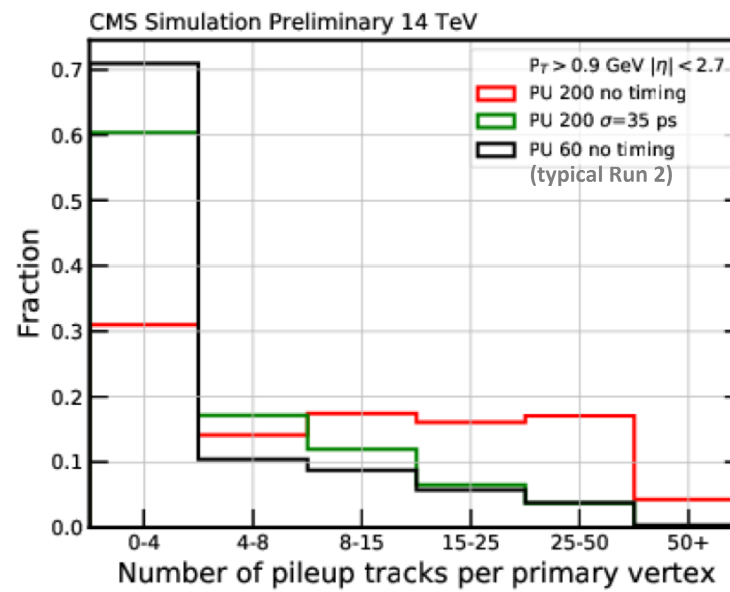
More in ETL talks in MTD breakout

Performance

- Primary mission of the MTD: **pileup mitigation**
- **Time-aware primary vertex reconstruction** reduces incorrect association of tracks from nearby pileup interactions by a factor of 2:
  - Fully offsets the impact of the transition from 140 → 200 PU running
  - Brings per-vertex track purity close to typical current LHC running conditions
- Further, there are **additional profound benefits to:**
  - lifetime tagging
  - long-lived exotica searches
  - particle ID for Heavy Ion physics.
- June 2018 IPR:

  "Overall, the addition of the MTD corresponds to a 20-30% effective luminosity increase for CMS. The physics case for the MTD detector is very strong."
- We do not discuss physics performance in this review. See the relevant sections of the CDR.





Charge #3

US-MTD Scope

threshold scope
objective scope

- BTL:
  - Purchase of **18% of the production-era BTL LYSO crystals**.
  - Prototype, pre-production BTL SiPM studies. **Provision of 57% and QC testing of 50% of the production-era SiPMs**.
  - Design and prototyping of the BTL Concentrator Card (CC). **Provision and QC testing of 100% of the production-era CCs** (432 cards plus 10% spares).
  - Lead R&D for BTL assembly and define procedures. **Perform assembly of 45% (60%) of the BTL trays and associated QC testing**, delivery to CERN.
  - **Participation in BTL integration** of trays into the TST and checkout commissioning
- ETL:
  - Design and prototyping of the ETL FE ASIC. **Provision and QC testing of 50% of the production-era ASICs.**
  - Lead R&D and prototyping for assembly procedures. **Perform assembly of 38% (50%) of the ETL modules and associated QC testing**, delivery to CERN
  - **Participation in ETL integration** of modules onto the ETL support structure, installation on the endcap and checkout commissioning

Draft KPPs

Charge #3,7

CMS-doc-13237

Threshold KPP	Objective KPP
T-KPP-TL-1: TIMING LAYER CONSTRUCTION	O-KPP-TL-1: TIMING LAYER CONSTRUCTION AND INSTALLATION
The project shall construct and qualify concentrator cards (CCs) and trays of modules+readout units (RUs) for the BTL. The project shall deliver to CERN 100% of the CCs and approximately 45% of the total trays needed for the BTL. In addition, the project shall design the front-end ASIC and construct and qualify modules for the ETL. The project shall deliver to CERN 50% of the ASICs and assemble 38% of the modules needed for the ETL. BTL and ETL component performance will match the specification of production prototypes, which shall be demonstrated in cosmic ray, source, and/or test beam exposures to be capable of measuring the arrival time of minimum-ionizing particles with a resolution corresponding to < 60 ps per track.	The project shall construct and qualify concentrator cards (CCs) and trays of modules+readout units (RUs) for the BTL. The project shall deliver to CERN 100% of the CCs and approximately 60% of the total trays needed for the BTL. In addition, the project shall design the front-end ASIC and construct and qualify modules for the ETL. The project shall deliver to CERN 50% of the ASICs and assemble 50% of the modules needed for the ETL. BTL and ETL component performance will match the specification of production prototypes, which shall be demonstrated in cosmic ray, source, and/or test beam exposures to be capable of measuring the arrival time of minimum-ionizing particles with a resolution corresponding to < 60 ps per track. The project shall participate in the integration of the BTL trays and ETL modules into the MTD detector at CERN . The project shall additionally participate in the installation, testing and calibration of the detector.

- Recent updates:
  - Consolidated KPPs to combine BTL and ETL
  - Generated scope contingency by moving 25% of the BTL and ETL Assembly to objective scope
- This was done pursuant to addressing recommendation R12 from the Director's Review in March, 2019:

  "R12: Before CD-1 IPR, reassess the number and definition of the KPPs and move threshold KPP scope to objective KPP scope to generate scope contingency."

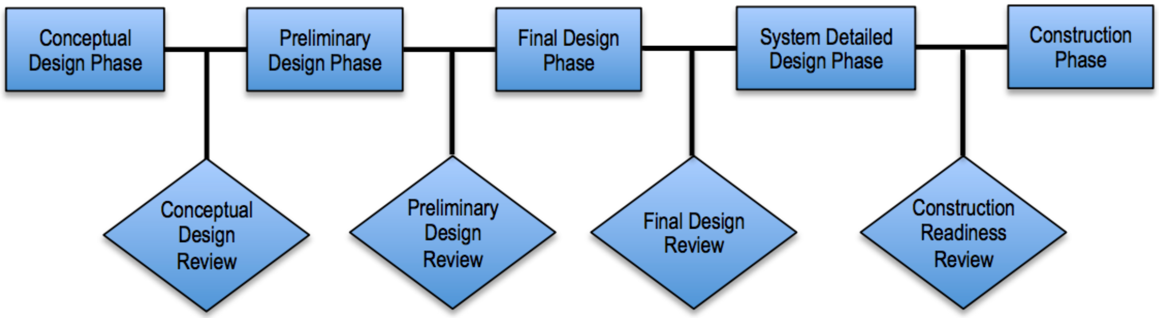
Technical Progress Since June, 2018 IPR

- Significant progress made on all technical fronts since June 2018 IPR. Highlights most relevant to US scope:
  - Form factor for BTL LYSO crystal and SiPM **implementation optimized for timing performance** within power constraints
  - **Extensive work with two SiPM vendors** to develop high PDE, radiation tolerant devices
  - BTL CC has gone through **two prototyping stages**, now entering integrated system tests
  - BTL module and tray design transitioning from conceptual to **engineering stage**
  - ETL FE ASIC (ETROC) has made considerable progress, going from conceptual stage to having now **submitted two prototypes** with a well-defined plan for transition from prototype to production era
  - Significant evolution in ETL module design, **mechanical prototypes being developed**, and assembly procedure well defined
  - Integration of ETL services with the full CMS defined, **design completed**
- Moreover, since the June, 2018 IPR:
  - US-MTD has been the subject of a Technical Review (Nov, 2018)
  - The international MTD project has written a TDR (public release imminent, more in a moment)

This is just a brief summary.
More in BTL and ETL talks in MTD breakout

MTD Design Maturity

Charge #2,7



This review

MTD at L3 and total:

	L3s							
	BTL		ETL		AVE		BAC	
TL	Mgmt	Tech	Mgmt	Tech	Mgmt	Tech	Mgmt	Tech
Conceptual Design	100%	100%	100%	100%	100%	100%	100%	100%
Preliminary Design	90%	86%	90%	94%	90%	90%	90%	90%
Final Design	38%	21%	38%	21%	38%	21%	38%	21%
Detailed Design	0%	8%	0%	8%	0%	8%	0%	8%
Construction Readiness	8%	10%	8%	10%	8%	10%	8%	10%

All sub-projects:

	BAC Weighted									
	OT		CE		TD		TL		Total	
	Mgmt	Tech	Mgmt	Tech	Mgmt	Tech	Mgmt	Tech	Mgmt	Tech
Conceptual Design	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Preliminary Design	100%	100%	96%	89%	94%	91%	90%	90%	97%	94%
Final Design	99%	91%	47%	34%	100%	67%	38%	21%	72%	59%
Detailed Design	50%	31%	0%	10%	0%	40%	0%	8%	20%	21%
Construction Readiness	26%	30%	9%	11%	75%	50%	8%	10%	22%	22%

- Overall maturity beyond the conceptual design stage
- Preliminary design is well-advanced
- There remain a handful of technical choices that need to be made before the preliminary design is complete
  - Choice related to redundancy and consolidation in the functionality of the BTL CC
  - Implementation choice for the SiPM-FE connection in BTL
  - Pixel footprint of the ETROC2 prototype
  - Final design of the flex connector that provides data readout and power to ETL sensors
- Maturity level similar to other upgrade projects' current values

Int'l MTD Project and US Participation

- MTD received Step 1 approval from the LHCC and CERN RB in March 2018
- TDR was submitted to the LHC Experiments Committee (LHCC) in late March 2019, followed by LHCC and UCG reviews in June and September, respectively
- Culminated in strong endorsement from LHCC and UCG committees, and recommendation to the CERN RB to proceed. **Step 2 approval was agreed in mid-September.**
  - Significant contributions from US-MTD personnel in the development of the project documentation and TDR
- The MTD has **broad international participation**
  - 36 institutes from 13 countries
- The US is a **major technical and intellectual driver** of the international MTD project
  - Personnel from twelve US institutions, significant contributions to hardware R&D and prototyping, performance studies and project management
- Hence **US has large footprint** within MTD project

Belarus
China
Finland
France
Germany
Hungary
Italy
Lithuania
Portugal
Russia
Spain
Switzerland
US

MTD Organization Chart

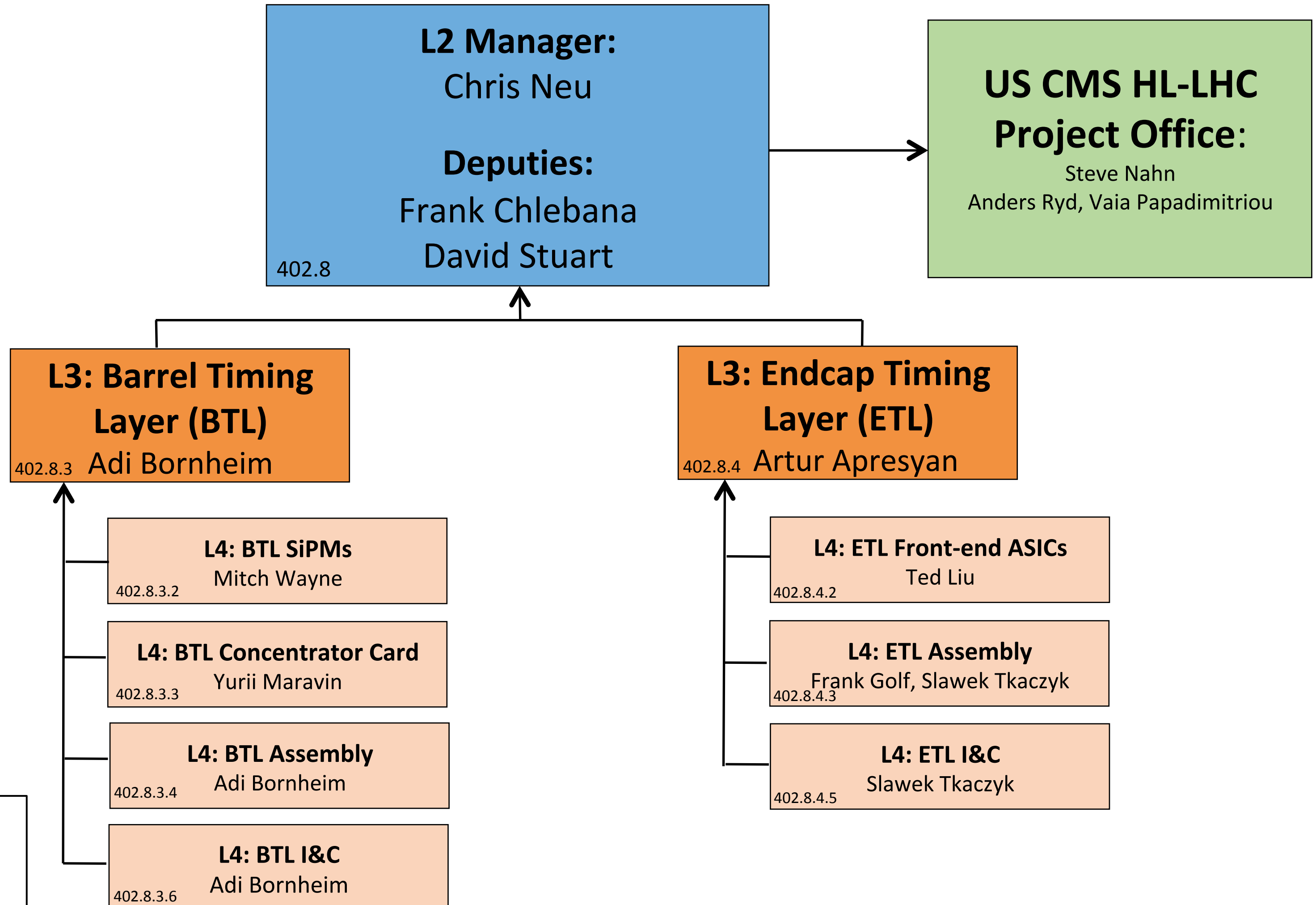
★ : US personnel

- ★ **Steering Committee** incl F. Chlebana, C. Neu
- ★ **Project office** (S. Tkaczyk – link person to CMS Technical Coord.)
- **Institution Board** Chair: L. Bauerdick ★
- **Editorial Board Conference Committee** ★ T.Orimoto, K. Kaadze ★
- **PM**: T. Tabarelli, **Deputy**: J. Butler ★
- **Resource Manager** M. Paganoni
- Finance Board C. Neu ★

- **BTL Technical Manager** A. Bornheim ★
  - **BTL Sensors** M Lucchini ★
  - **BTL Front End** J. Varela, W. Lustermann
  - **BTL Engineering** *A. Bornheim* ★
  - **BTL Validation and system tests** A. Benaglia
- **ETL Technical Manager** ★ D. Stuart
  - **ETL Sensors** N. Cartiglia
  - **ETL Front End** ★ T. Liu
  - **ETL Engineering** ★ A. Apresyan
  - **ETL Validation and system tests** M. Costa, C. Rogan ★
- **Operation and online manager** TBD
  - **DAQ and clock distribution** O. Sahin
  - **L1 Trigger** *I. Ojalvo (*)* ★
  - **Power and HV systems** TBD
  - **Safety and control** TBD
- **Detector Performance Group** ★ L.Gray + P.Meridiani
  - **Simulation and Reconstruction** Casarsa + Tannenwald ★
  - **Test beam analysis and performance** M.Malberti + R.Heller ★
  - **Calibration and monitoring** TBD
  - **UPSG contact and MTD physics case** P. Martinez Ruiz

CMS-doc-13653

US-MTD Organization Chart



Management structure is now in place and fully staffed.

Charge #5

CMS-doc-13678

Charge #5

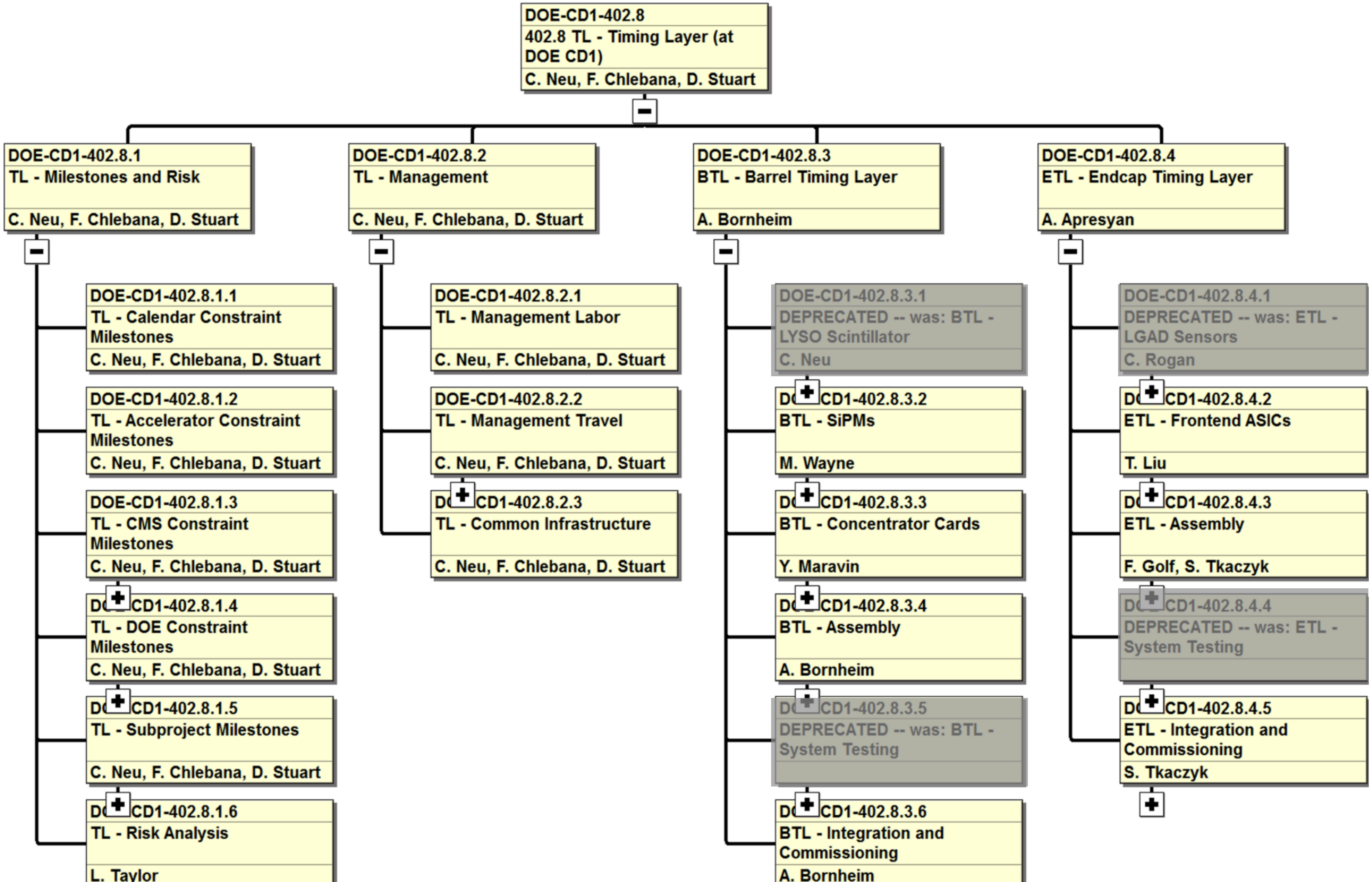
Deputy L2 Managers

- Frank Chlebana
  - Senior Scientist, Fermilab
  - Experience in construction, commissioning, operations, and project planning while on CMS, CDF, and ZEUS
  - Deputy head of the Fermilab CMS Department
  - Deputy L2 manager for the HCAL Phase 1 upgrades
  - HGCal DPG co-convener (ramping down)
  - Former CMS HCAL DPG convener
  - Former head of the DAQ group at CDF
- David Stuart
  - Professor, UCSB
  - Serving as ETL Technical Coordinator in MTD
  - Experience with design, construction, and operation of tracking detectors at AMY, CDF, CMS
  - Track reconstruction and b-tag development
  - Searches for new phenomena at CDF and CMS
  - Convener of CDF exotics and CMS SUSY groups
  - Fast timing R&D for SSC with Charpak group

Frank and David bring considerable technical, project management, and leadership experience to the US-MTD management team.

Work Breakdown Structure

Charge #5,7



- BTL and ETL are independent systems using different technologies on different development timescales, hence this WBS arrangement is a natural choice

Charge #4

US-MTD Expertise Matches Contributions

- US institutes involved in the MTD have expertise and capabilities matched to their area of contribution. Primary examples:
  - **Boston University** has an excellent Electrical Engineering team that has a long history on developing readout and test electronics for HEP experiments
  - **Caltech** has a history in generic R&D in **precision timing applications** in particle detection techniques, as well as institutional expertise in scintillating crystals. Experience in CMS ECAL.
  - **Fermilab** has a unique capability in terms of the **ASIC design group**, allowing for value engineering from development of other chips. ETL module assembly can utilize existing infrastructure at the **SiDet facility**.
  - **Iowa** has an experienced **mechanical engineering team.**
  - **Kansas** has new lab space, with sufficient space to perform QC tests on LGAD modules.
  - **Kansas State** has **an excellent digital electrical engineer** within the department for design of the CC, with experience from similar electronics for mu2e.
  - **Nebraska** has extensive **experience in silicon detector assembly** projects and related infrastructure.
  - **Northeastern** is planning to engage in the backend electronics for the ECAL barrel upgrade, an experience that will be useful in integrated system testing.
  - **Notre Dame** has significant experience on CMS with **SiPM evaluation and qualification**, for instance in the HCAL Phase 1 upgrade.
  - **Princeton** has experienced **mechanical engineering** support on staff able to contribute to the studies for the impact of the BTL on the TST, as well as leadership in **scintillating crystal evaluation**.
  - **UCSB** has significant institutional experience in **building silicon detectors** and the necessary infrastructure for ETL module R&D.
  - **Virginia** has experience in **scintillating crystal R&D**, **radiation tolerant photodetectors**.
- Institutes involved are engaged in areas where they have a history of expertise and current available infrastructure + personnel

Charge #4

US-MTD Assembly Centers

- Assembly centers:
  - US MTD institutions have the expertise, capability, space, human resources and bandwidth to contribute to the ultimate assembly of the MTD
  - BTL:
    - **Caltech and Virginia**, with equal split of US scope
    - Production starts in April 2022
  - ETL:
    - **FNAL and Nebraska**, US scope split 50/50
    - Production starts in October 2023

See backup for site descriptions

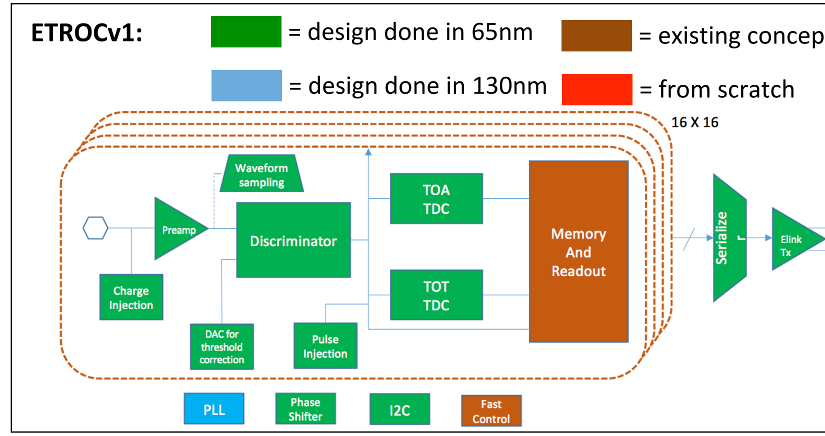
- Site visits and verification:
  - Each assembly center is familiar with the necessary oversight of ongoing construction projects and we understand its importance
  - Our strategy is to have common procedures at each BTL and each ETL assembly center to simplify the assembly portion of the project
  - A detailed schedule for site visits and QA audits is in development

More in TJ Sarlina's talk in Project Management breakout session

Charge #4,7

Value Engineering

- Value engineering is a planned evaluation of a project to identify alternative approaches to providing the needed assets.
- There are many ways that we are leveraging existing infrastructure and experience for cost and schedule efficiency, see CMS-doc-13475
- Examples:
  - Pre-assembly of LYSO crystal matrices and reflective coating will be **performed by the manufacturer** rather than doing the work in-house at US-MTD institutes
  - Assembly procedures for a system similar to that of BTL were **pioneered by CALICE**, an international collaboration working on calorimeter designs.
  - Reuse of **existing ASIC library blocks** is part of the design plan the ETROC ASIC rather than rewriting these blocks from hand.
  - Rather than design our own service chips, many of the MTD detector elements were developed as **common CERN projects**, in industry, or by other CMS projects. These include the low-power GBT transceivers, versatile link drivers, FEAST family of DC-to-DC converters, the e-link protocol, etc.
  - Instead of designing+building a new test stand, we plan to re-use of the **cosmic-ray test stand and DAQ** developed for use in the checkout of mu2e cosmic-ray veto modules being assembled at UVa for BTL module QA



UVa mu2e cosmics teststand

Charge #7

Interfaces

- Interface management is a responsibility shared among management team members
- Often the reporting hierarchy is seamless since several people have roles in both US-MTD and the international MTD project.
- Interfaces exist with other CMS subsystems, common services, with non-US parts of MTD and within US-MTD
- All interfaces have been identified. Organized into 6 categories:
  - General
  - BTL SiPMs
  - BTL CC
  - BTL trays and assembly
  - ETL Readout ASIC
  - ETL modules and assembly
- We have an Interface Control Document, CMS-doc-13536, which has the detailed complete list

Item	Interface Name	Interface Description	External-facing doc/data links	Project-side doc/data Owner	iCMS doc/data Owner	(Y/N)	doc/data link
2.01	SiPM - FE Board Interface	Data and bias voltage connections between the SiPM package and FE board that houses the readout ASICs.	To be added	Arjan Heering	Joao Varela	N	To be added
2.02	SiPM power interface	Power distribution, voltage and current monitoring – interface to Concentrator Card and Power Supply system.	To be added	Arjan Heering	Werner Lusterman	N	To be added
2.03	Mechanical specification for SiPM package	Dimensions, mechanical attachment to the LYSO crystals and to the Readout Unit (including heat removal).	To be added	Mitch Wayne	Adi Bornheim	N	To be added
2.04	SiPM Calibration Procedure	Procedures and software to maintain SiPM calibration	To be added	Yuri Musienko	Adi Bornheim	N	To be added
2.05	SiPM Annealing Procedure	Procedure to anneal SiPMs by raising the operating temperature, within the outer tracker annealing constraints.	To be added	Yuri Musienko	Adi Bornheim	N	To be added

Item	Interface Name	Interface Description	External-facing doc/data link	Project-side doc/data Owner	iCMS doc/data Owner	Stable (Y/N)	Interfacing doc/data link
5.01	ASIC dimensions and pinout	ASIC dimensions, full map and specification of all connections (pinout: location, connection name, connection type, description). List of internal registers (name, number of bits, description)	To be added	Ted Liu	Ted Liu	N	To be added
5.02	ASIC power	Voltage operating range and power up/down sequence (ASIC relative to sensor). Nominal power consumption under different ASIC operating settings.	To be added	Ted Liu	Ted Liu	N	To be added
5.03	Data formats and error codes	Full definition of the data format and all error codes.	To be added	Ted Liu	Ted Liu	N	To be added
5.04	Environment monitoring	List of environment monitoring parameters (temperatures, voltages), method of data access and data format.	To be added	Ted Liu	Ted Liu	N	To be added
5.03	ASIC test stand user guide	Description of ASIC test board, dimensions and location/pinout of all board connectors. Procedures for standard set of tests.	To be added	Ted Liu	Ted Liu	N	To be added

Charge #3

Cost Summary

HL-LHC CMS Upgrades	M&S				Labor					Risk	Total (M$)
Project costs including direct costs, indirect costs, escalation and cost contingency	Direct Cost (M$)	Base Cost (M$)	EU (M$)	M&S (M$)	Contrib (FTE-years)	Costed (FTE-years)	Base Cost (M$)	EU (M$)	Labor (M$)	Risk Contin-gency (M$)	
402.1 PROJECT MANAGEMENT	6.50	6.92	0.63	7.55	1.79	34.04	12.36	0.99	13.35	0.00	20.90
402.2 OUTER TRACKER	20.58	23.84	6.06	29.90	100.59	112.63	19.03	3.83	22.86	3.58	56.34
402.4 ENDCAP CALORIMETER	21.05	23.62	6.03	29.65	83.52	104.59	17.06	4.11	21.17	3.44	54.25
402.6 TRIGGER AND DAQ	4.00	4.45	1.37	5.82	30.26	30.51	4.63	1.07	5.70	1.11	12.63
402.8 TIMING LAYER	6.85	7.85	1.46	9.31	50.78	37.51	4.86	1.77	6.64	1.95	17.90
Total Cost	58.97	66.69	15.54	82.23	266.94	319.28	57.95	11.77	69.72	10.07	162.03
Funding Guidance											162.05

2019-10-07---cost-rollup---CD1-v2.xlsx
Last updated: Lucas Taylor 2019-10-08

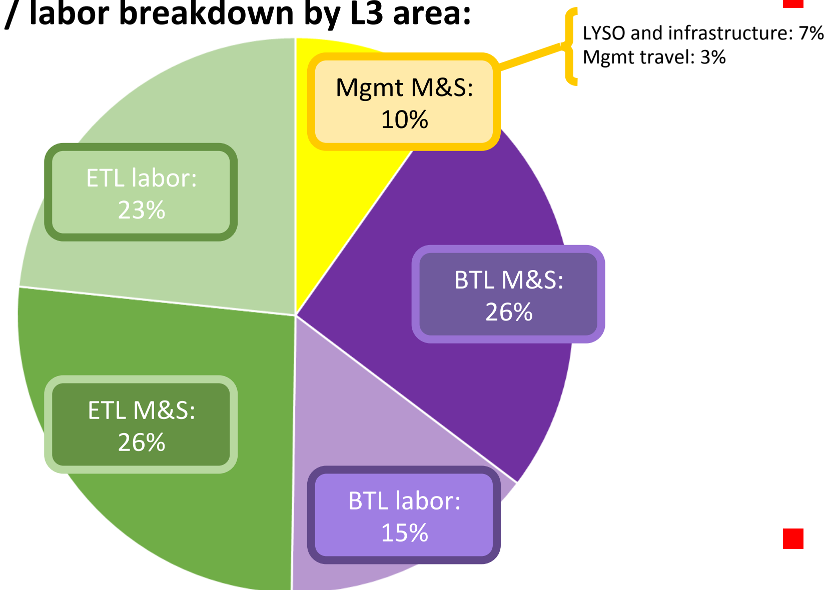
Note: Base Cost = Direct + Indirect + Escalation

- MTD total cost TPC = base + EU + risk = $12.71M + 3.23M + 1.95M = **$17.90M**
  - tKPP + oKPP = $16.47M + 1.43M
- Cost to date is $0.54M, meaning we are 4.2% complete (cost-weighted, wrt base)
  - Contingency on cost-to-go: $5.18M (EU+risk) on $12.17M CTG ➔ 42.5%

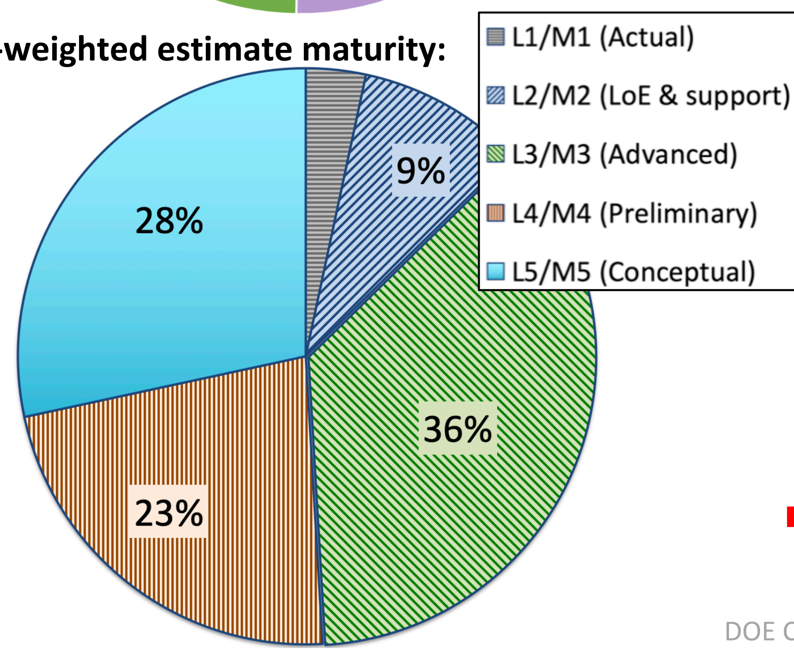
Details of the cost estimate will be discussed in Frank's MTD breakout session talk

Cost and EU Breakdowns

M&S / labor breakdown by L3 area:

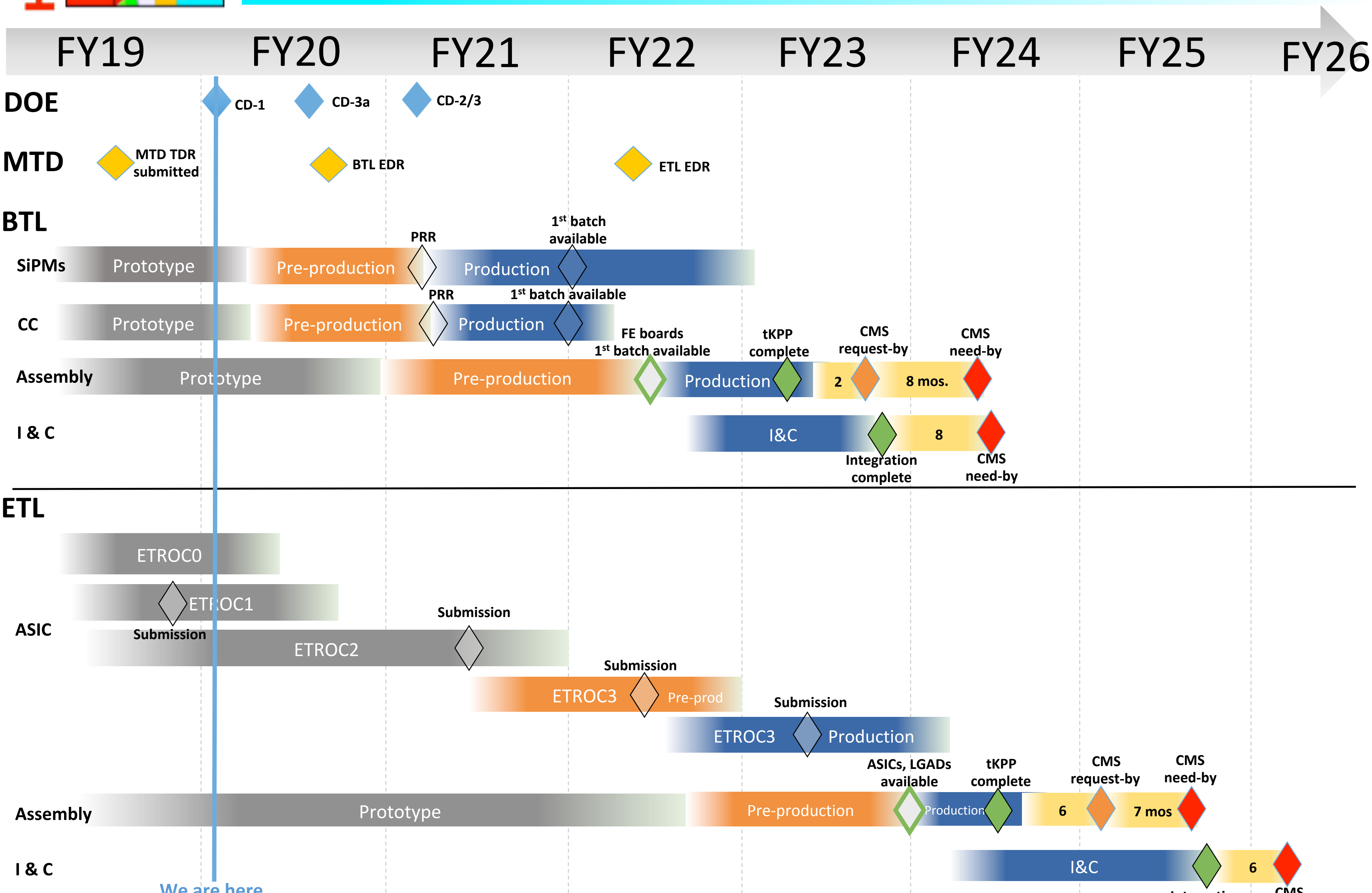


Cost-weighted estimate maturity:

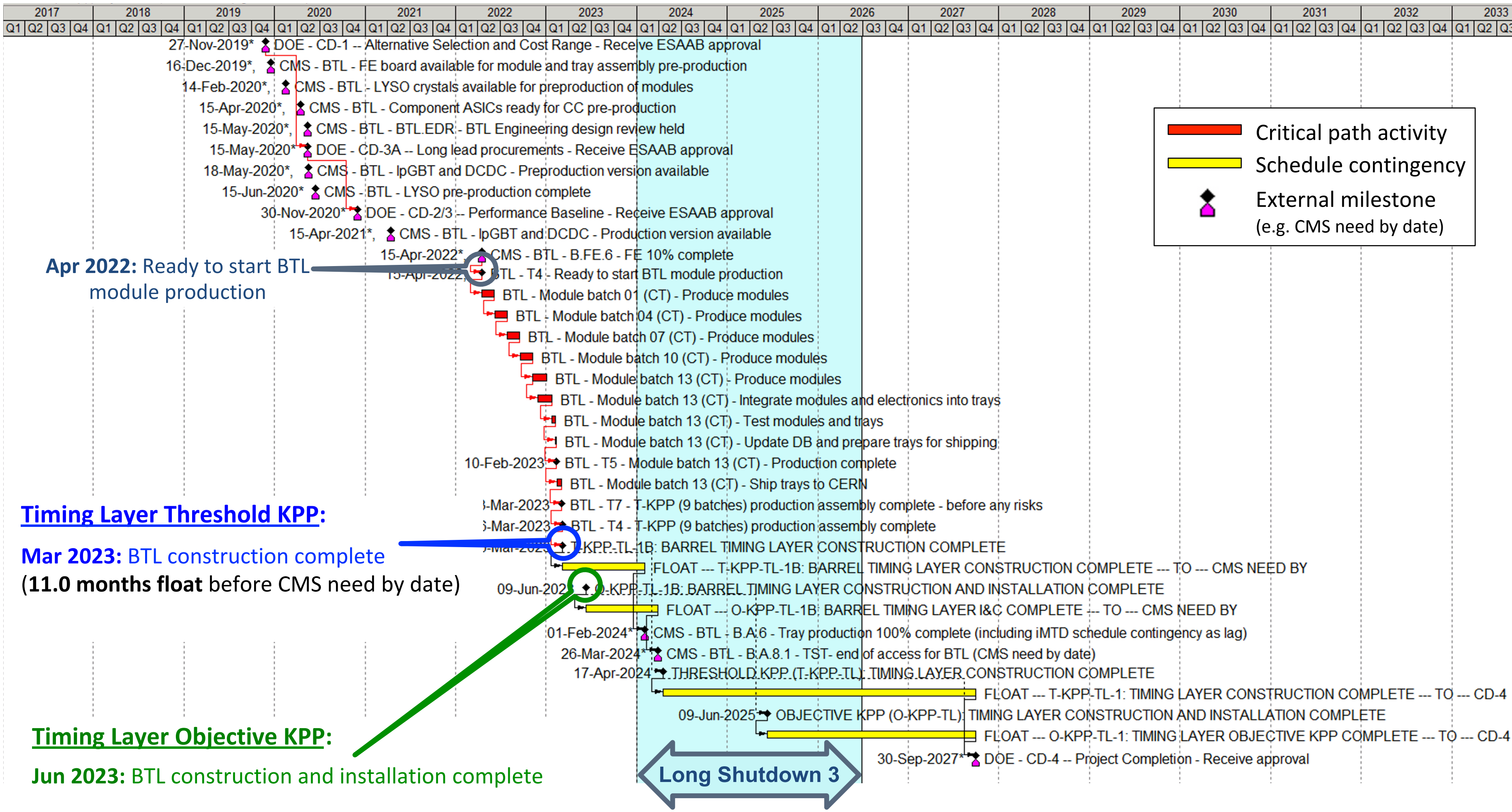


- Base cost: Total = $12.71M
  - By L3 area:
    - 402.8.2 Management: $1.24M (10%)
    - 402.8.3 BTL: $5.14M (41%)
    - 402.8.4 ETL: $6.33M (49%)
  - By type:
    - M&S: $7.85M (62%)
    - Labor: $4.86M (38%)
- M&S driven by large purchases of LYSO, SiPMs, ETROC ASICs
- Management area has an artificially high percentage
  - Contains contributions to common infrastructure provided to the project (319k) and commodity purchase of LYSO (500k)
- EU distribution suitable for preliminary design maturity

US-MTD Schedule



BTL Critical Path and Schedule Contingency



Apr 2022: Ready to start BTL module production

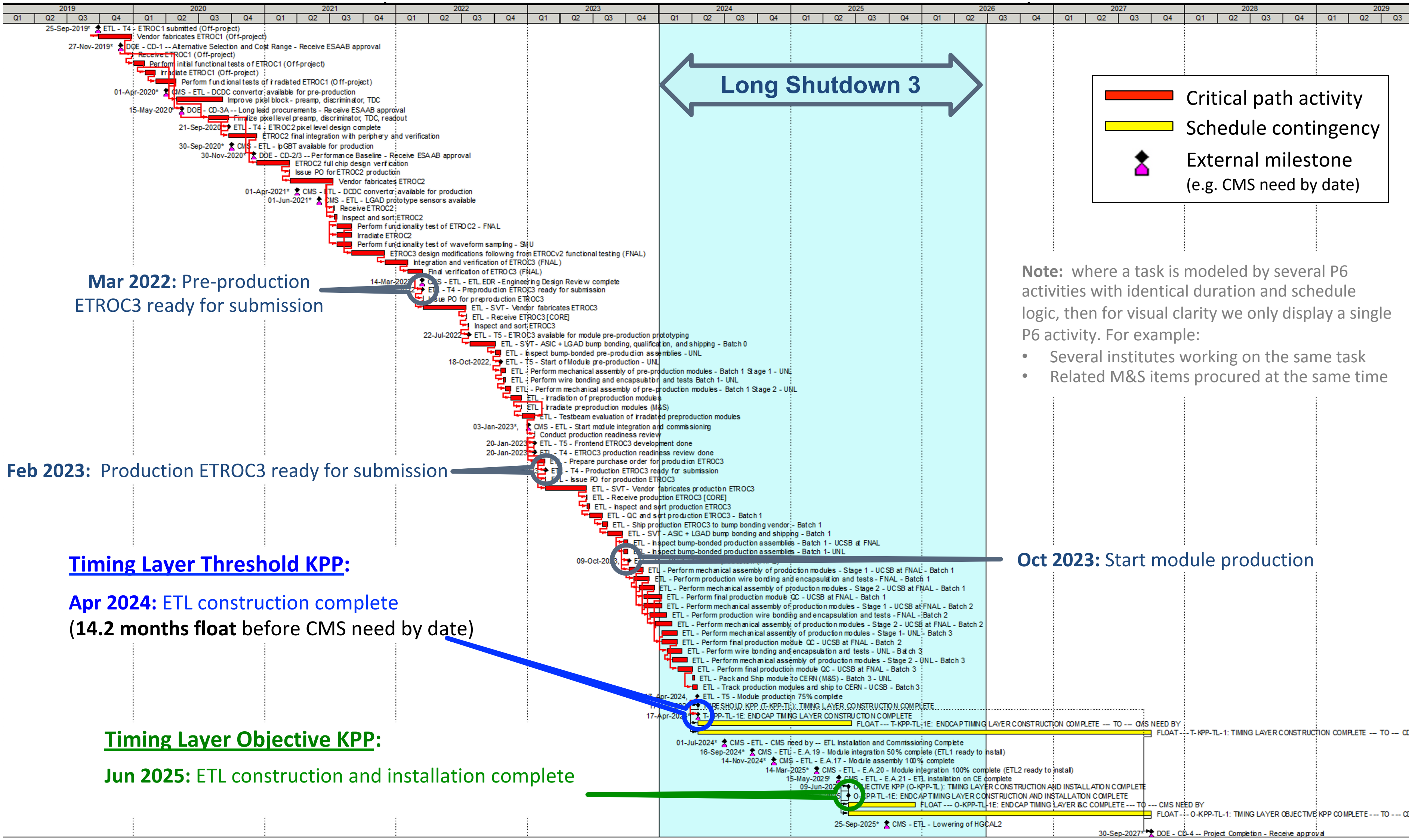
Timing Layer Threshold KPP:

Mar 2023: BTL construction complete
(**11.0 months float** before CMS need by date)

Timing Layer Objective KPP:

Jun 2023: BTL construction and installation complete

ETL Critical Path and Schedule Contingency



Mar 2022: Pre-production ETROC3 ready for submission

Feb 2023: Production ETROC3 ready for submission

Oct 2023: Start module production

Timing Layer Threshold KPP:

Apr 2024: ETL construction complete
(**14.2 months float** before CMS need by date)

Timing Layer Objective KPP:

Jun 2025: ETL construction and installation complete

- Critical path activity
- Schedule contingency
- External milestone (e.g. CMS need by date)

Note: where a task is modeled by several P6 activities with identical duration and schedule logic, then for visual clarity we only display a single P6 activity. For example:

- Several institutes working on the same task
- Related M&S items procured at the same time

Risks

Charge #3

- We have included the assessment of the impact of risks in our project planning to both cost and schedule
  - 25 threats, 1 opportunity
  - Ranks:
    - High: 3
    - Medium: 10
    - Low: 13
  - Subject of a dedicated MTD Risk Workshop in Nov 2018
  - Risks updated in Sept 2019
- Top 3 risks (cost-impact):
  1. Needing an additional prototyping cycle for ETROC ASIC
  2. Addt'l pre-production run for ETROC
  3. Shortfall in scientific labor

RI-ID	Title	Probability	Cost Impact	Schedule Impact	P * Impact (k$)
WBS / Ops Lab Activity : 402.8 TL - Timing Layer (general risks) (2)					
Risk Rank : 2 (Medium) (1)					
RT-402-8-91-D	TL - Shortfall in Timing Layer scientific labor	30 %	0 -- 0 -- 611 k$	0 months	61
Risk Rank : 1 (Low) (1)					
RT-402-8-90-D	TL - Key Timing Layer personnel need to be replaced	25 %	45 -- 135 -- 261 k$	0 -- 0 -- 3 months	37
WBS / Ops Lab Activity : 402.8.3 BTL - Barrel Timing Layer (14)					
Risk Rank : 3 (High) (2)					
RT-402-8-30-D	BTL - Concentrator Card requires significant design changes	50 %	40 -- 135 -- 175 k$	1 -- 3 -- 6 months	58
RT-402-8-07-D	BTL - Concentrator Card delay in external component deliveries	50 %	50 k$	3 -- 6 -- 9 months	25
Risk Rank : 2 (Medium) (4)					
RT-402-8-05-D	BTL - Change in interfaces of tray assembly components	20 %	150 -- 250 -- 350 k$	3 months	50
RT-402-8-46-D	BTL - Problems with sensor gluing facility	50 %	90 k$	1 -- 2 -- 3 months	45
RT-402-8-33-D	BTL - Difficulties procuring LYSO from international suppliers	10 %	100 -- 250 -- 400 k$	3 -- 6 -- 9 months	25
RT-402-8-14-D	BTL - Problems with SiPM vendor	20 %	32 -- 96 -- 128 k$	2 -- 6 -- 8 months	17
Risk Rank : 1 (Low) (8)					
RT-402-8-15-D	BTL - Batch shipment of SiPMs lost in transport	5 %	224 k$	1 months	11
RT-402-8-35-D	BTL - Delays or damage of tray in transport to CERN	5 %	220 k$	1 months	11
RT-402-8-04-D	BTL - LYSO matrices not meeting specifications	10 %	100 k$	1 -- 2 -- 3 months	10
RT-402-8-36-D	BTL - Interface to iCMS changes	20 %	30 k$	1 -- 2 -- 3 months	6
RT-402-8-34-D	BTL - Delay in delivery of components from iCMS	20 %	10 -- 20 -- 30 k$	1 -- 2 -- 3 months	4
RT-402-8-18-D	BTL - Concentrator card production & testing facility problem	20 %	10 k$	0.5 -- 1 -- 2 months	2
RT-402-8-08-D	BTL - Delay in cooling plate delivery	10 %	10 -- 20 -- 30 k$	1 -- 2 -- 3 months	2
RT-402-8-42-D	BTL - Problems with module assembly site	10 %	10 -- 20 -- 30 k$	1 -- 2 -- 3 months	2
WBS / Ops Lab Activity : 402.8.4 ETL - Endcap Timing Layer (10)					
Risk Rank : 3 (High) (1)					
RT-402-8-01-D	ETL - Additional FE ASIC prototype cycle is required	40 %	500 -- 600 -- 700 k$	4 -- 5 -- 6 months	240
Risk Rank : 2 (Medium) (5)					
RT-402-8-03-D	ETL - FE ASIC does not meet specs - needs another pre-prod rur	10 %	874 -- 930 -- 986 k$	6 -- 7.5 -- 9 months	93
RT-402-8-55-D	ETL - Schedule delay in submitting ETROC2	30 %	55 -- 110 -- 165 k$	2 -- 4 -- 6 months	33
RT-402-8-02-D	ETL - ETL module facility unavailable	50 %	20 k$	2 months	10
RT-402-8-10-D	ETL - Sensor quality problem during production	15 %	28 -- 52 -- 109 k$	2 -- 3 -- 6 months	9
RO-402-8-01-D	ETL - Use AltiROC	10 %	-720 k$	-8 months	-72
Risk Rank : 1 (Low) (4)					
RT-402-8-54-D	ETL - Schedule delay in submitting ETROC3	20 %	27.5 -- 55 -- 82.5 k$	1 -- 2 -- 3 months	11
RT-402-8-53-D	ETL - Integration facility at CERN runs out of components	25 %	21 k$	3 months	5
RT-402-8-31-D	ETL - Storage-related degradation of LGADs	10 %	18 k$	3 months	2
RT-402-8-51-D	ETL - Problem with vendor provision of module components	5 %	0 -- 15 -- 30 k$	1 -- 2 -- 3 months	1

We understand the need to keep our risk assessment in sync with evolving designs and plans

Charge #6

ES&H

- MTD included in the HL-LHC CMS Upgrade Preliminary Hazard Awareness Report (CMS-doc-13394)
  - Performed hazard identification for both university and lab sites.
  - Overall there are ten hazards identified with MTD activities. Examples:
    - There is a cryogenics hazard associated with operation of the CO_2 cooling system at FNAL-SiDet
    - Each BTL tray will have a length of 2.5m and mass of ~19kg. Transported in pairs, this implies a mechanical hazard requiring a 2-person protocol for handling and training on proper lifting techniques.
    - There are radiation hazards associated with use of the FNAL testbeam facility and use of radioactive sources in component testing
  - Conclusion: **No unique hazards encountered in MTD**
- All R&D and assembly-era work will be performed at **existing facilities**
  - No new environmental impact studies are needed beyond those that have already been performed for these sites.
- The commodities used in the construction of the MTD – scintillating crystals, SiPMs, silicon sensors, cooling plates, PCBs, electrical components, cables, connectors, power supplies – **are benign and similar or identical to ones found commonly in industry**.
  - The MTD poses no unique environmental risks.

More in TJ Sarlina's talk in Project Management breakout session

Quality Assurance and Quality Control

- The primary goal of Quality Assurance for U.S. CMS deliverables is to ensure that the CMS experiment achieves its science requirements and goals

- For MTD, this means ensuring all components satisfy our Science-Engineering and Engineering requirements, as described earlier.

- The QA work in MTD will draw upon guidance from the overall USCMS HL-LHC Quality Assurance Plan (CMS-doc-13093)
  - Specific QA plans for MTD are outlined for each WBS area in our QAP Appendix
  - An example: BTL SiPMs 402.8.3.2
    - Activity:
      - Measurement and characterization of approximately 175,000 channels of SiPM
    - Requirement:
      - SiPM radiation hardness
    - Measurement:
      - IV curves will be measured for each channel to determine breakdown voltage; capacitance and pulse shape will be measured for 2% of channels; radiation studies and other destructive tests will be done on 1% of channels
    - Training:
      - Training on use of bench test system and data base. Radiation training as needed.

More in C. Wilkinson's talk in Project Management breakout

Responses to Recommendations from Previous Reviews

Charge #8

- We are tracking responses from four reviews:
  - USCMS HL-LHC 2018 June IPR
  - Technical Review, November 2018
  - OPSS Review of Cost, Schedule, Risk Jan-Feb 2019
  - CD-1 Director's Review, March 2019

- Responses are recorded at CMS-doc-13604

- Here I will summarize recommendations from the June, 2018 IPR and March, 2019 DR – followed by responses.
  - All recommendations from every review have been addressed.

Responses to Recommendations from June 2018 IPR

Charge #8

- R37: MIP: ETL—Allocate sufficient expert ASIC design engineering resources to ensure meeting the requirements on the ASIC design schedule.

A redesign of the ETL FE ASIC workplan and schedule has been completed. The engineering resources are understood and mapped to **identified individuals with appropriate expertise and bandwidth** to complete this project in the coming years. An **external review team** has been assembled to focus specifically on the ETL FE ASIC.

✓ Status: Closed 15 February 2019

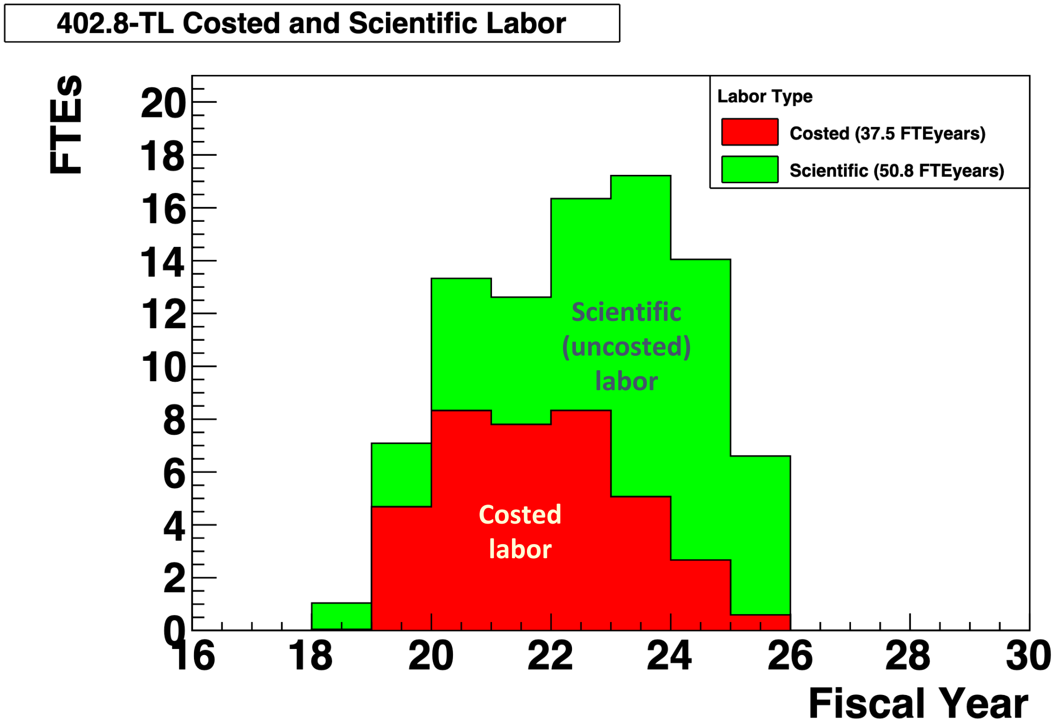
From the Technical Review closeout:
"…the ASICS team is world class, and as capable to succeed as any assembled."

More details on the ETROC project in Ted Liu's talk in the breakout session tomorrow.

Responses to Recommendations from June 2018 IPR

Charge #8

- R36: MIP: BTL/ETL—Reduce reliance on contributed labor and improve its estimate.
  - This has been done. **The number used at the June 2018 IPR was not an estimate of contributed labor.** We now have a bottom-up estimate of our labor needs, both costed and contributed (scientific) labor.
  - The approximate FTE-years of contributed labor is now ~51 FTE-years-- at the time of CD-1 is was ~150.



402.8 MTD	FTE-years
Management	15.0
BTL	11.4
ETL	24.3
Total	**50.7**

Further, removing the management contributions and focusing on sub-projects with assembly projects:

Sub-project	FTE-years
402.2 OT	75.96
402.4 CE	44.12
402.8 MTD	35.7

Responses to Recommendations from June 2018 IPR

- R35: MIP: BTL/ETL—As soon as possible, and no later than Q3 CY 2018 develop the managerial part of the project, i.e. nominate L2/3/4 managers, develop milestones, cost uncertainty and risk/mitigation analyses, and planning packages into work packages.

Management structure L2/L3/L4 was put in place by October 2018. Milestones (internal and external) have been set, and cost uncertainty and risk/mitigation analyses have been presented to DOE at the December 3, 2018 PEMP Notable briefing. The planning packages have been already developed into work packages.

✓ Status: Closed 25 January 2019 (the time of the OPSS review)

Responses to Recommendations from June 2018 IPR

- R50: Cost & Schedule: Prior to seeking ESAAB approval for CD-1, the schedule, WBS Dictionary, risk register, cost estimates, and other relevant CD-1 documents for 402.8 Timing Detector need to be developed to achieve CD-1 quality.

These documents have been developed through the preparations for this Review and we feel they are at CD-1 quality.

✓ Status: Closed 5 March 2019

- R04: MTD: Add a delay risk for each ASIC submission

Risks have been added to the RR to cover the possibility of additional development time being needed for each of ETROC2 and ETROC3. These new risks are different for ETROC2 and 3, given their different technical goals.

These new risks are in addition to an existing risk for the project that an additional development cycle will be needed at pre-production.

Status: Closed 6 June 2019

Charge #7

Documentation for CD-1

- We have a complete set of documentation:
  - **Science goals and requirements**: DocID:13337
  - **Engineering requirements**: DocID:13536
  - **CDR**: DocID:13151 (chapter 6 focuses on MTD)
  - **Interfaces**: DocID:13536
  - **KPPs**: DocID:13237
  - **Scope options**: DocID:13357
  - **QAP**: DocID:13093
  - **BOEs:** all areas available in BOE index
  - **WBS Dictionary**: DocID:13213
  - **Risks:** analysis completed and collection in Risk Register
  - **Project Management Plan:** DocID:13104
  - **Value engineering**: DocID:13475
  - **Estimate of Completeness of Design**: DocID:13417
  - **pHAR:** DocID:13394
- All documents are available from this SharePoint repository

More in V. Papadimitriou's talk in Project Management breakout

Wednesday Breakout Session

- Review talks are designed to address the technical aspects of the MTD project with emphasis on the areas related to US scope
- We will address every aspect of the charge of the review
  - Look for purple call-outs
- The US-MTD management team is available beyond the structured session times to go into specific topics in further detail

Boardroom (WH5SW)

08:00 - 12:30 Breakout: MIP Timing Detector

Please join the meeting by using this link: https://vidyoportal.cern.ch/join/i9XpslMIRQwe

If you want to join by phone, please use +16308405470 or one of the phone numbers listed in the link below: http://information-technology.web.cern.ch/services/fe/howto/users-join-vidyo-meeting-phone

and enter the meeting extension 1010400884 in order to join.

Conveners: Christopher Neu (University of Virginia), Frank Chlebana (Fermilab), David Stuart
Location: Fermilab (Boardroom (WH5SW))

08:00 **B01: BTL Overview** *20'*
Speaker: Dr. Adi Bornheim (Caltech)
Material: Slides

08:20 **B02: In-depth: BTL SiPMs** *20'*
Speakers: Prof. Mitchell Wayne (University of Notre Dame), Mitchell Wayne
Material: Slides

08:40 **B03: In-depth: BTL Concentrator Card** *20'*
Speaker: Yurii Maravin
Material: Slides

09:00 **B04: In-depth: BTL Assembly** *25'*
Speaker: Dr. Adi Bornheim (Caltech)
Material: Slides

09:25 **Coffee** *15'*

09:40 **B05: ETL Overview** *20'*
Speaker: Artur Apresyan (Fermilab)
Material: Slides

10:00 **B06: In-depth: ETROC ASIC** *35'*
Speaker: Dr. Ted Liu (Fermilab)
Material: Slides

10:35 **B07: In-depth: ETL Assembly** *25'*
Speaker: Frank Golf (UCSD)
Material: Slides

11:00 **B08: Cost and schedule overview** *15'*
Speaker: Frank Chlebana (Fermilab)
Material: Slides

11:15 **B09: Milestones demonstrating readiness for CD-2** *15'*
Speaker: David Stuart
Material: Slides

Summary

- The conceptual design of the MTD satisfies the performance requirements needed to achieve the CMS scientific goals in the HL-LHC era.
- The DOE O413.3b documentation is complete and justifies the sub-project’s costs and duration.
- All recommendations from previous reviews have been addressed
- The project team is well-prepared to deliver a credible technical, cost, and schedule baseline.
- MTD is now ready to proceed to CD-1.

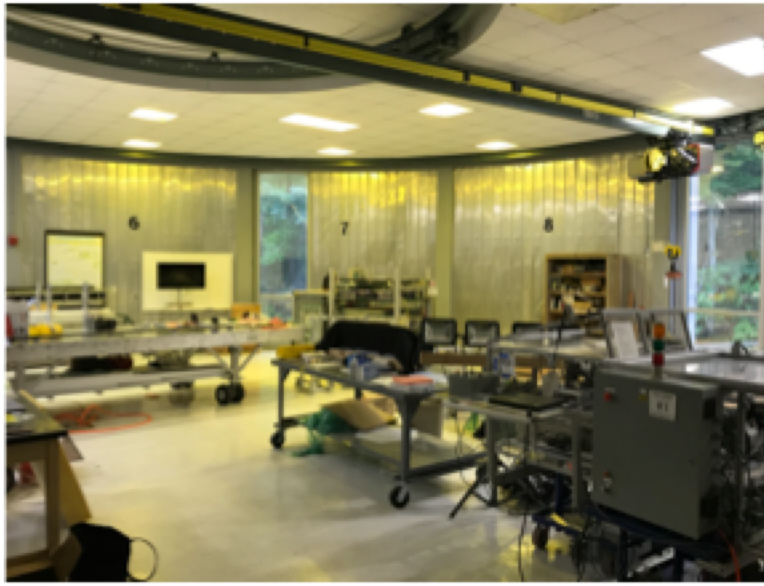
Extra Material

University of Virginia

- High Energy Physics Laboratory
  - Dedicated building just for experimental HEP
- Facilities
  - Assembly room: 2000 ft^2
    - Temperature controlled: 72±1°F
    - Humidity controlled: 50±5%
    - 5-ton overhead crane
  - Electronics lab
    - Used for many projects including CMS HCAL and ECAL Phase 2 electronics upgrades, scintillator and photodetector R&D
  - Clean room capabilities
    - Formerly operated at ISO class 5 level
  - Small mechanical shop for light machining

- People:
  - Three senior faculty
  - One senior scientist, one emeritus
  - Three postdocs
  - Eight PhD students
  - Numerous active undergraduates
  - Electrical technician: **Thomas Anderson**

University of Virginia



Caltech

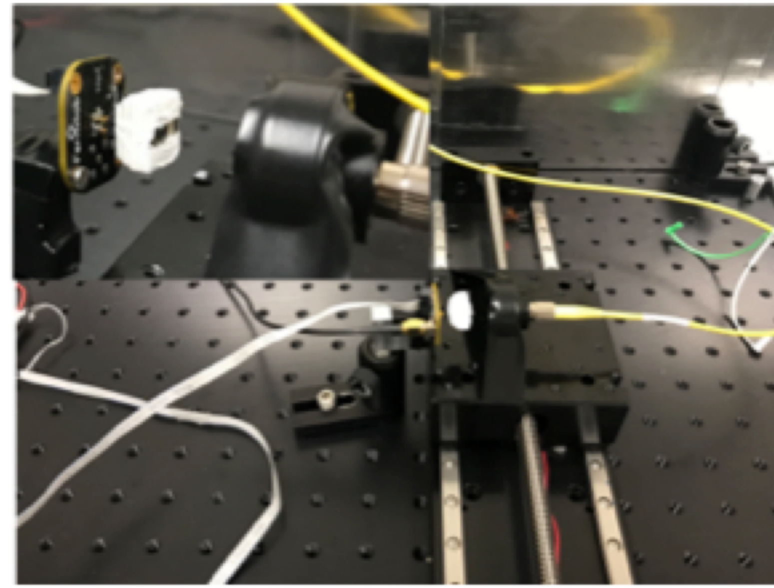
- Facilities: **Lauritsen High Energy Particle Physics Laboratory**
  - Crystal lab (Zhu), Mu2e (Hitlin), NOVA (Patterson), LIGO (vast engineering personnel), AMO/QIS/NP (Hutzler), CMP(Endres)
  - CPT Labs/Assembly Hall (Spiropulu): 1800 ft^2
    - Temperature stability ±1°F, -30 C cold box, optical tables
    - High performance electronics equipment: 25 Gs/s AWG, 50 ps width lasers373 nm (LYSO scintillation light) 407 nm1060 nm, (63 GHz, 160 Gs/s) oscilloscope (6 GHz, 20 Gs/s) oscilloscope, precise x-y stage for BTL module scan, 16 Channel DRS4 digitizer700 MHz, 5Gs/s, Photek 240 MCP-PMT< 10 ps time resolution
  - Clean Rooms Access (ISO-6-7)
  - Mechanical Shops, 3D printing
  - MicroDevices Lab (MDL) at JPL
  - Access: FQNET (FNAL), CERN/ETH labs, Test Beams (FNAL & CERN)

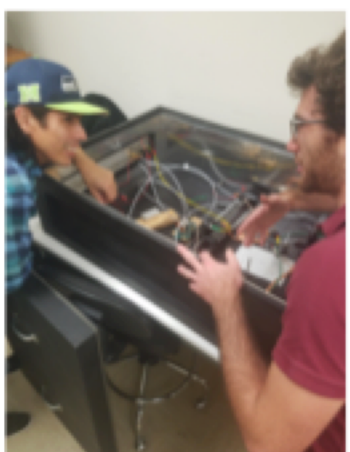
- People:
  - 1 faculty CPT , 1 Faculty ECAL
    - Spiropulu, Newman
  - 3 research faculty/scientists
    - Bornheim, Xie, Zhu
  - 2 postdocs
    - Lu
  - 7 graduate students
  - Many undergraduates
  - Senior EE (Abott), Junior EE (Narvaez), HEP Tech Support (Trevor)

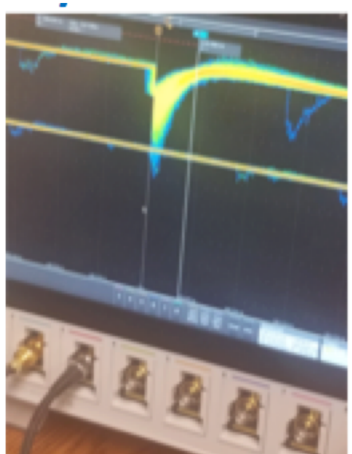
- R&TD/Expertize
  - Sensor R&D , characterization, systems integration, QA, assembly
  - Radiation Damage Studies
  - Scintillator R&D, SiPM readout electronics, TOFPET2 Interface Board, Test Beams

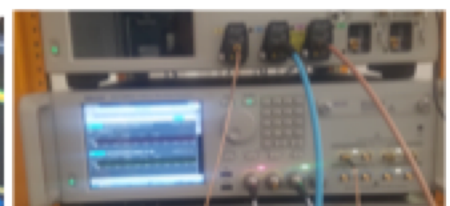
Caltech

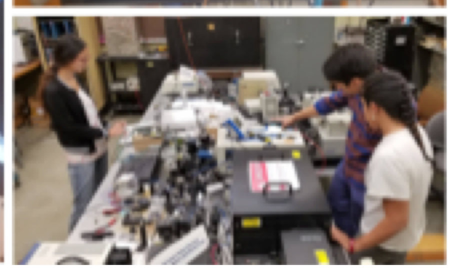
- Facilities:
  - BTL Module assembly:
    - LCE measurements
    - Na22 and beta source measurements
    - Energy and time resolution 373 nm picosecond laser measurements
    - Time resolution DAQ X-Y scan.
- Module cooldown and monitoring being commissioned now
- PCB stuffing: Pick and place robots for module assembly

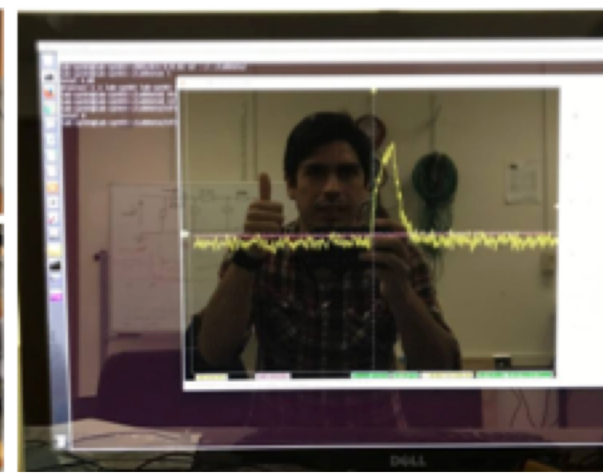




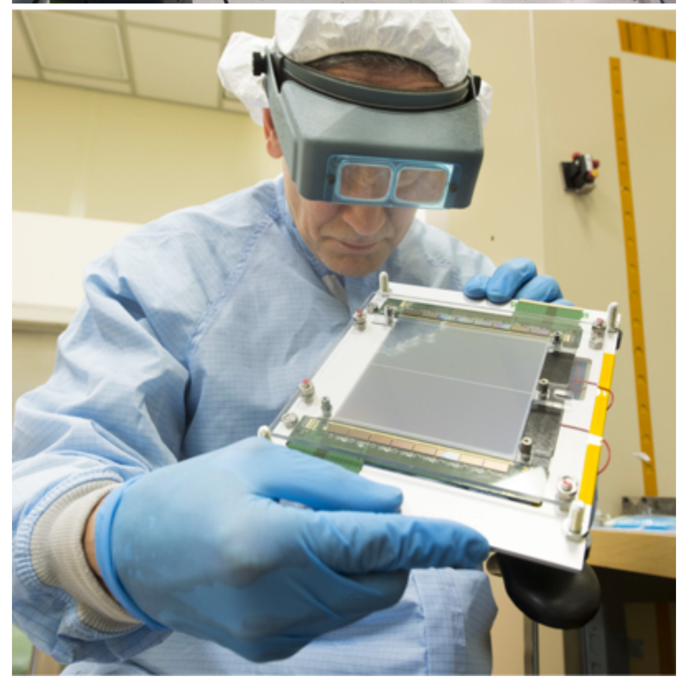






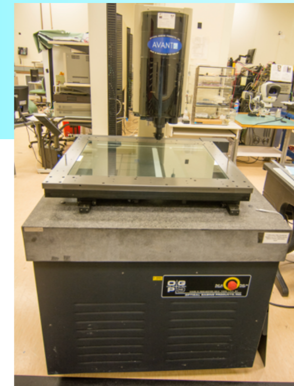


- **Facilities:**
  - Test beam facility
  - Silicon Detector facility
  - Precision Metrology facility
  - Rapid prototyping and Special Materials
  - Scintillator Detector Development
  - ASIC Development Facility
- **Engineering groups:**
  - ASIC development,
  - Cryogenics
  - Data Acquisition
  - Mechanical Engineering
- **MTD People:**
  - 6 scientists
    - Apresyan, Bauerdick, Chlebana, Gray, Liu, Tkaczyk
  - 1 Lederman Fellow
    - Peña
  - 1 Postdoc
    - Heller

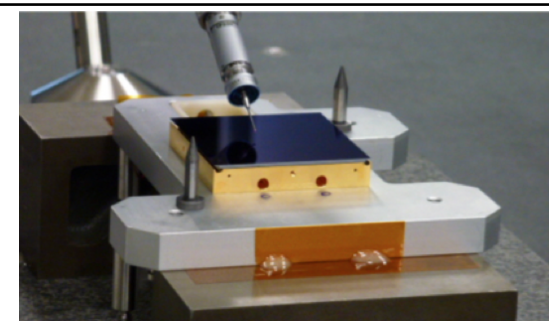


SiDET

- **Precision Metrology:**
  - several CMMs, few μm accuracy
  - Micro/macro assembly and quality control
  - Recent new additions is the large volume CMM
  - Trained operators provided by the facility
- **Quality control on Silicon components (Front-End readout chips and Sensors), debugging of modules**
  - Good optics for visual inspection,
  - Probe stations equipped with testing equipment
  - Fully-automatic micro-bonding machines

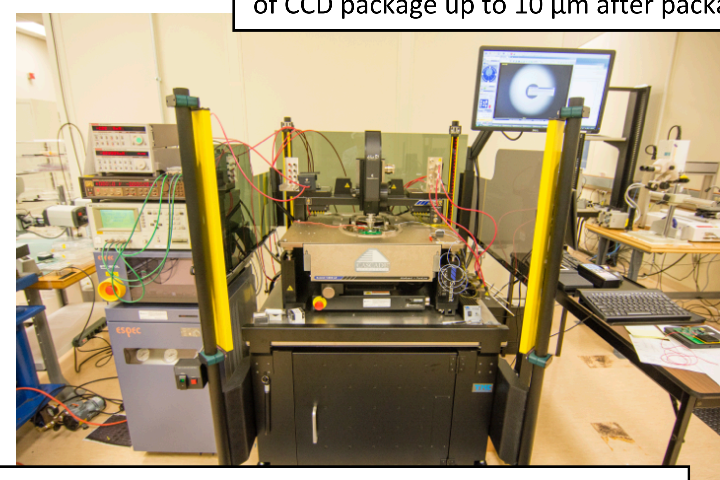


High accuracy Optical Gauging Product (OGP)



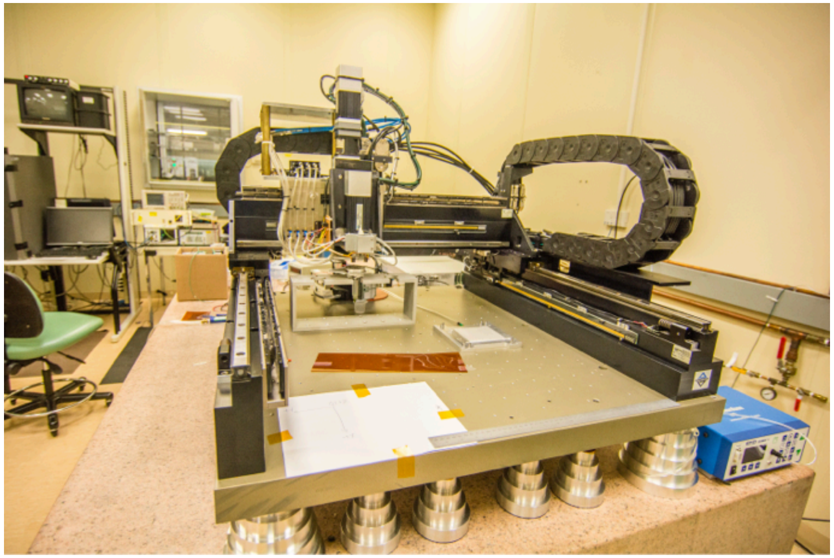
Precision metrology: measuring the flatness of CCD package up to 10 μm after packaging

- Clean rooms: 6000 ft2 class 10k, 240 ft2 class 100
- Wirebonding lab, with deep access capabilities
- Large volume CO_2 cooling plant



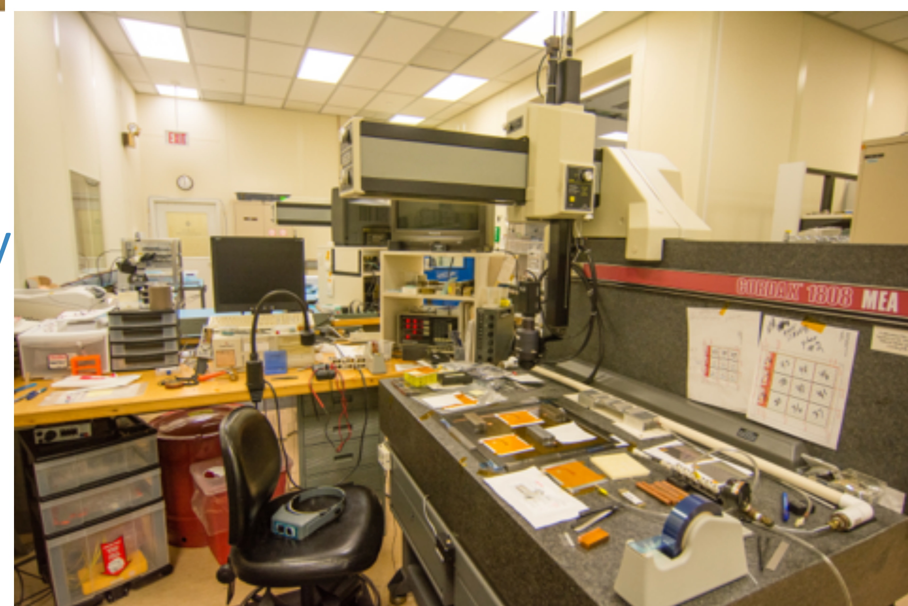
Semi-Automatic probe station CASCADE Summit 12000 AP, 8 inch wafer chuck, capable of cold testing

Assembly/Integration



- Aerotech gantry robot AGS10000
  - High velocity to 3 m/s and high acceleration to 3 g
  - High-power linear brushless servomotors
  - Customizable Z and theta axes

- CMMs and production tables
  - 5 micron repeatability accuracy



University of Nebraska-Lincoln

- Jorgensen Hall
  - Modern building with dedicated space for HEP group
- Facilities
  - HEP laboratory: >2000 ft^2
    - Temperature and humidity controlled
    - Adjacent high bay and loading area
  - Clean room: ~400 ft^2
    - Previously used for Phase-I FPIX module assembly
    - Potential to ~double size if needed
  - Instrument shop
    - Experienced staff, including with prior HEP projects (e.g. Phase-I FPIX)
    - Custom CAD/CAM design, CNC, EDM, lathes, grinding, welding, etc.

- People:
  - Four faculty
  - Three postdocs, hiring fourth
  - Five PhD students
  - Numerous active undergraduates
  - Technicians: Anatoly Mironov, Brian Farleigh
    - Experienced wire bonders, worked on Phase-I FPIX module assembly

University of Nebraska-Lincoln