HL-LHC Detectors

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for the U.S. ATLAS and U.S. CMS Collaborations

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Many thanks to everyone who provided input, in particular H. Evans, J. Kotcher, S. Nahn.

INTRODUCTION

- The HL-LHC, the cornerstone for EF for the next two decades, will advance the investigation of the most fundamental questions in physics **(Why the Electroweak Symmetry breaking occurs? What is the origin of the matter vs. antimatter asymmetry? What is dark matter?).**
  - **EF has been a fundamental pillar of the DOE mission from its inception and one of the main programs in NSF EPP.**
- To fully exploit the discovery potential of the machine, the 2014 P5 recommended the HL-LHC as the highest-priority near-term large project.
  - Recommendation 10: "*Complete the LHC phase-1 upgrades and continue the strong collaboration in the LHC with the phase-2 (HL-LHC) upgrade of the accelerator and both general-purpose experiments (ATLAS and CMS). The LHC upgrades constitute our highest-priority near-term large project*".
- **Snowmass2021 "supports continued strong US participation in the success of the LHC, and the HL-LHC construction, operations, computing and software, and most importantly in the physics research […]".**

Snowmass 2021

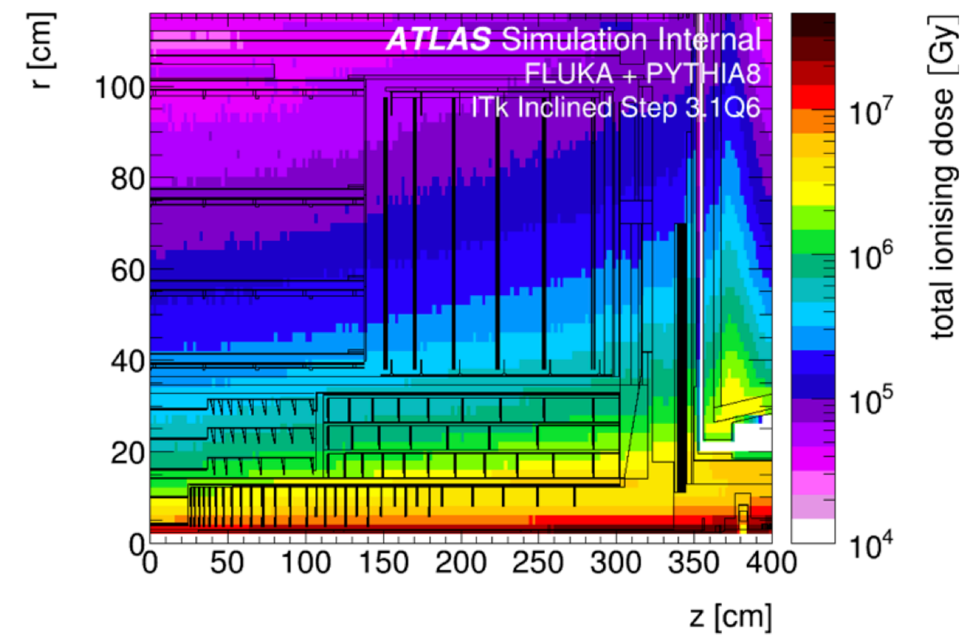
U.S. DEPARTMENT OF ENERGY | Office of Science

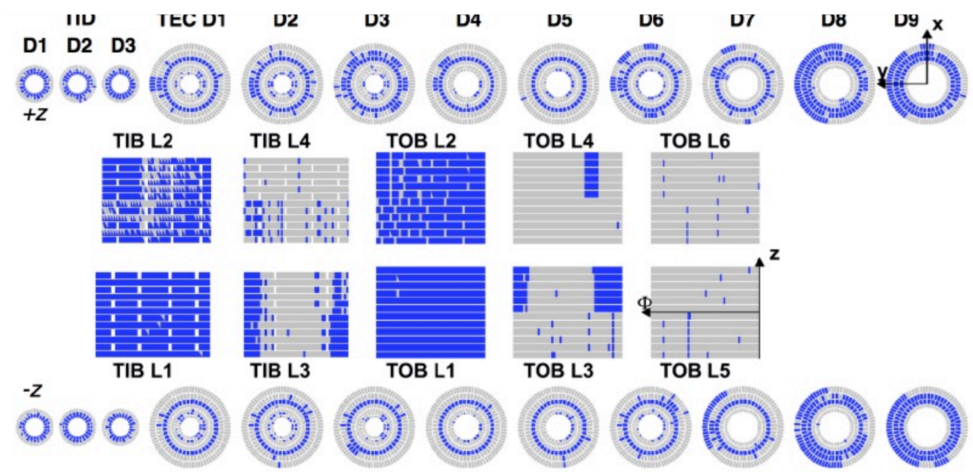
https://science.osti.gov/hep

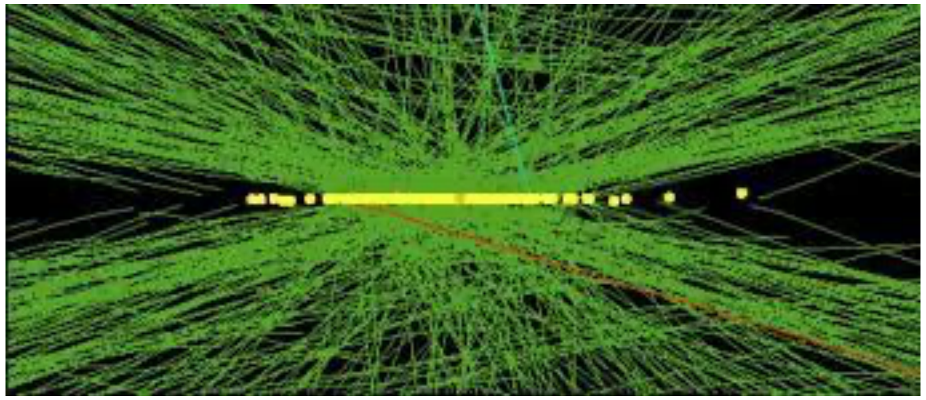
TECHNICAL MOTIVATION FOR DETECTOR UPGRADE

- **The HL-LHC will reach instantaneous luminosities up to 7.5 x nominal and will and operate for a ~ decade.**
- **The current ATLAS and CMS detectors cannot realize the physics opportunities presented by 3000 fb^{-1} of data expected during the HL-LHC era:**
  - **Accumulated radiation dose makes sub-detectors inoperable.**
    - Need for radiation hard sensors and electronics.
  - **High instantaneous luminosities lead to complex events (200 pileup collisions per bunch crossing).**
    - Need for high granularity, 4D information, redundancy.
  - **Rate plus complexity lead to x10 data volume.**
    - Need for faster readout ASICs and next generation TDAQ.

(plus paradigm shift in software and computing)



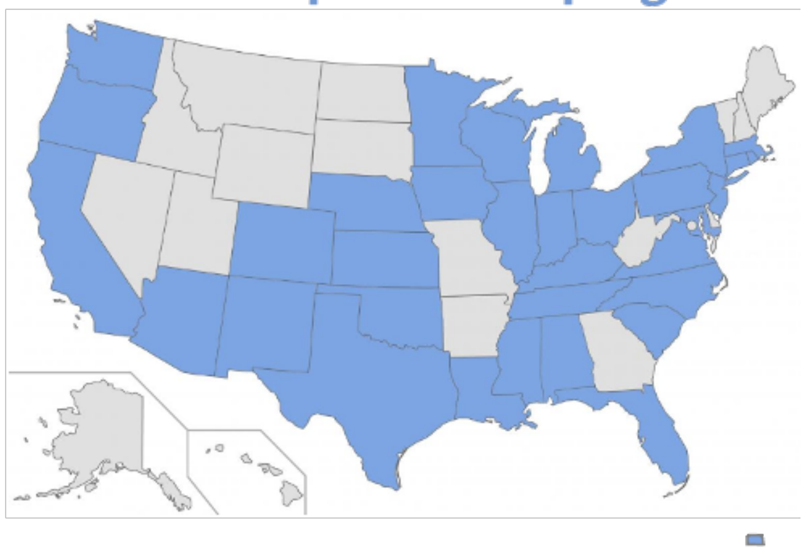




OVERVIEW OF THE U.S. LHC PROGRAM

- The U.S. ATLAS and U.S. CMS collaborations include ~ 600 physicists each, from ~ 90 university groups and 5 DOE national laboratories.
- **U.S. LHC represents the largest fraction of the U.S. particle physics community and the U.S. is the single largest collaborating nation at the LHC.**
- U.S. ATLAS and U.S. CMS coordinate U.S. contributions with international partners and CERN.
  - **The U.S. LHC program is a successful interagency partnership of DOE and NSF.**
- The scope of the U.S. deliverables leverages <u>unique</u> expertise and interests of U.S. scientists as well as U.S. facilities and capabilities.

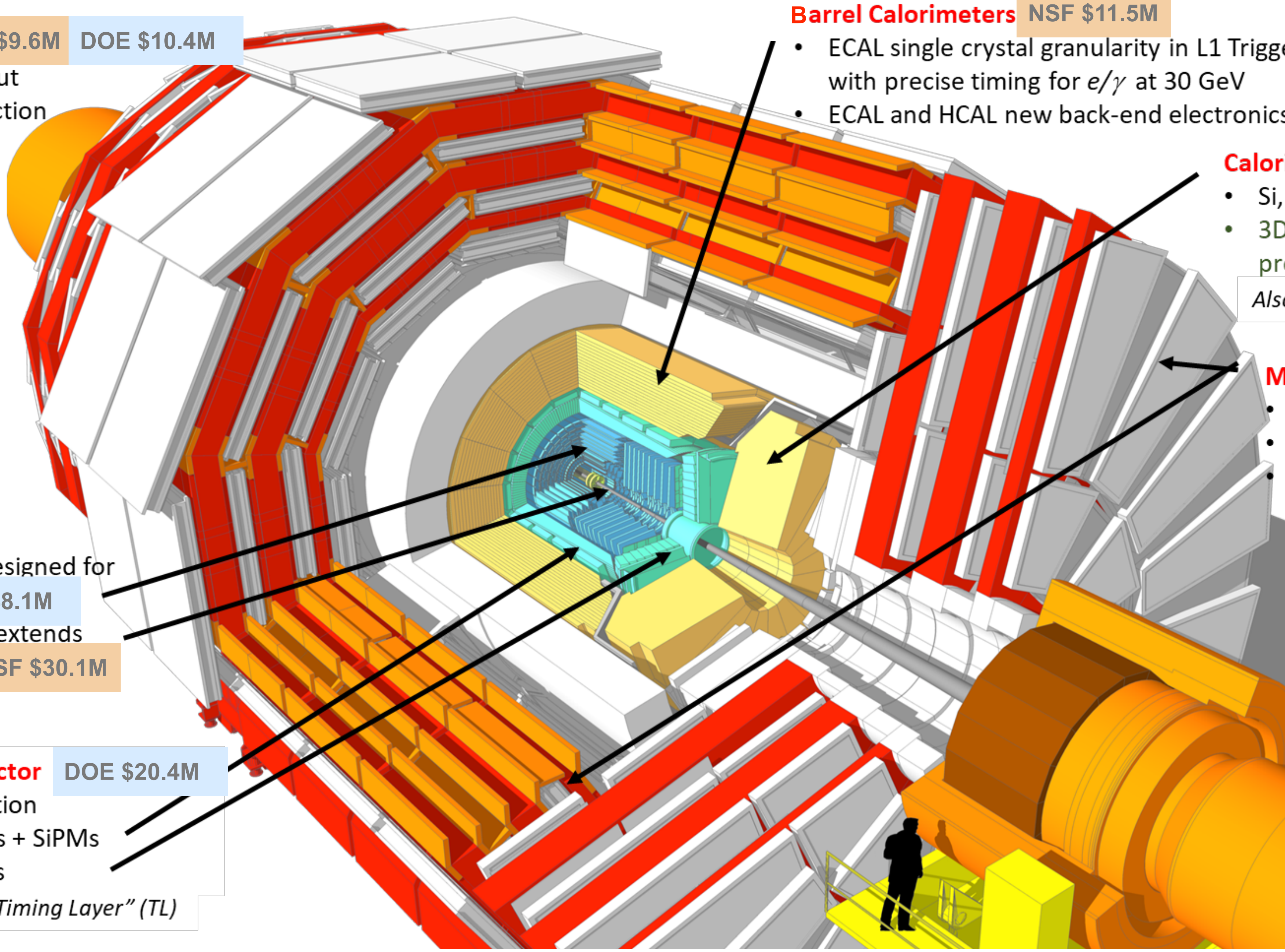
States hosting members of the U.S. LHC experimental program



	DOE Univ.	DOE Labs.	NSF Univ.	# US Collab.	% International Collab.
ATLAS	30	4	11	604	19
CMS	31	1	18	642	27*

* Increases to over 29% if the groups supported by Nuclear Physics are accounted for.

CMS HL-LHC UPGRADE



L1 Trigger/HLT/DAQ NSF $9.6M DOE $10.4M
- L1 40 MHz in/750 kHz out
- Tracking for PF-like selection
- HLT 7.5 kHz out

Barrel Calorimeters NSF $11.5M
- ECAL single crystal granularity in L1 Trigger with precise timing for e/γ at 30 GeV
- ECAL and HCAL new back-end electronics

Calorimeter Endcap DOE $54.2M
- Si, Scint + SiPM in Pb-W-SS
- 3D shower imaging with precise timing

Also known as HGCal

Beam Radiation and Luminosity, Common Systems, Infrastructure

Muon System NSF $7.8M
- DT & CSC new FE/BE readout
- New GEM/RPC $1.6 < |\eta| < 2.4$
- Extended coverage to $|\eta| < 3.0$

Tracker
- Si Strip **O**uter **T**racker designed for L1 Track Trigger DOE $48.1M
- Pixelated **I**nner **T**racker extends coverage to $|\eta| < 3.8$ NSF $30.1M

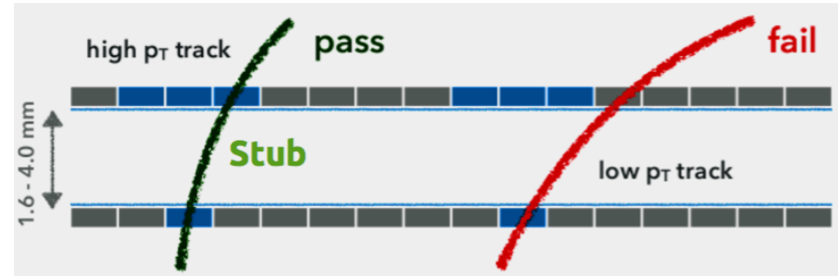
MIP Timing Detector DOE $20.4M
- < 75 ps resolution
- Barrel: Crystals + SiPMs
- Endcap: LGADs

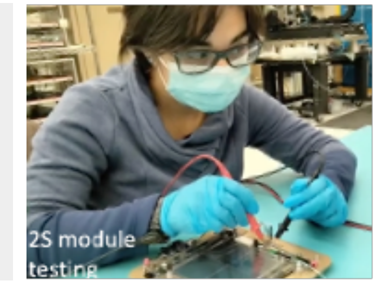
Also known as "Timing Layer" (TL)

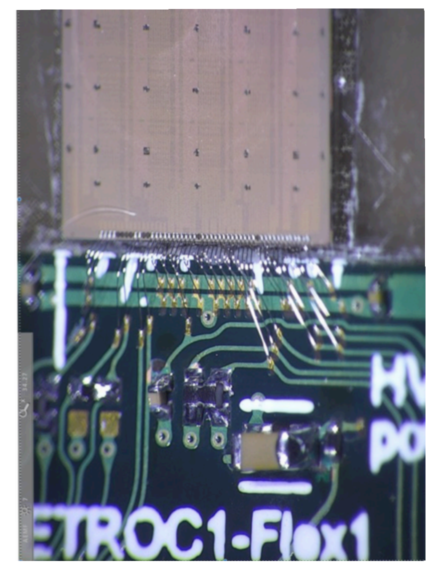
DOE also supports Integration and Installation

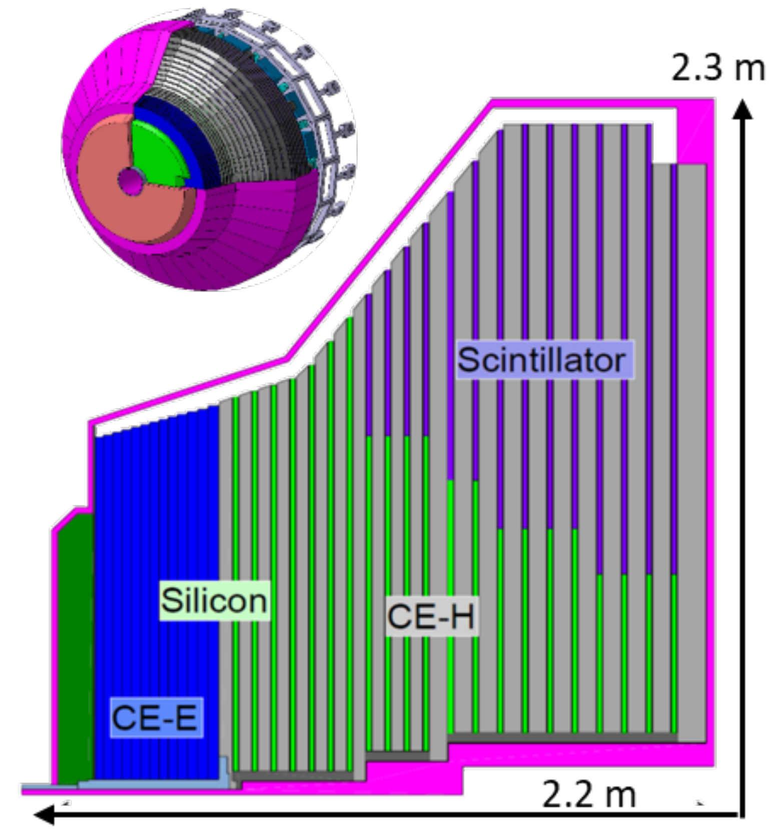
NEW DETECTORS

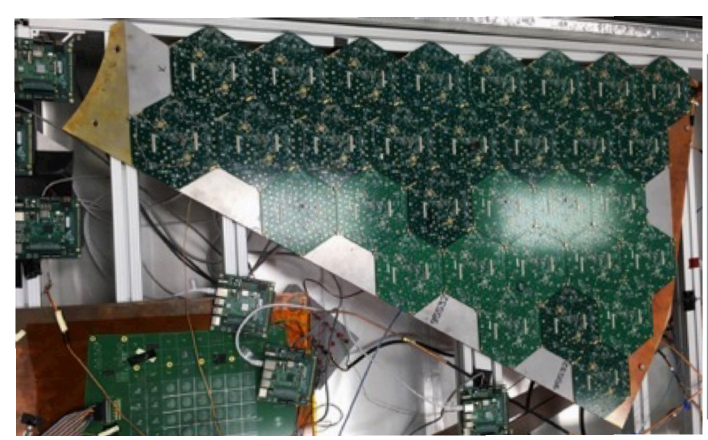
- **Entire tracking system**
  - **Outer Tracker: novel module design providing track information to the Level-1 trigger**
  - **Inner Tracker: from ~ 66 M to ~ 2 B pixels**
    - 3D pixel sensors at inner radii, extension to $|\eta|<4$
- **Novel timing detector**
  - **Pushing technology to few ~10ps resolution**
    - 16x16 pixel readout ASIC in the end-cap, one of the largest ASICs in HEP
- **Imaging Calorimeter Endcap**
  - **High granularity 5D shower information**
    - Silicon based sensing (in high dose area)
    - AI/ML on ASIC (concentrator)
- **Muon Detectors**
  - **Extending coverage in eta gaps, increasing redundancy with new muon technology - GEMs, RPCs -**
    - First GEM Detectors installed for Run 3











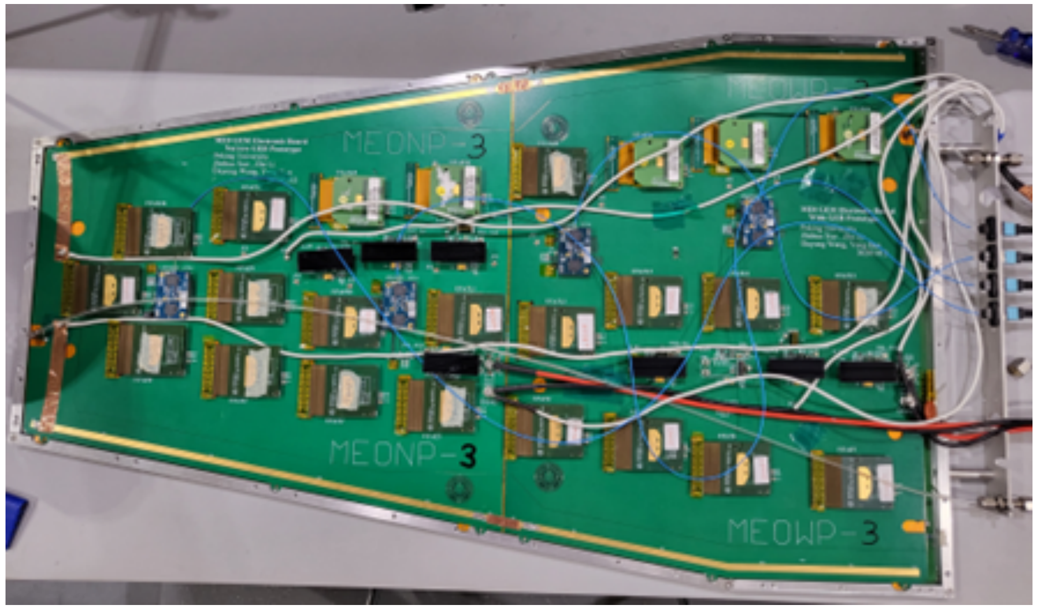
High Density: 444 cells (432+12)

NEW ELECTRONICS

- **Upgraded frontend and backend readout electronics for ~ all sub-detectors to accommodate:**
  - **Higher Level-1 rate**
  - **More and more granular detector information, including from existing sub-detectors**
    - *e.g.* Barrel Calorimeter: single crystal information to Level-1
- **More performant trigger system**
  - **Level-1 (lowest level)**
    - Tracking information - new for CMS!
    - More and more granular information
    - Particle flow, scouting - new!
    - Latency 3.5 μs → 12 μs
    - Rate 100 kHz → 750 kHz
  - **Accelerators at the High Level Trigger**
- **ATCA x 25 Gbps platform as new standard, with large ultrascale FPGAs (→ modern AI/ML)**

New paradigm for High Level Synthesis

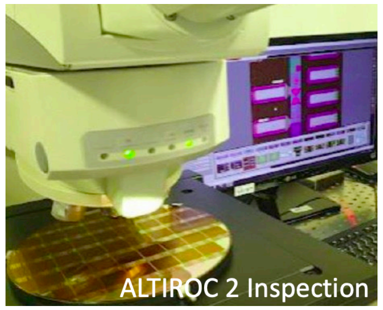
R&D in portability



ATLAS HL-LHC UPGRADE

New HGTD detector (based on LGAD) in 2.4<|η|<4.0

- < 70 ps resolution per hit, 4 layers of silicon modules, at least 2 hits per track; bunch-by-bunch luminosity
- **NOT in US scope**



NSF $18.861M | DOE $6.804M

Liquid Argon Calorimeter (LAr)
- electronics only - 40 MHz r'dout

Tile Calorimeter (Tile)
- electronics only - 40 MHz r'dout

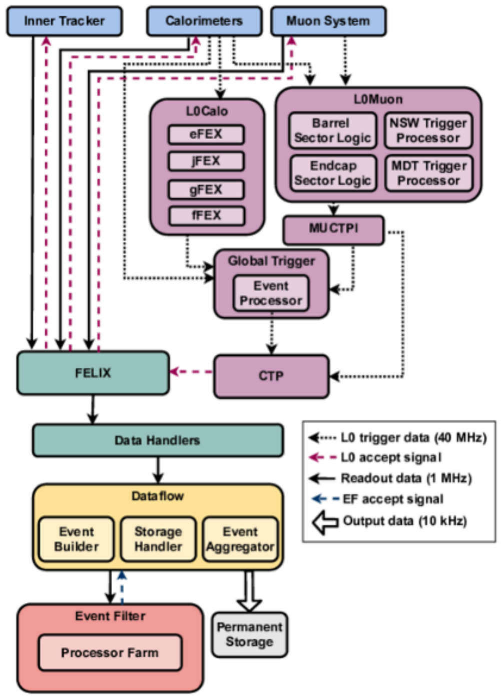
NSF $4.493M

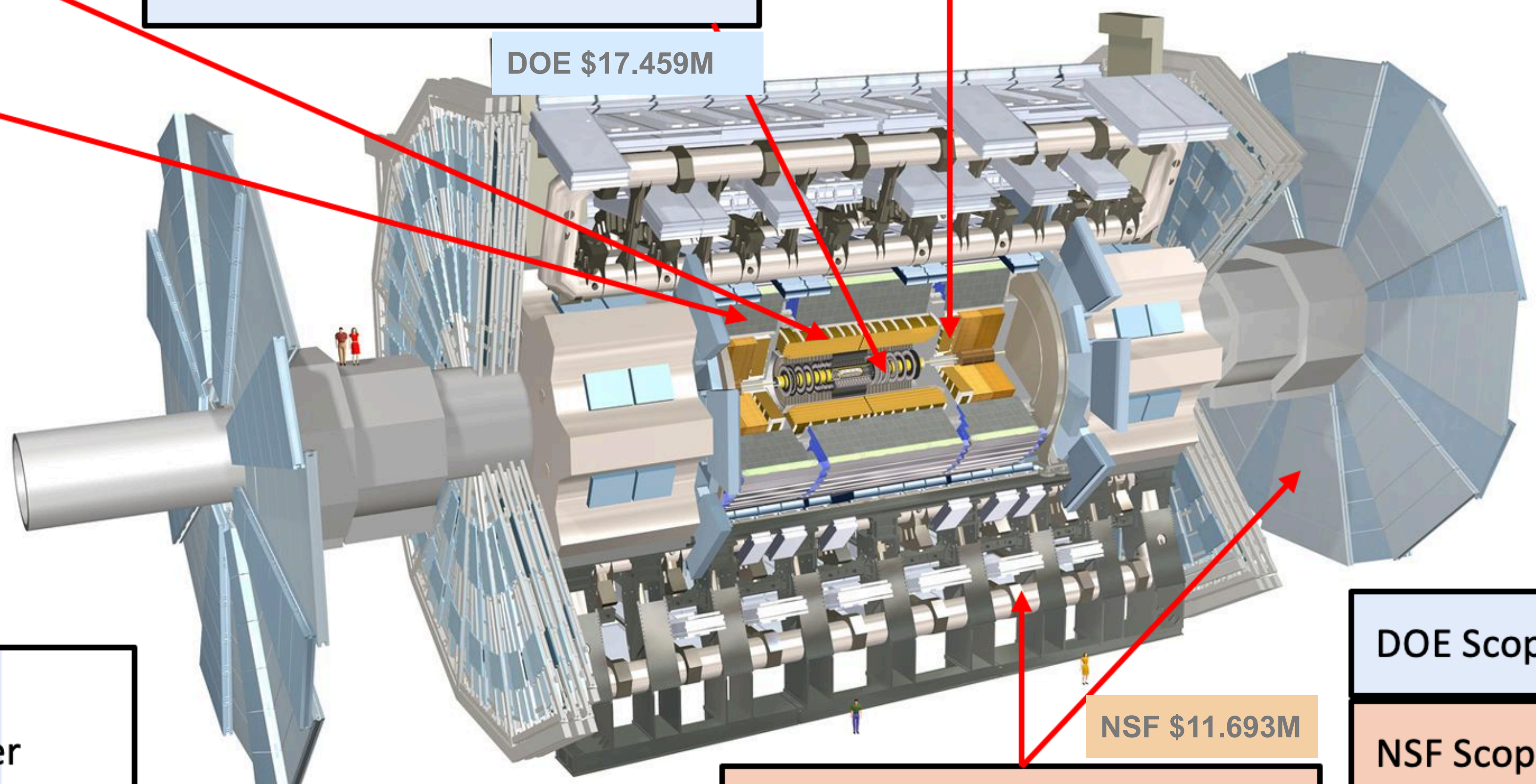
DOE Pixel $34.921M; Strips $48.055M

Inner Tracker (ITk)
- Pixel & Strips Detectors
- Mechanics & Electronics

DOE $17.459M

High Granularity Timing Detector (HGTD)
- improve pileup rejection at high eta





Trigger & DAQ (TDAQ)
- 1 MHz L0 Trigger
- tracking trigger
- new DAQ & dataflow

NSF $12.75M | DOE $14.188M

NSF $11.693M

Muon Spectrometer (Muon)
- add chamber coverage
- replace electronics

DOE Scope

NSF Scope

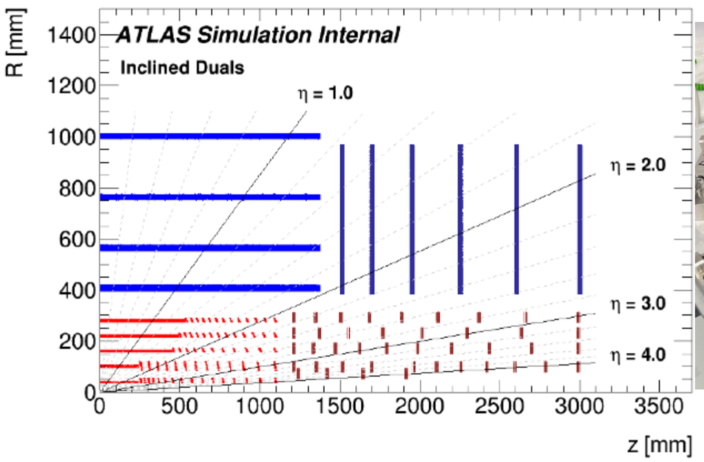
DOE also supports Integration and Installation

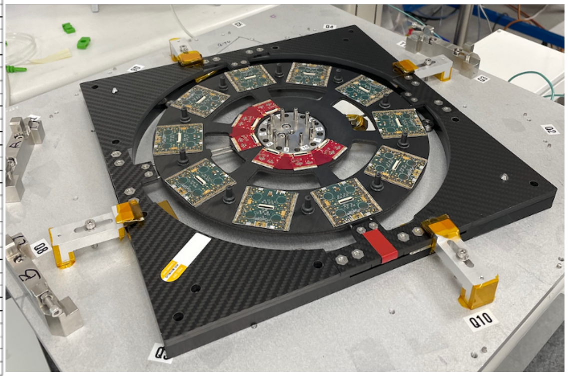
NEW DETECTORS

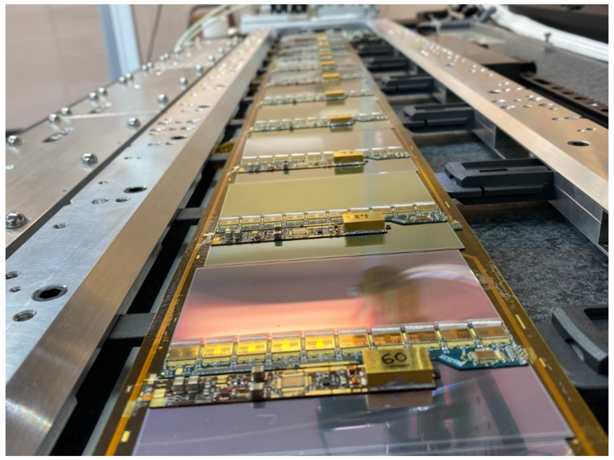
- **Entirely new silicon based tracking system (ITk)**

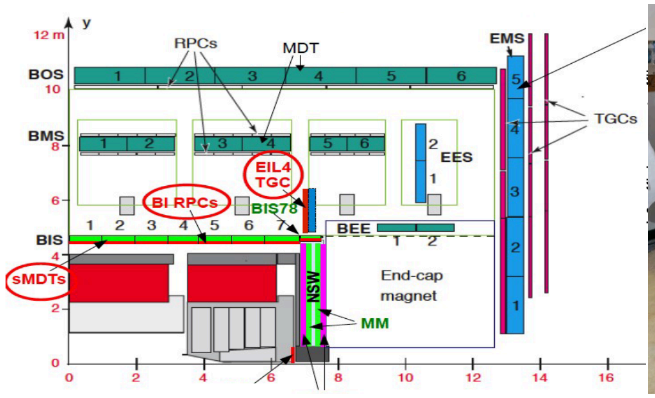
ITk (ID)	Area (m²)	# Modules	# Channels (M)
Pixels	13 (1.6)	9164 (2000)	5100 (92)
Strips	165 (61)	17888 (4088)	60 (6.3)

  - **3D pixel sensors at inner radii, |η|<4**
  - **Inclined modules and innovative serial powering scheme in the pixels**
  - **ASICs in either 130 or 65 nm CMOS technology (joint R&D ATLAS and CMS ASIC in TSMC 65 nm)**
  - **Dual phase CO_2 cooling and extensive use of carbon fiber for mechanical structures**
- **New Muon Detectors**
  - **Increase trigger acceptance by adding chambers in areas of poor coverage**
    - To create space for added coverage use new sMDT chambers in the inner barrel



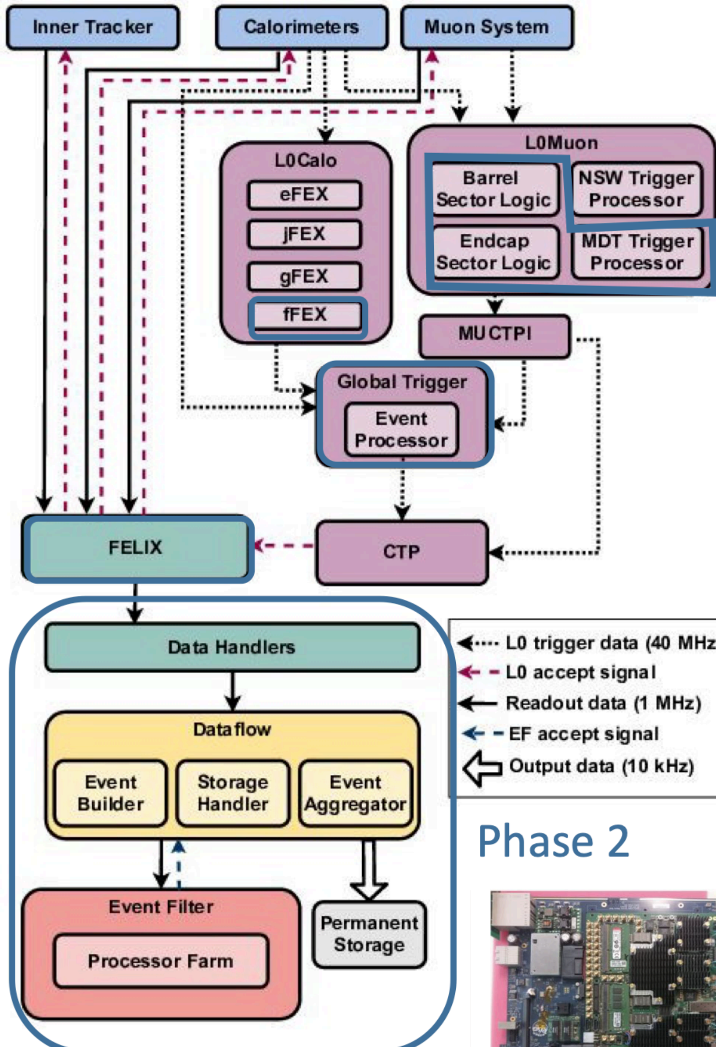






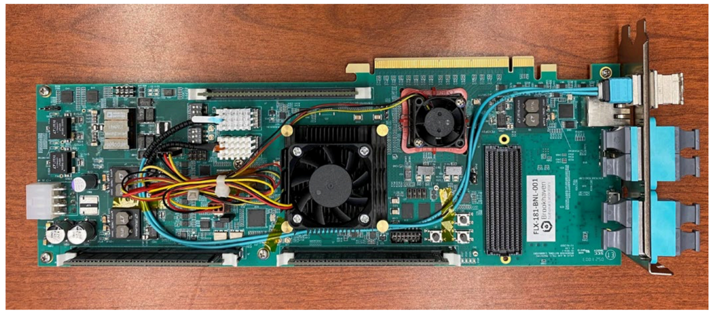
NEW ELECTRONICS

- New frontend and backend readout electronics
  - Calorimeters: readout all data from frontend to off-detector at 40 MHz bunch-crossing
  - Muon Chambers: precision MTD information made available at Level-0
- Completely new trigger system
  - Move from 100 kHz to 1 MHz single-level hardware trigger!
    - Latency from 2.5 µs to 10 µs
  - Event Filter from 1 kHz to 10 kHz
    - Exploits full detector granularity and extended tracking range
    - Modern FPGAs, EF tracking based on CPUs and accelerators
- Upgraded communication between frontend electronics and data acquisition through FELIX
  - Commodity hardware and networking to handle 5.2 TB/s



Phase 2

L0 muon trigger prototype



FELIX Phase-II prototype

STATUS OF THE US PROJECTS

- DOE guidance
  - U.S. ATLAS $200M; U.S. CMS $200M
- NSF MREFC
  - Total of ~ $150M split ~ equally (jointly submitted)
- The total contributions to each upgrade, when expressed in core accounting, are based on the “fair share” fraction of each U.S. collaboration in each international collaboration.
- Both projects are well advanced:
  - “Baselined”
  - Designs complete → entering production phase
  - Percent complete:
    - ATLAS: DOE 47%; NSF 36%
    - CMS: DOE 42%; NSF 33%

CY	DOE	NSF
2016	CD-0	CDR
2017		PDR
2018	CD-1 ATLAS	
2019	CD-3a ATLAS CD-1 CMS	FDR
2020	CD-3a CMS	
2022	CD-3b CMS CD-2/3 ATLAS	
2023	CD-2/3c CMS	Re-“baseline”
2030	*CD-4 ATLAS/CMS	

* Includes 2 years of top-down float

U.S. ATLAS, U.S. CMS, DOE, and NSF coordinate the scope of each upgrade project regularly (each project has been formulated to avoid duplication).

EXPERIENCES

- The U.S. provided intellectual and leadership roles in developing and building the LHC and HL-LHC detectors.
- The pivotal role played by U.S. ATLAS and U.S. CMS was made possible by:
  - Excellent coordination among U.S. institutions, DOE, NSF;
  - Strong collaborations with international partners within the ATLAS and CMS collaborations.
  - Investments in detector R&D prior to CD-0 / CDR approval.
- The HL-LHC detector upgrades leverage cutting edge technologies (and represent a test bed for future detectors):
  - Extensive use of AI/ML in hardware and firmware designs (closer and closer to the interaction);
  - Experience with 65 nm ASIC technology;
  - Systems engineering of fast timing detectors;
  - Imaging calorimetry providing 5D shower;
  - and more …
- Innovation promoted through the Instrumentation Frontier was key.
- Finally, these upgrades are a unique training ground for the next generation.

LESSONS LEARNED

- **The HL-LHC detector efforts naturally feed into the next phase of collider experiments, and lessons learned at the LHC can inform future projects.**
  - **Cooperation within the U.S. (among research institutions and between agencies) and with international partners allows to lay essential groundwork for future efforts.**
  - **Early investments in detector R&D are critical.**
  - **Development of common solutions (across experiments and in coordination with international partners) ensures return on investment and risk mitigation.**
    - Extensive risk analysis in the project itself allows to handle internal and external factors (*e.g*. issues related to supply chain).
  - **A healthy balance between adoption of diverse technical solutions and risk mitigation is important.**
  - **In addition to technical expertise, significant scientific leadership (and thus research funding) is critical.**

CONCLUSIONS

- The priority to pursue the next phase of LHC physics has been established.
- The HL-LHC upgrades of the ATLAS and CMS detectors are essential to fully exploit the discovery potential of the HL-LHC:
  - 90% of the total dataset will be collected by the upgraded detectors;
  - The HL-LHC *will be* the EF collider for the next two decades.
- The projects are technically advanced ("baselined") and the upgraded detectors will start operating in ~ 6 years.
- Continued support from the community and the funding agencies is vital for the completion of the upgrades, as well as for subsequent detectors' operations and analysis of the HL-LHC data:
  - Serving as a successful model for current (e.g. LBNF/DUNE) and future U.S. hosted large projects;
  - Demonstrating that the U.S. is a reliable partner within large international collaborations;
  - <u>Enabling science past 2040.</u>

WE BELIEVE THAT THE HL-LHC MUST REMAIN

THE HIGHEST-PRIORITY NEAR-TERM LARGE PROJECT

DETECTOR BUILDERS

EXTRA

US ATLAS KPPS

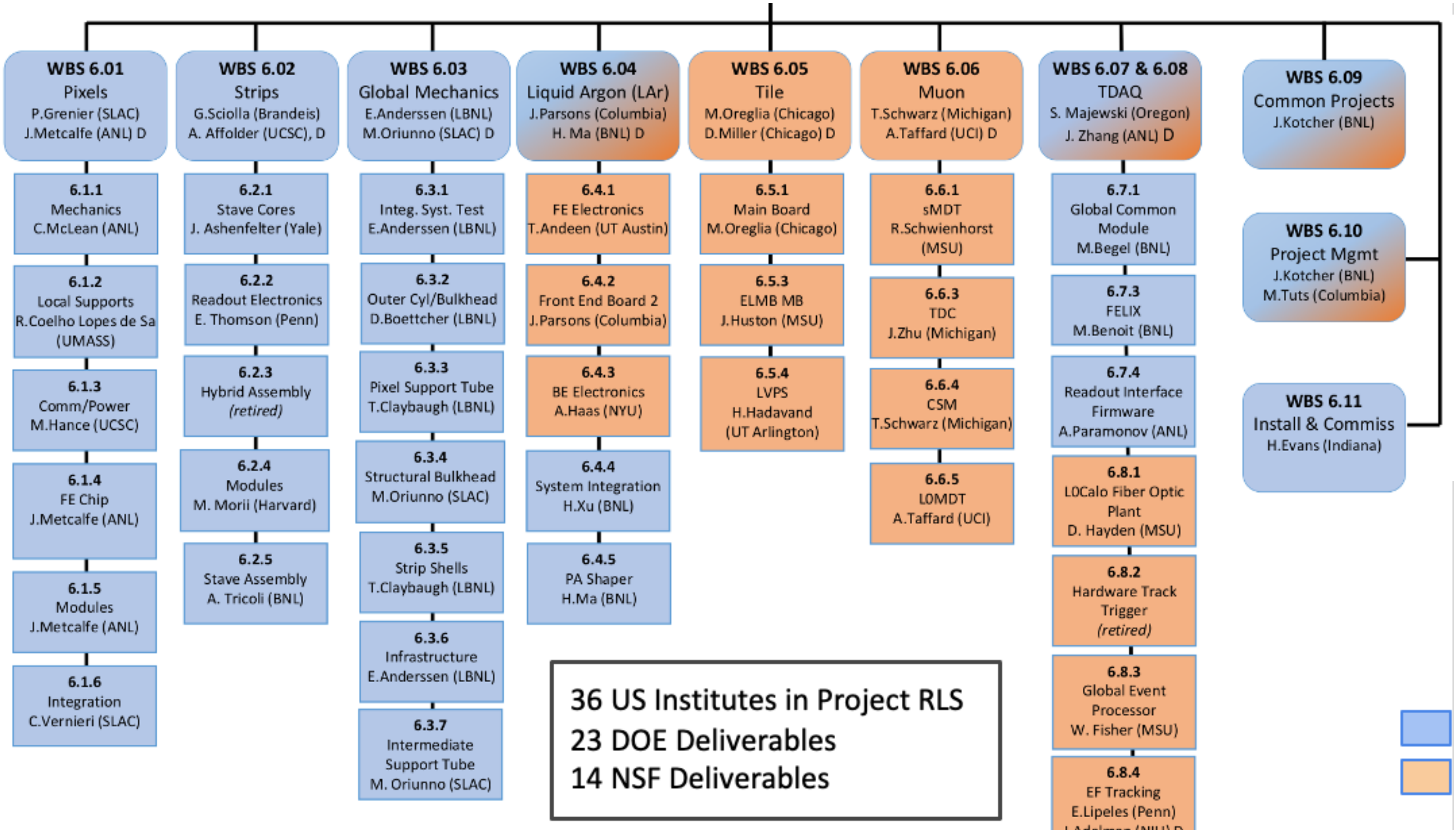
	Threshold	Objective (Includes Threshold KPPs)
WBS 6.1 – Silicon Pixels	Design, fabricate, test and deliver to CERN an inner pixel system with coverage to |eta| < 3.0, constructed to ATLAS specifications	Fabricate, test and deliver to CERN an inner pixel system with coverage to |eta|< 4.0, constructed to ATLAS specifications. Install and integrate the inner pixel

ATLAS

Strips	Threshold	Objective (Includes Threshold KPPs)
WBS 6.2 – Silicon Strips	Fabricate, test and deliver to CERN 156 staves for the barrel of the silicon strip detector, constructed to ATLAS specifications.	Fabricate, test and deliver to CERN 196 staves for the barrel of the silicon strip detector, constructed to ATLAS specifications. Contribute, in proportion to the US contributions to the barrel strip detector, effort required to install and integrate the silicon strip barrel staves into the ITk and connect and check-out in the ATLAS detector in the pit.
WBS 6.3 – Global Mechanics	Fabricate, assemble, test and deliver to CERN all the components for the: (i) outer cylinder and bulkheads; (ii) pixel support tube; (iii) structural bulkheads; (iv) strip stave support shells; and (v) inner layer support tube for the Inner Tracking (ITk) detector, according to ATLAS specifications.	Integrate the U.S. mechanical structure deliverables into the ITk and into the ATLAS detector in the pit.

	Threshold	Objective (Includes Threshold KPPs)
WBS 6.4 – Liquid Argon Readout	Develop, produce, test and deliver to Columbia University one half of the multi-channel preamp-shaper ASICs, which perform according to ATLAS specifications, to be mounted on the liquid argon front-end boards (FEB2).	Perform system integration of the liquid argon front-end boards (FEB2) and back-end electronics. Participate in the installation and integration of the liquid argon front-end electronics in the ATLAS detector in the pit in proportion to the US contributions to the ATLAS LAr electronics upgrade.
WBS 6.7 – DAQ/Data Handling	Design and prototype Global Common Module (GCM) and Front-End Link Exchange (FELIX) boards that perform according to ATLAS specifications; fabricate and deliver to CERN 10 ATLAS GCMs and 110 FELIX production boards.	Fabricate and deliver to CERN the full US share of the ATLAS GCM (18) and FELIX (200) production boards. Participate in the installation and integration of the GCMs and the FELIX system into the ATLAS Trigger and Data Acquisition (TDAQ) system in proportion to the US contributions to the ATLAS GCM and FELIX production.

US ATLAS WBS



U.S. ATLAS HL-LHC Upgrade Project Office

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DOE Scope
NSF Scope

US CMS KPPS

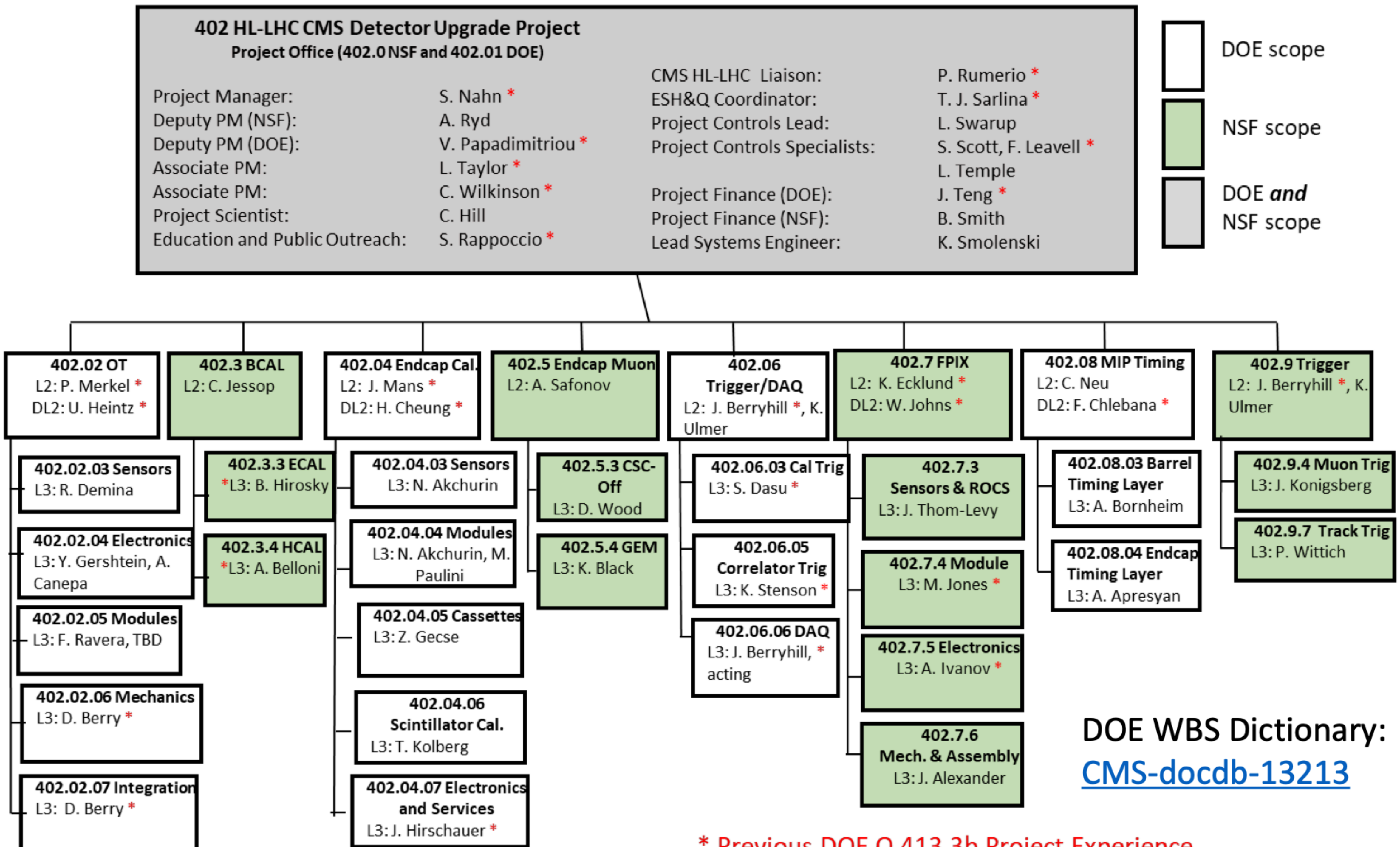
Threshold KPP
T-KPP-OT-1: OUTER TRACKER CONSTRUCTION
The Project will build, test, and grade approximately 27% of the total number of Modules needed for the Outer Tracker. 952 Modules will be used to construct the "Flat" Inner Barrel, the inner three layers of barrel modules. The modules and Flat Barrel shall have sufficient granularity and noise performance to ensure a projected occupancy of < 5%, and capable of forming and sending track pT information to the L1 trigger at LHC bunch crossing rates.
Objective KPP
O-KPP-OT-1: OUTER TRACKER CONSTRUCTION AND INTEGRATION
The Project will build, test, and grade approximately 33% of the total number of Modules needed for the Outer Tracker. 952 Modules will be used to construct the "Flat" Inner Barrel, the inner three layers of barrel modules. The modules and Flat Barrel shall have sufficient granularity and noise performance to ensure a projected occupancy of < 5%, and capable of forming and sending track pT information to the L1 trigger at LHC bunch crossing rates. The project shall integrate the “Flat” Inner Barrel detector into the full Outer Tracker, and test and calibrate it.

WBS	Threshold KPP	Objective KPP
402.4	T-KPP-CE-1: CALORIMETER ENDCAP CONSTRUCTION	O-KPP-CE-1: CALORIMETER ENDCAP CONSTRUCTION AND INTEGRATION
Endcap Calorimeter	The project shall construct the silicon modules and scintillator modules for the hadron section of the endcap calorimeter, and integrate them onto cassettes. In addition, the project shall assemble the odd-sized modules for the electromagnetic calorimeter for delivery to collaborators, and design, produce, and test the data/trigger concentrator ASIC(s) required for the endcap calorimeter. Calorimeter silicon and scintillator modules shall have sufficient granularity, noise level, and radiation tolerance to enable cell-by-cell calibration at the 5% level through the end of operation. The cassettes shall be demonstrated to operate standalone and delivered to CERN.	The project shall construct the silicon modules and scintillator modules for the hadron section of the endcap calorimeter, and integrate them onto cassettes. In addition, the project shall assemble the odd-sized modules for the electromagnetic calorimeter for delivery to collaborators, and design, produce, and test the data/trigger concentrator ASIC(s) required for the endcap calorimeter, and procure power supplies for the hadron section of the calorimeter. The fabrication shall include sufficient components for a testbeam calibration system. Calorimeter silicon and scintillator modules shall have sufficient granularity, noise level, and radiation tolerance to enable cell-by-cell calibration at the 5% level through the end of operation. The cassettes shall be demonstrated to operate standalone and delivered to CERN, where they shall be assembled, and integrated into the endcap calorimeter. The project shall additionally participate in the installation, testing and calibration of the detector.

WBS	Threshold KPP	Objective KPP
402.6	T-KPP-TD-1: TRIGGER CONSTRUCTION	T-KPP-TD-1: TRIGGER AND DAQ CONSTRUCTION AND INSTALLATION
Trigger and DAQ	The project shall design, produce, and test both the Barrel Calorimeter electronics required for receiving and processing data from the barrel calorimeter and the Corrrelator Trigger electronics required for receiving and processing data from the calorimeter, muon, and track trigger systems, both of which transmit output to the downstream trigger components and DAQ. The project also includes development of software and firmware needed to operate the electronics and implement L1 trigger reconstruction. The Barrel Calorimeter trigger shall be validated, based on test data patterns from simulations verified against detector readout data, to provide a position resolution of R = 0.01 and energy resolution of 10% for electrons and photons in the energy range 20-30 GeV. The Correlator trigger shall be validated, based on simulated test data patterns verified against detector readout data, to correlate identified input track, calorimeter cluster, and muon trigger-level primitives efficiently. For 20 GeV electrons (muons), the matching efficiency of the Correlator trigger between received primitive tracks and received primitive clusters (muons) must be greater than 95%.	The project shall design, produce, and test both the Barrel Calorimeter electronics required for receiving and processing data from the barrel calorimeter and the Corrrelator Trigger electronics required for receiving and processing data from the calorimeter, muon, and track trigger systems, both of which transmit output to the downstream trigger components and DAQ. The project also includes development of software and firmware needed to operate the electronics and implement L1 trigger reconstruction. The Barrel Calorimeter trigger shall be validated, based on test data patterns from simulations verified against detector readout data, to provide a position resolution of R = 0.01 and energy resolution of 10% for electrons and photons in the energy range 20-30 GeV. The Correlator trigger shall be validated, based on simulated test data patterns verified against detector readout data, to correlate identified input track, calorimeter cluster, and muon trigger-level primitives efficiently. For 20 GeV electrons (muons), the matching efficiency of the Correlator trigger between received primitive tracks and received primitive clusters (muons) must be greater than 95%. The project shall specify, procure, and test the equipment needed for the startup online Storage Manager and Transfer System, 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. Both the Calorimeter trigger and Correlator Trigger shall be installed, commissioned and validated in situ using full-speed connections from testing data sources and to data storage using the simulated test data patterns.

WBS	Threshold KPP	Objective KPP
402.8	T-KPP-TL-1: TIMING LAYER CONSTRUCTION	O-KPP-TL-1: TIMING LAYER CONSTRUCTION AND INSTALLATION
Timing Layer	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 83% of the CCs and approximately 42% of the total trays needed for the BTL. The project shall design the front-end ASIC and construct and qualify modules for the ETL. The project shall deliver to CERN 25% 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 < 75 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 50% of the total trays needed for the BTL. The project shall design the front-end ASIC and construct and qualify modules for the ETL. The project shall deliver to CERN 25% 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 < 75 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.

US CMS WBS



DOE WBS Dictionary: [CMS-docdb-13213]

* Previous DOE O 413.3b Project Experience