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U.S. CMS HL-LHC Upgrades

Outline

- Project Background
  - Motivation
  - Timeline
  - HL-LHC upgrades
- U.S. Overview
  - U.S. in CMS
  - U.S. planned upgrade deliverables and status
- Recent reviews and review status
- Conclusions

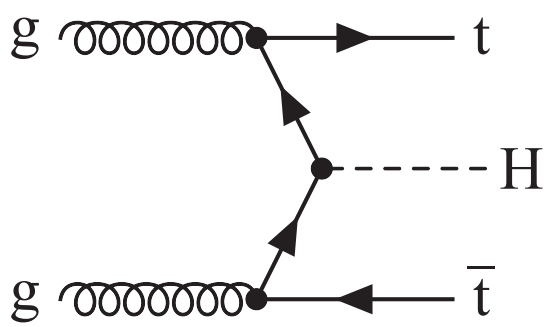
- **Note: due to time limitations, I will talk mainly about the DOE projects.**

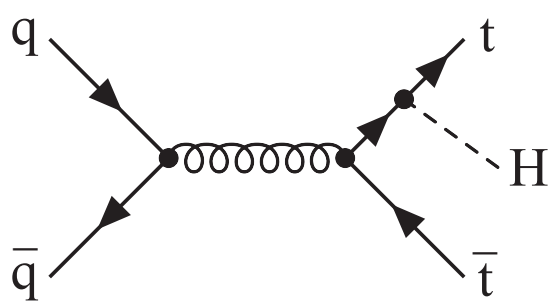
Why HL-LHC?

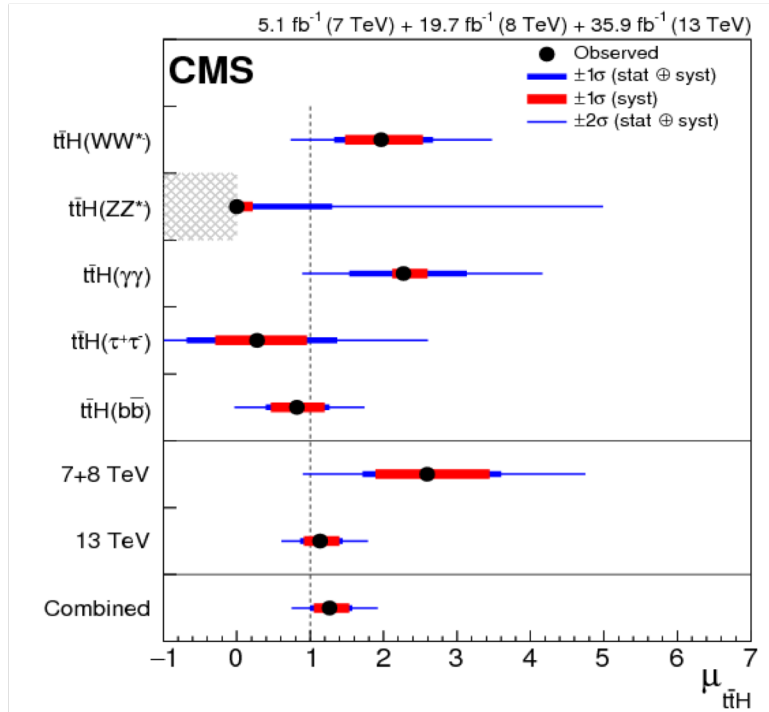
- Many phenomena unexplained by the SM
  - Light Higgs, Baryon Asymmetry of the universe, neutrino masses and mixing, flavor problem, Dark Matter / dark matter candidates
- We have three basic methods for exploring this large, but **as yet still largely uncharted**, territory
  - Searching directly for new particles and new forces
  - Studying the properties of the the Higgs that through its coupling directly to mass can make contact with hidden sectors that are invisible to us otherwise
  - Looking for deviations from the precise predictions of the SM, especially from quantum loops involving new particles or forces
    - These can be sensitive to mass scales well above what can be reached "directly" at the LHC
- All three strategies require more statistics, for which particle physics has a plan based on the extraordinary capabilities of the LHC machine and its detectors

The U.S. LHC upgrades were highlighted in the May 2014 P5 report as the highest priority near-term large project.

Observation of ttH: 7,8, 13 TeV Combined (PRL June, 2018)



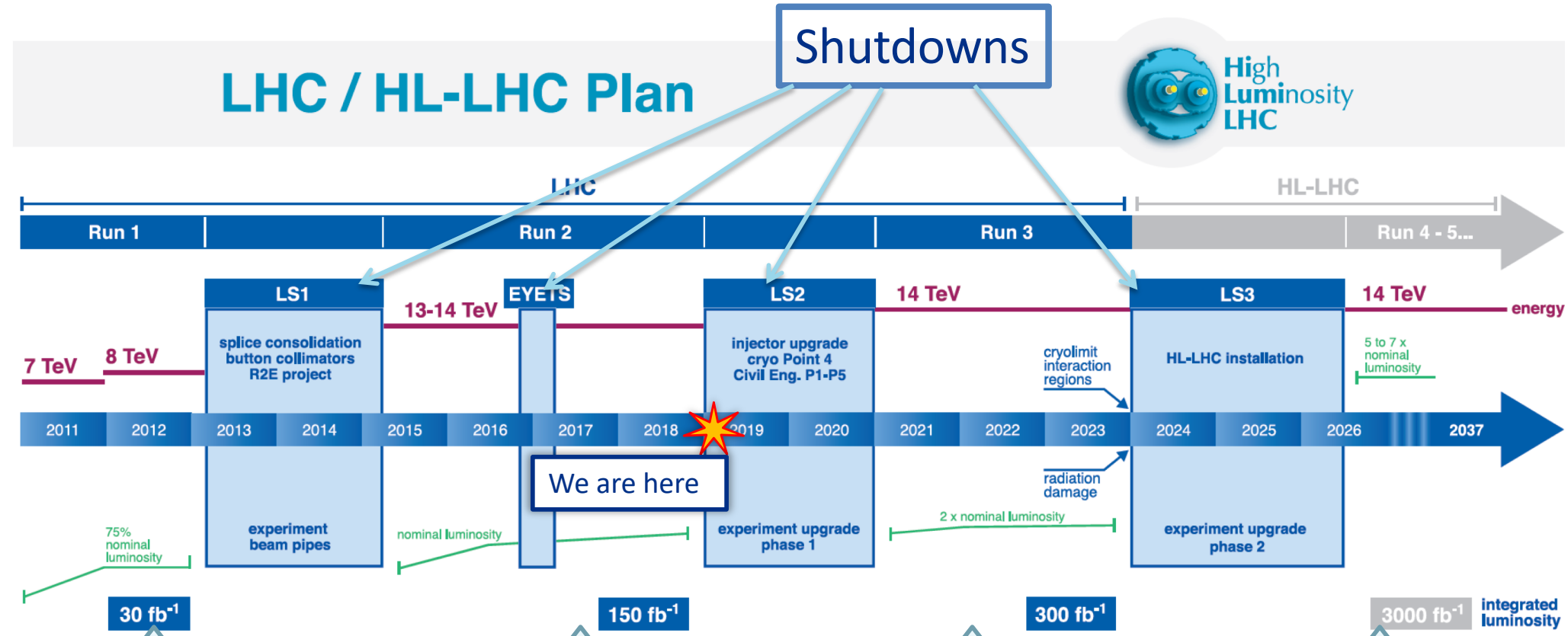




Best fit value of couplings for (upper section) the five individual decay channels considered, (middle section) the combined result for 7+8 TeV alone and for 13TeV alone, and (lower section) the overall combined result.

CMS reached this milestone with less data than expected in 2010 when we first started data taking because we use much more advanced analysis techniques and combine many more channels together to arrive at the results.

The path to the HL-LHC



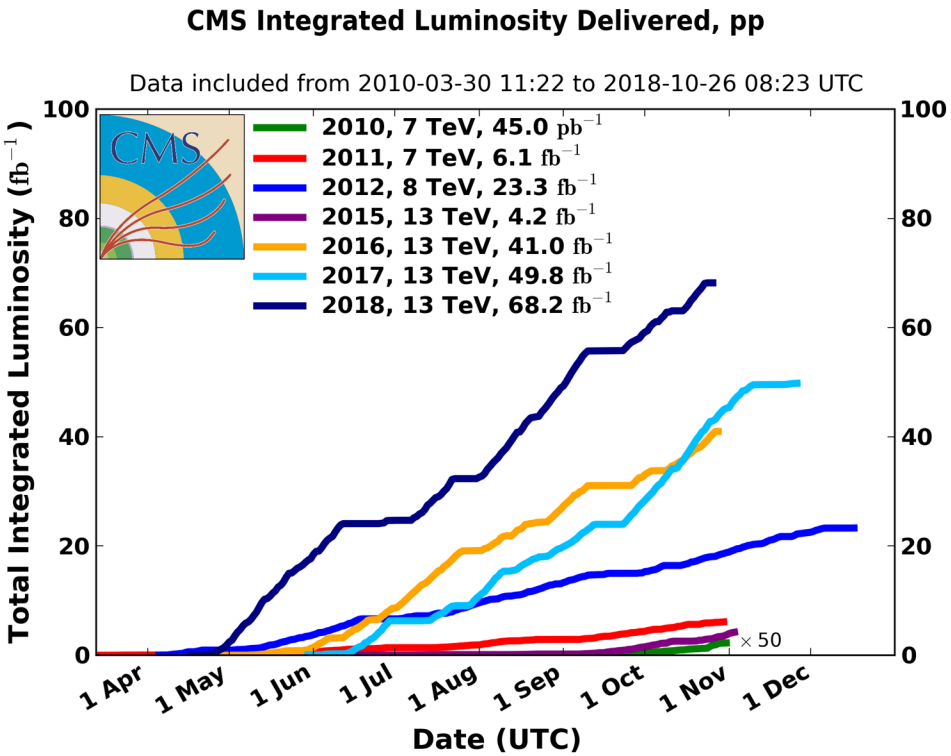
Run 1
0.75 10^{34} $cm^{-2}s^{-1}$
50 ns bunch
pileup ~40

Run 2
1.5 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
pileup ~40

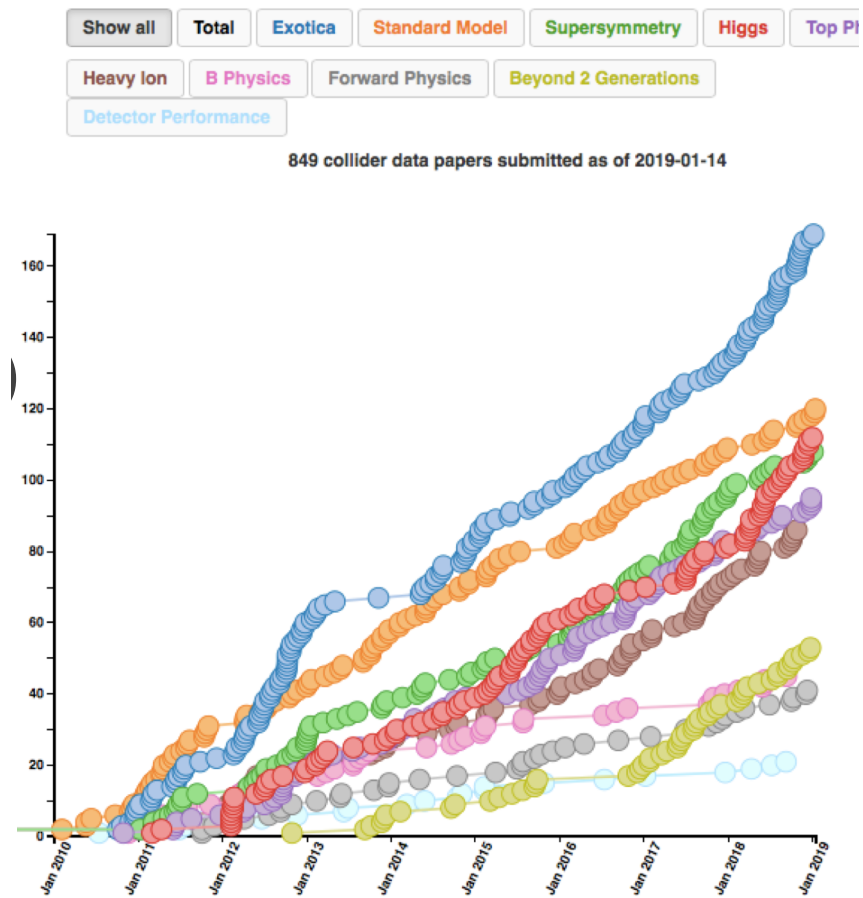
Run 3
1.7-2.2 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
pileup ~60

Run 4-6
~5(7.5!) 10^{34} $cm^{-2}s^{-1}$
25 ns bunch
pileup ~140 - 200

Current Status: Run 2 ended in December



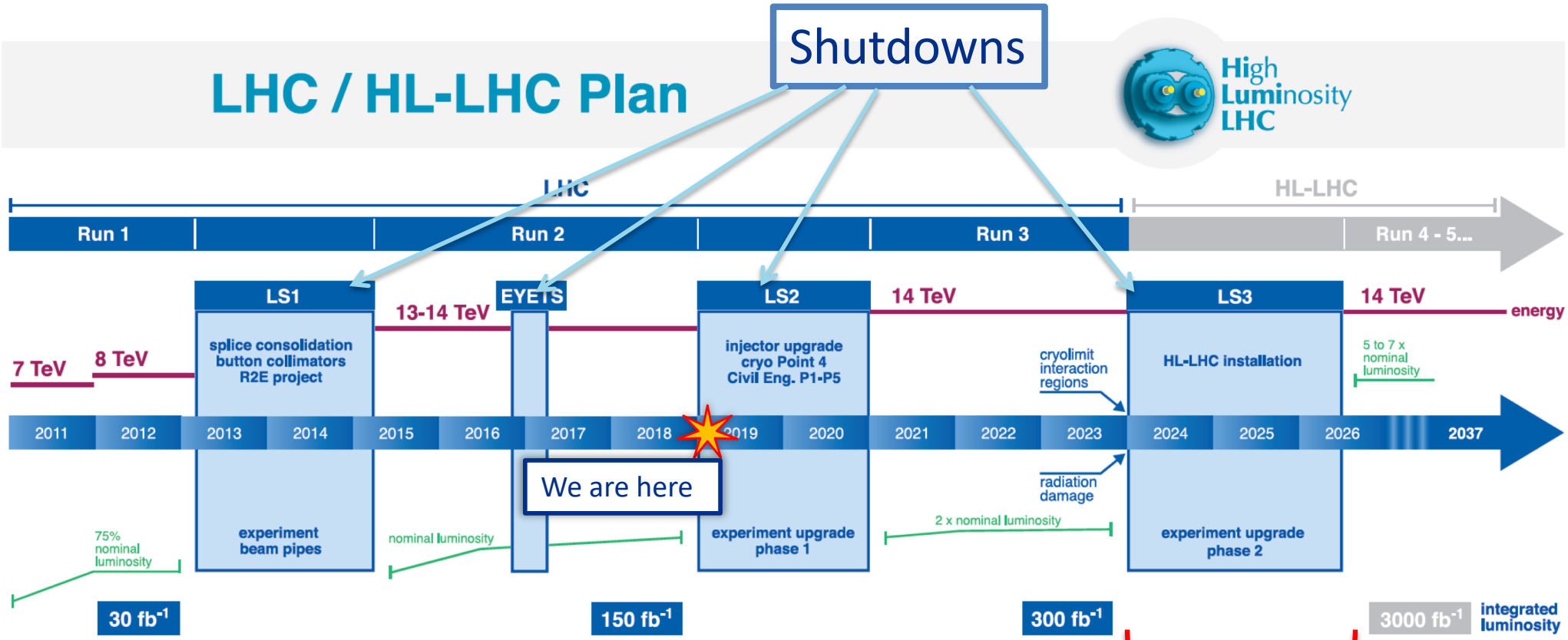
163 fb^{-1} delivered to CMS during Run 2 / 150 fb^{-1} collected by the experiment



849 papers submitted by CMS

We have a great machine and detector and are doing great physics at a prodigious rate!

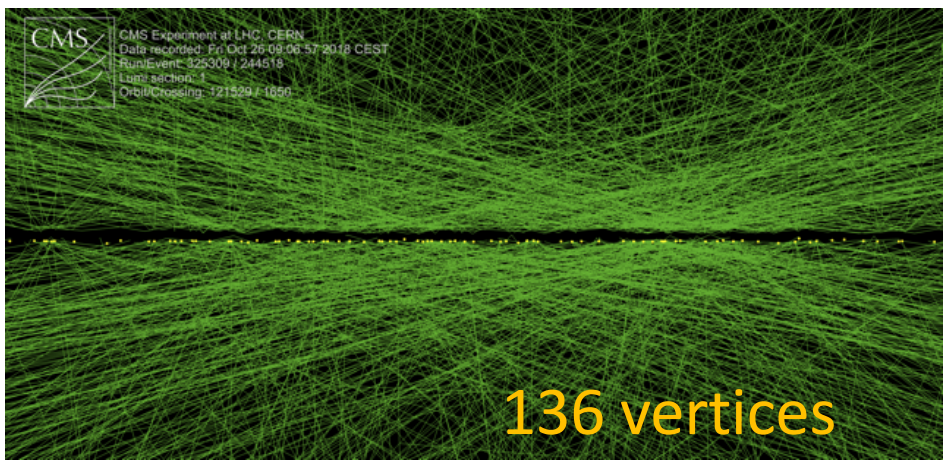
The path to the HL-LHC



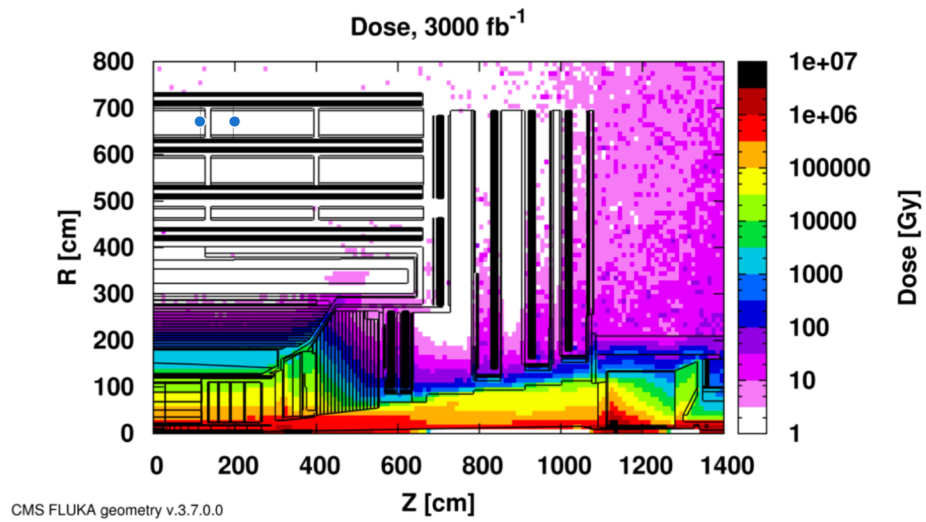
HL-LHC Upgrades: Installed during LS3
(CY 2024 – mid 2026)
HL-LHC operations continues through 2037

Main Challenges for CMS at the HL-LHC

- HL-LHC will deliver ~140-200 collisions/beam crossing (40 MHz)
- This means CMS must be able to:
  - **Separate and identify** particles in extremely dense collision debris
  - Trigger on events at 40 MHz rate, keeping only 7.5 kHz of data
  - And do all of this in a high radiation environment



Event with 136 collisions in one pp bunch crossing from 10/26/2018 special "High Luminosity" running (only a few very bright bunches colliding). We expect the HL-LHC pileup to approach 200.



Absorbed dose in the CMS cavern after an integrated luminosity of 3000 fb^{-1}.

CMS Upgrades for HL-LHC

Areas where U.S. is a critical partner

Areas where Fermilab is a critical partner

L1-Trigger/HLT/DAQ

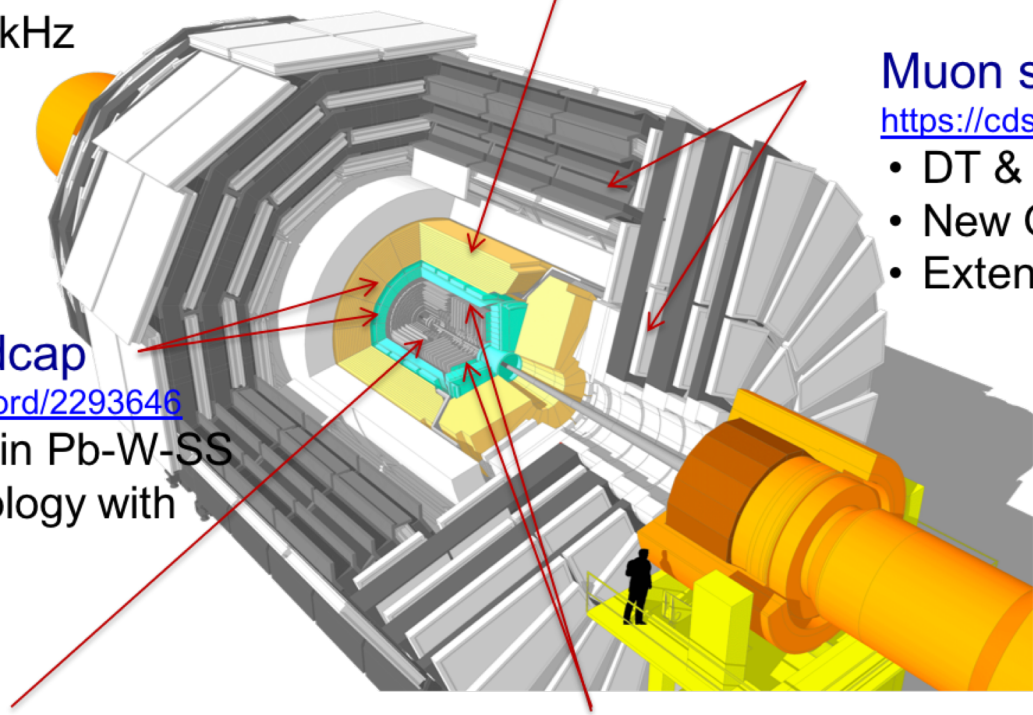
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193

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

Barrel Calorimeters

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

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



Muon systems

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

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

Calorimeter Endcap

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

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

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure

https://cds.cern.ch/record/2020886

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

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

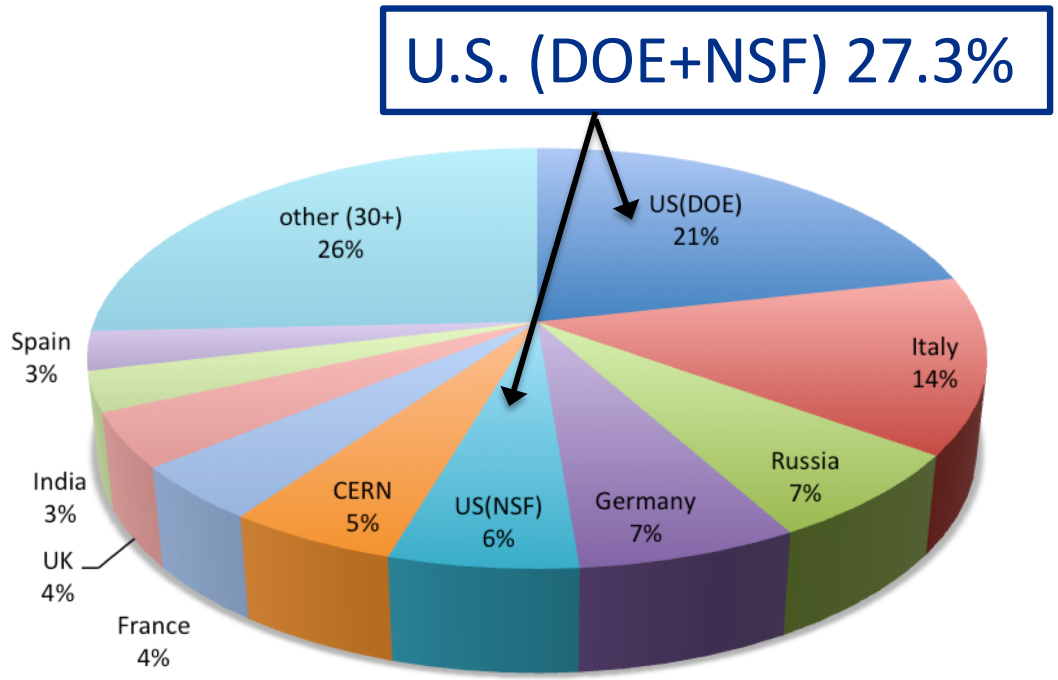
MIP Timing Detector

https://cds.cern.ch/record/2296612

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

*(TDR, interim TDR and TP references)

The CMS Scientific Collaboration



Collaboration of institutes

47 countries	207 institutes
1850 PhD physicists	928 PhD students
1021 undergrads	930 engineers

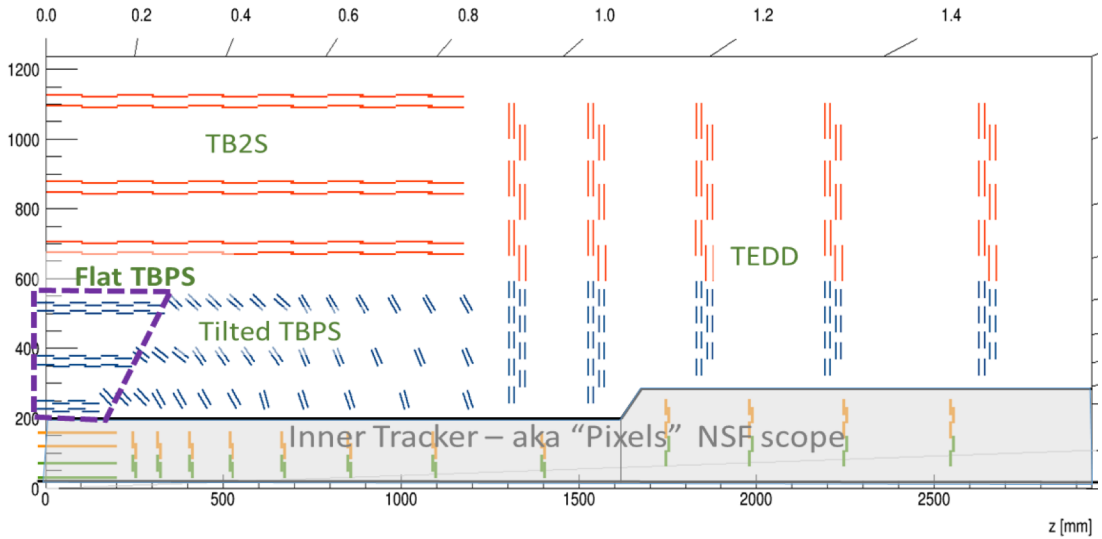
- **<u>The U.S. is by far the biggest nation in CMS</u>**
  - DOE and NSF HEP taken together are 27.3% / DOE NP adds 1.9%
- The U.S. has infrastructure and experience giving it even greater weight
- There is no way that CMS could continue as is, if the U.S. were to significantly reduce its level of activity
- Fermilab plays critical roles on CMS

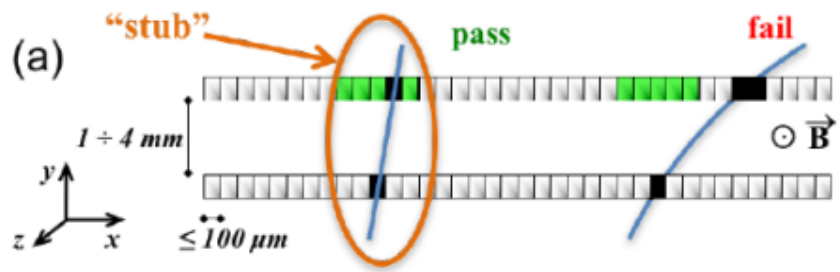
U.S. CMS in HL-LHC Upgrades

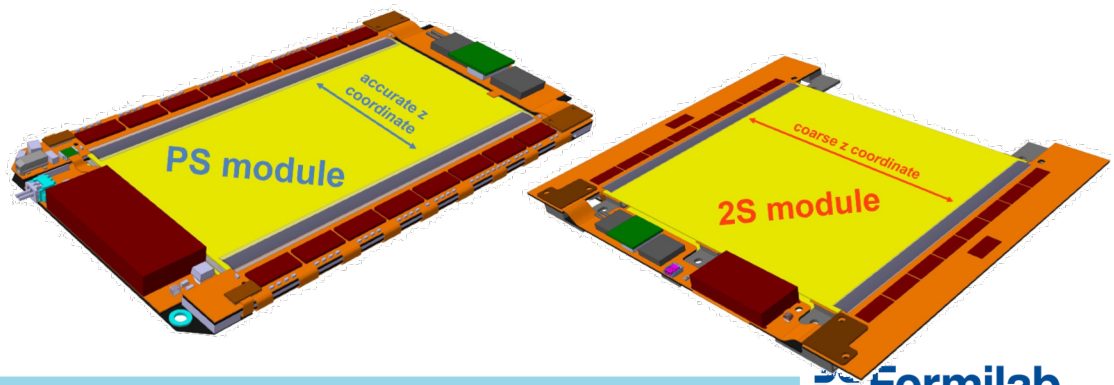
- U.S. CMS chose areas to contribute based on:
  - Interest of the community and large physics impact
  - Past experience
    - Calorimetry, Muons, Tracker, Forward Pixels, Trigger, DAQ
  - Unique capabilities and facilities
    - Experience and facilities for Silicon Detectors, Electronics for Trigger, Muons, DAQ
- The U.S. has an exciting suite of upgrades
  - L1 Track Finder coupled with p_T modules in the Outer Tracker, Silicon based calorimetry, MIP Timing Detector, extended Forward Pixels and Muon detectors give upgraded CMS new capabilities and strong handles for pileup mitigation
- In this talk I will focus on the DOE and Fermilab deliverables

Outer Tracker – overview of the upgrade

- 6 Barrel+ 5 endcap layers
  - Sensor "sandwich" provides local curvature information for trigger
- Two types of module
  - **Pixel**-Strip (PS): Strip sensor (PS-s) provide 1D information, Pixelated sensor (PS-p) provide 2D information at low radius
  - Strip-Strip (2S): Strip Sensors (2S) for both slices of sandwich at high radius
- U.S. Scope
  - Assembly of ~30% of modules
    - Including procurement of components and design and fabrication of QA apparatus for component and module testing
  - "Flat Barrel" Structure
    - Mechanics and assembly of Central portion of inner 3 layers





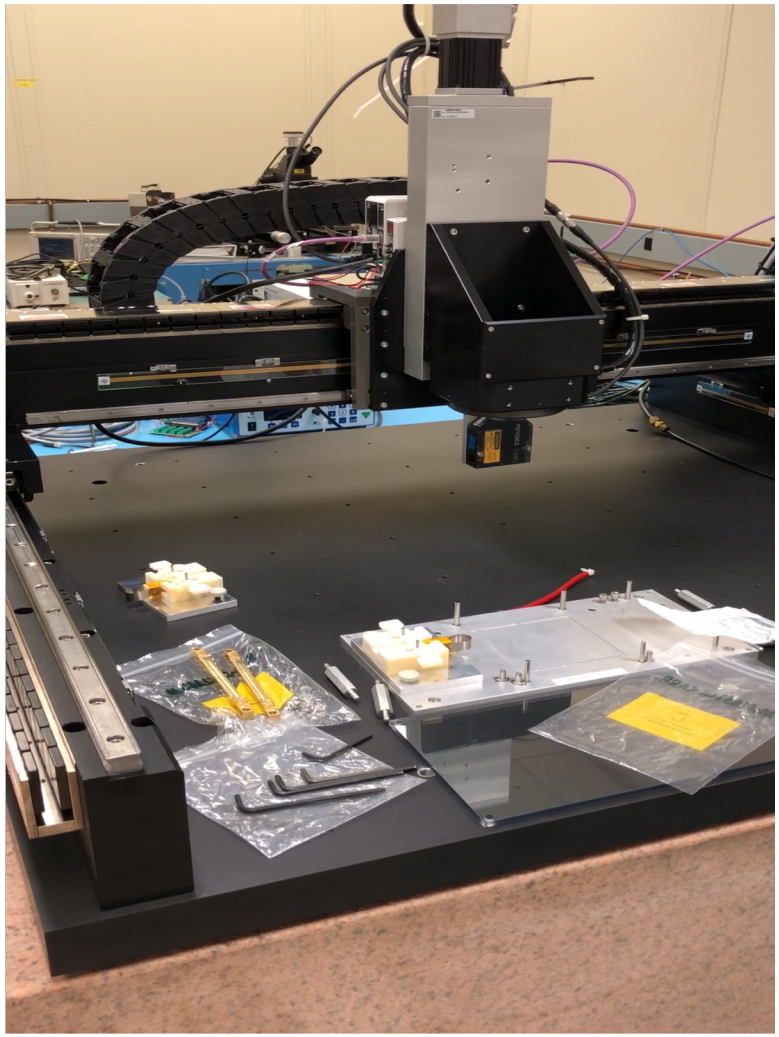


Outer Tracker– Components and Testing

- Sensors
  - Thickness is the last open question
    - Default “deep diffusion float zone” process abruptly discarded by vendor last year, requires re-addressing thickness parameter
      - Balance of charge collection capability vs. material budget vs. radiation tolerance
    - Thickness variants now under pre-irradiation testing, then will be irradiated and evaluated
      - Irradiation planned using FNAL Irradiation Test Area in April
  - Sensor QC established at both testing sites (Brown, Rochester)
- Macro-Pixel Sub Assemblies (MaPSAs)
  - The pixel side of the Pixel-Strip (PS) modules
  - FNAL is responsible for delivering MaPSAs for all PS modules (bump bonding chips to sensors)
  - These will be bump bonded at a vendor: we are responsible for the oversight & QC
  - First prototypes being assembled at vendors
  - Testing apparatus designed and fabricated
- Module Test stands
  - Full burn-in box capable of 10 modules simultaneously at low temperature designed and in fabrication
  - Development of DAQ software well advanced

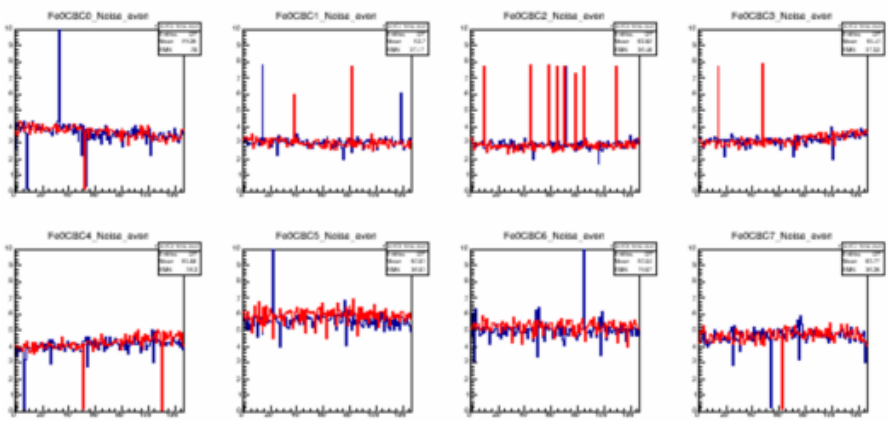
Outer Tracker – Module Assembly

- Two module assembly lines to minimize site outage delays
  - East Coast: Brown, Princeton, Rutgers
    - R&D focused on PS
  - Fermilab
    - R&D focused on 2S
  - Both sites assemble both types
- Current focus on
  - Setting up infrastructure
  - R&D on materials to explore cost reductions, verify adequate performance, or simplify construction
    - Adhesives, encapsulants, ultra-light support structures
  - Gantry-based Assembly automation to reduce manual labor
    - Certain steps can be automated, new gantry at FNAL to explore options
  - Building Prototype Modules
    - Somewhat limited by availability of prototype components



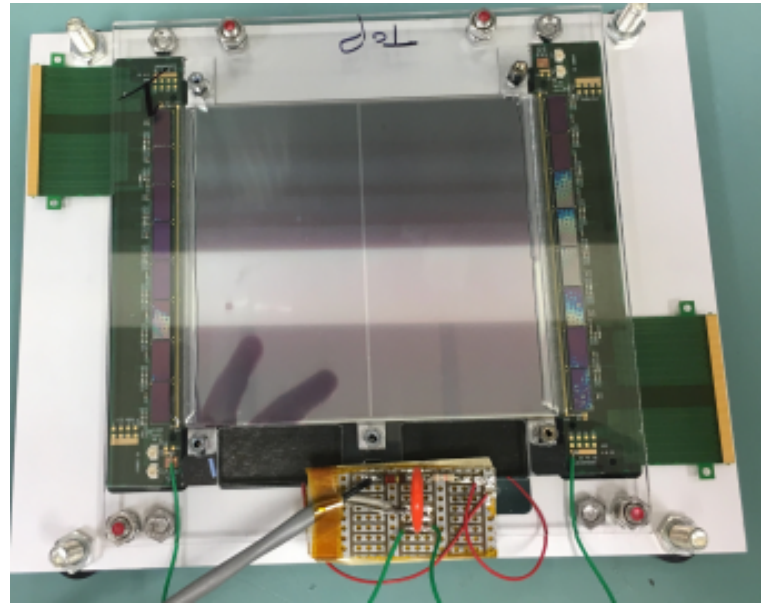
First functional modules

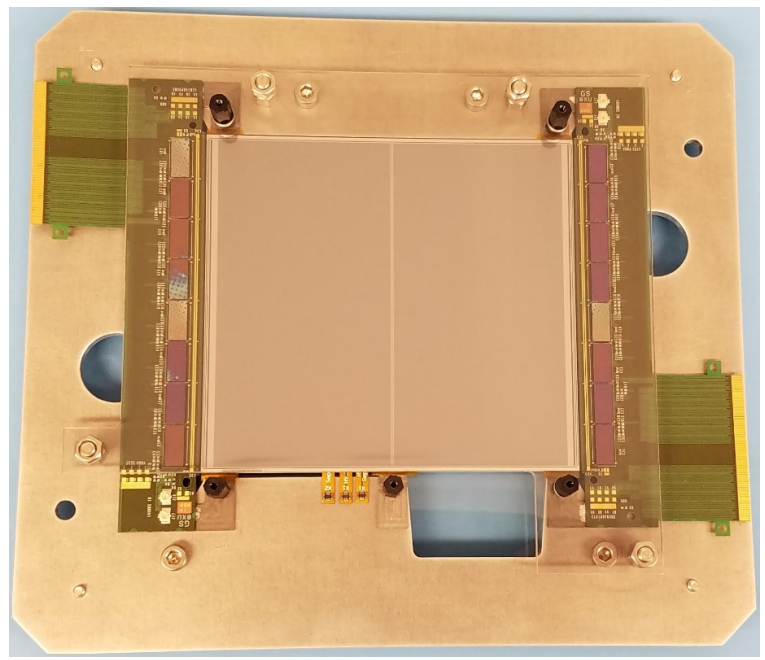
- 2S @Fermilab in March 2018
  - Needed to use some workarounds for missing components



Module readout scan: noise level as expected

- 2S @Brown in January 2019
  - Focused on PS assembly development while missing components
  - Module is now heading for Rutgers/Princeton for wirebonding

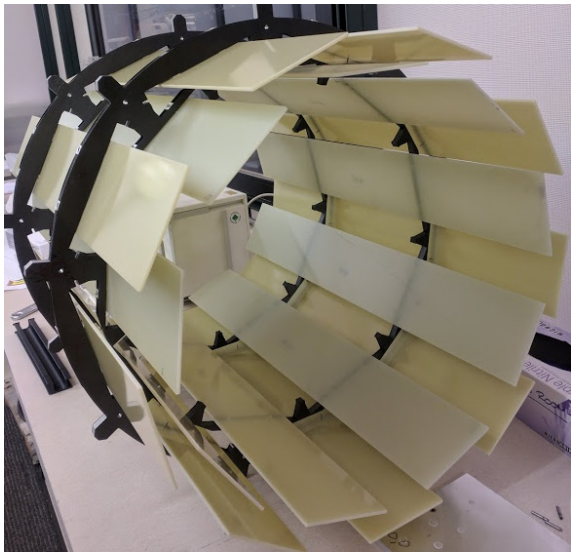


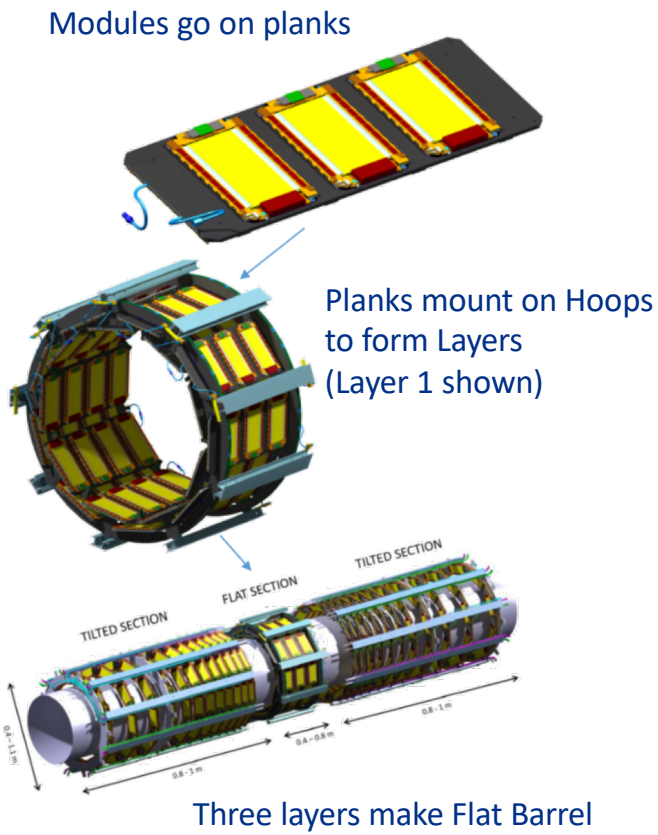


Prototype mechanics for flat barrel

- Fabrication of Carbon Fiber/Carbon foam Planks and Hoops
  - Stiffness, Heat transmission are key parameters
- System design and integration aspects of Flat Barrel
  - Challenge is mechanical strength with minimal material, adequate cooling, grounding and noise mitigation
- Status: Prototype design complete, prototypes being built

Mockup of layer one with prototype hoops and g10 for planks



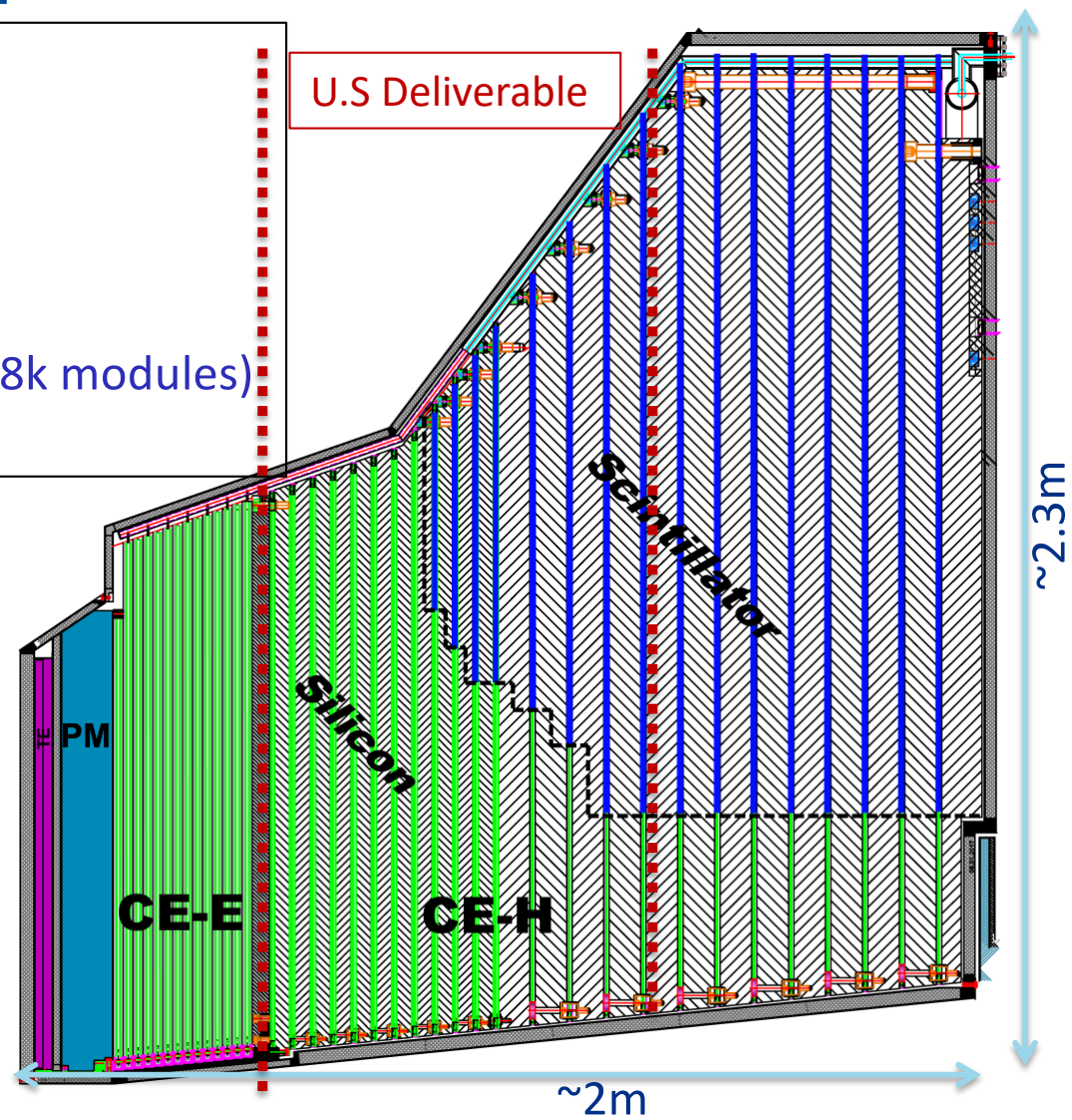


High Granularity Endcap Calorimeter

- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- Scintillating tiles with SiPM readout in low-radiation regions of CE-H
- Covers $1.5 < \eta < 3.0$
- **~600m²** of silicon sensors (6M channels, 28k modules)
- **~450m²** of scintillators (350k channels)

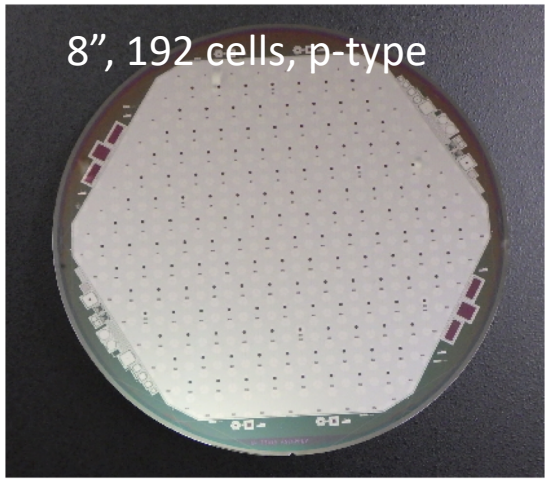
US Deliverables

- Silicon module construction procedures + ~13k Silicon modules
- Concentrator ASIC for overall calorimeter, motherboards
- Cassette Assembly for front 15 layers of the hadronic section
- LV/HV power supplies for hadronic section

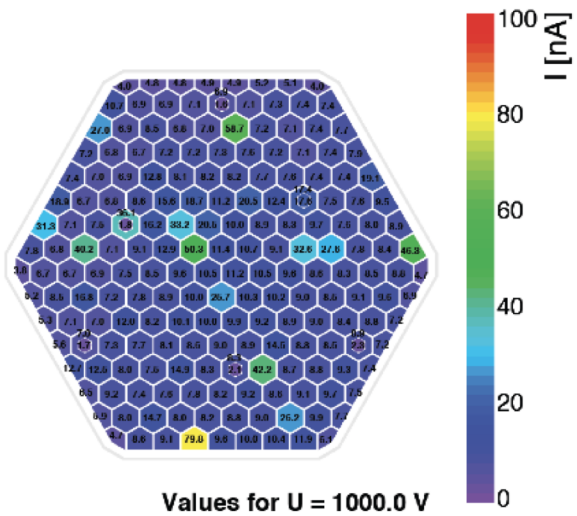


Electromagnetic calorimeter (**CE-E**): **Si**, Cu/CuW/Pb absorbers, 28 layers, 26 X_0 & ~2λ
Hadronic calorimeter (**CE-H**): **Si** & **scintillator**, steel absorbers, 22 layers, ~8λ

High Granularity Endcap Calorimeter



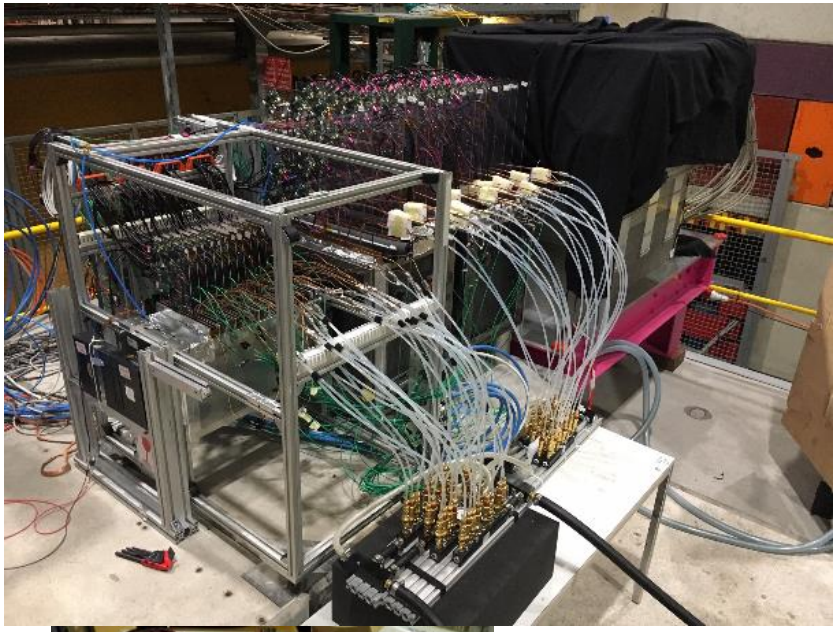
An excellent, defect free, sensor

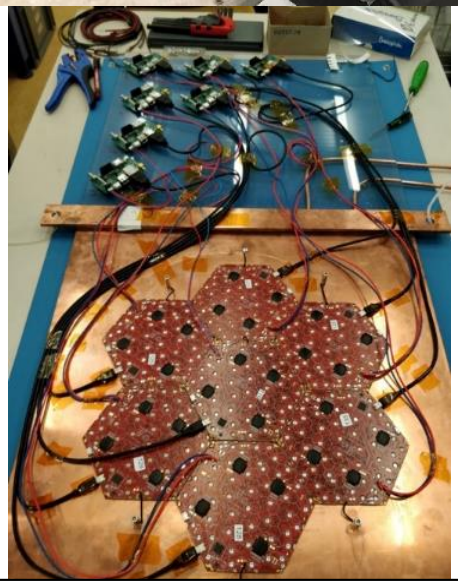


- Final-design silicon sensors received from HPK
  - Sensor quality generally good, some scratches on a few sensors from newly commissioned equipment
- Full-scale thermal-mockup cassette constructed at FNAL to validate mounting technologies, cooling scheme
  - Identified low-cost, high-performance baseplate material for hadron calorimeter modules: PCB

Endcap Calorimeter Workshop at Fermilab with cassette thermal mockup

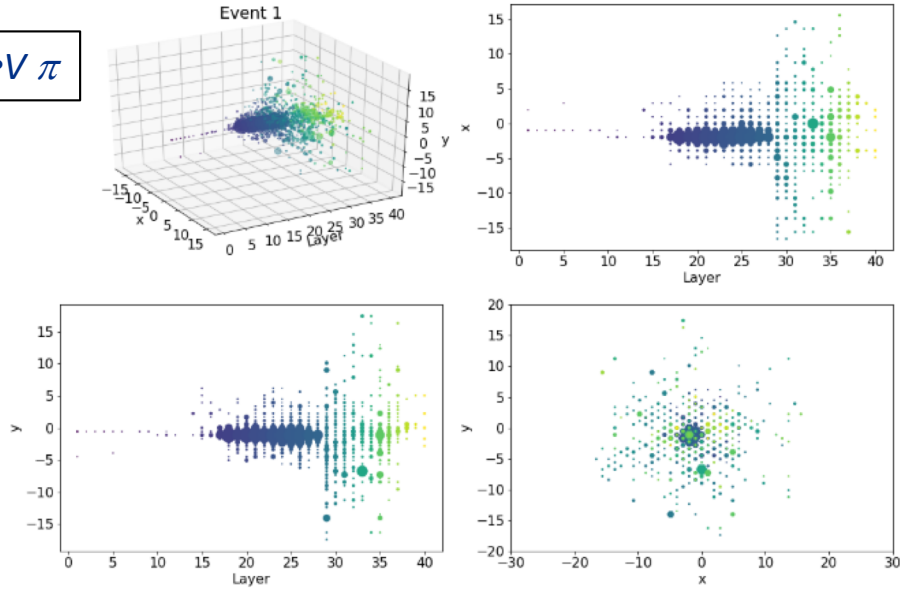
Testbeam 2018





7 hexagonal Si modules in 1 plane

300 GeV π

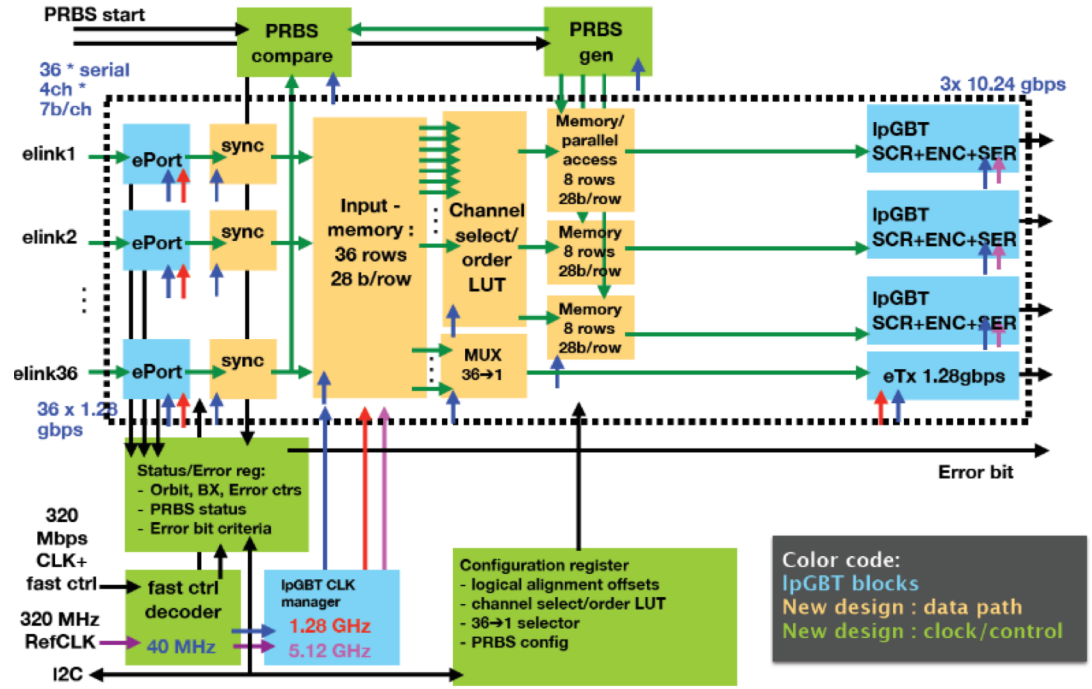


- US-built modules (~100) using automated system at UCSB
- US-developed DAQ/readout system (Minnesota)
  - Recycling FPGA mezzanine cards from CMS calorimeter trigger
- Excellent performance, good opportunity to study reconstruction, grounding, use of precision timing in hadron calorimetry, etc

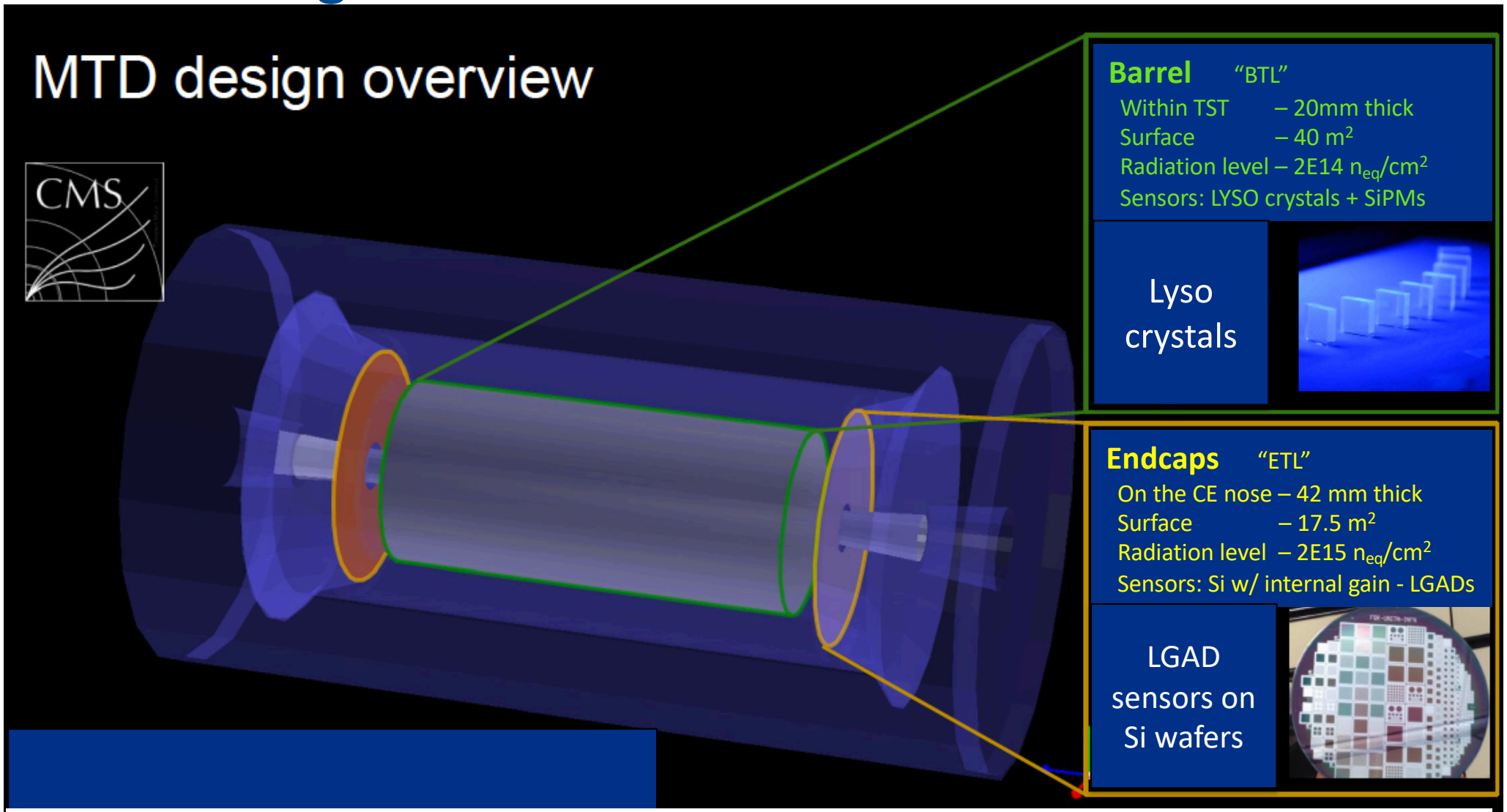
ECON ASIC

- Responsible for selecting data for readout and trigger computations
- Key component, has had a slow start due to limited ASIC engineering availability
- 2019 goal : Submit ECON prototype 1 for fabrication at end of August 2019.
  - Detailed conceptual specification for 1st prototype ECON is complete.
  - Gregory Deptuch is the lead engineer for the ECON and has made progress turning conceptual specification into a formal floor plan and creating a plan of work leading to 1st prototype submission.
- Rapidly building up team
  - FNAL has hired new Senior Engineer for ASIC design who will start work on ECON (100% FTE) the week of Jan 22, 2019.
  - FNAL is negotiating for effort from other labs (BNL / ANL), which should be starting soon.
  - FNAL has arranged for contributions from EE faculty and post doc from University of Split / FESB, Croatia. Visitors will come in mid-February 2019.

ECON prototype 1 concept diagram



MIP Timing Detector

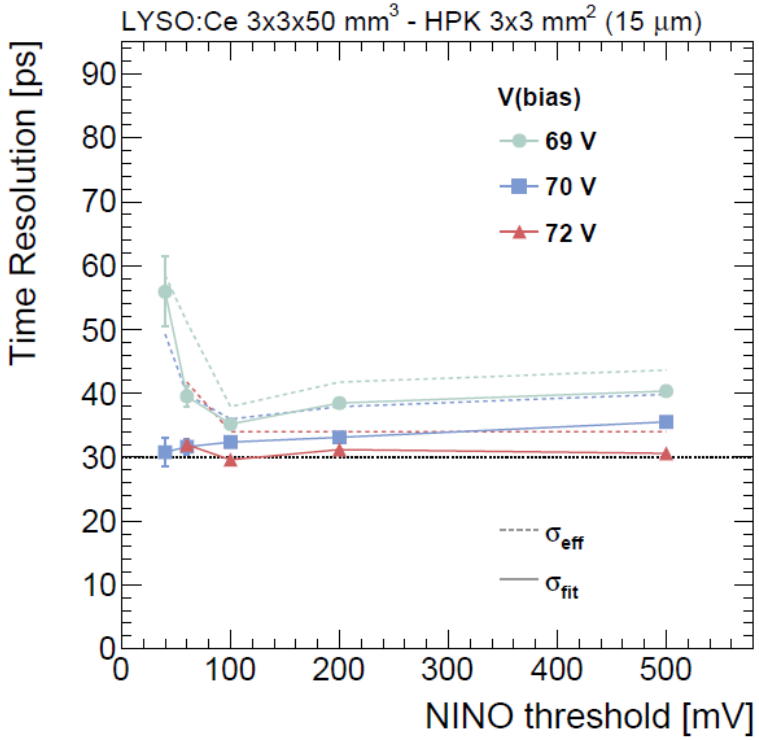


Design Requirements: Provide precision time measurement for MIPs with σ_t=30-40ps with sufficient radiation tolerance to maintain σ_t<60ps up to 4000/fb.

Barrel Timing Layer (BTL)

- Active element : LYSO crystals with SiPM readout.
  - Demonstrated time resolution ~30 ps in test beam
  - Operate at -30 C to mitigate radiation effects, maintaining time resolution up to the end of life of HL-LHC.
- First ASIC prototype (TOFHIR) delivered in December 2019, under test in the laboratory.
  - Test beams expected in summer 2019

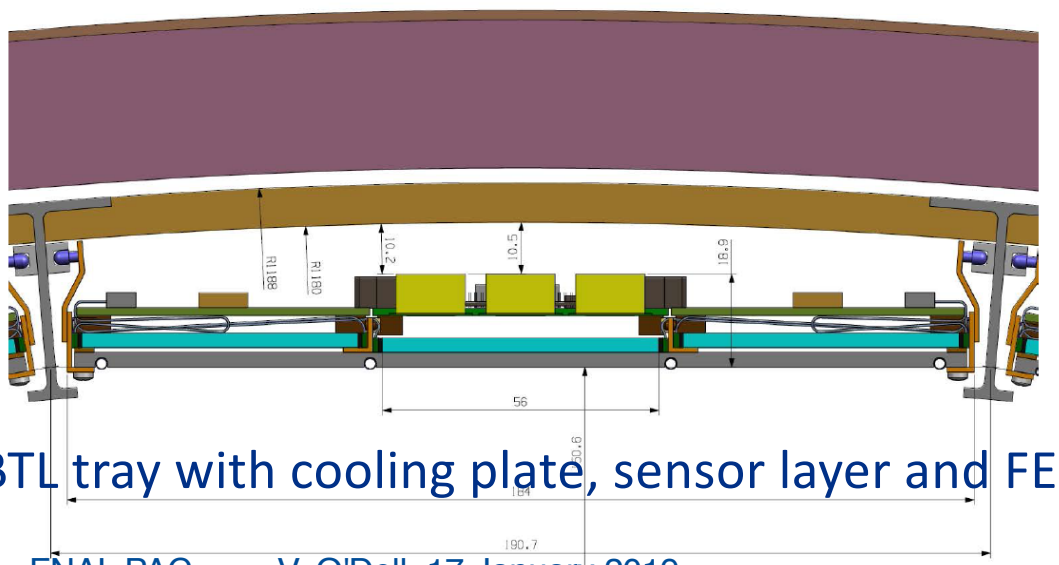
First Prototype of the TOFHIR ASIC (LIP)



Test beam results for BTL sensors

Barrel Timing Layer (BTL)

- BTL integrated into the tracker support tube, a carbon fiber structure serving as the mechanical support frame and thermal enclosure.
- BTL segmented into trays, consisting of 3 layers :
  - An aluminum cooling plate hosting the CO2 cooling pipes and serving as a mechanical support.
  - The sensor layer, consisting of LYSO elements with approximately 3 mm thickness, read out by SiPMs.
  - The front end electronics, consisting of the TOFHIR ASIC cards and concentrator cards providing connectivity between the ASICs and the backend.



BTL tray with cooling plate, sensor layer and FE

U.S. deliverables:

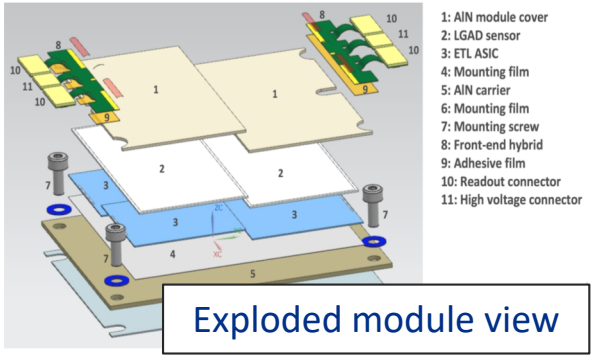
R&D and prototyping for assembly procedures. Assemble 60% of the BTL trays and associated QC testng, delivery to CERN

BTL Concentrator Card Prototype, pre-producton BTL SiPM. 40% of the BTL SiPMs

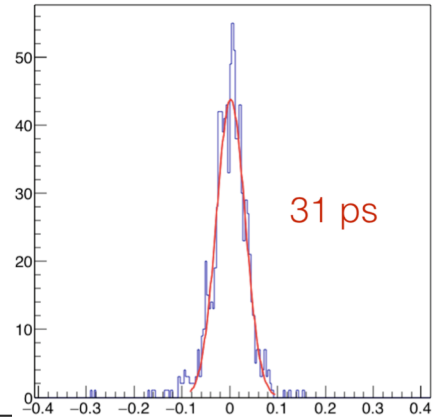
40% of production BTL LYSO crystals

Endcap Timing Layer

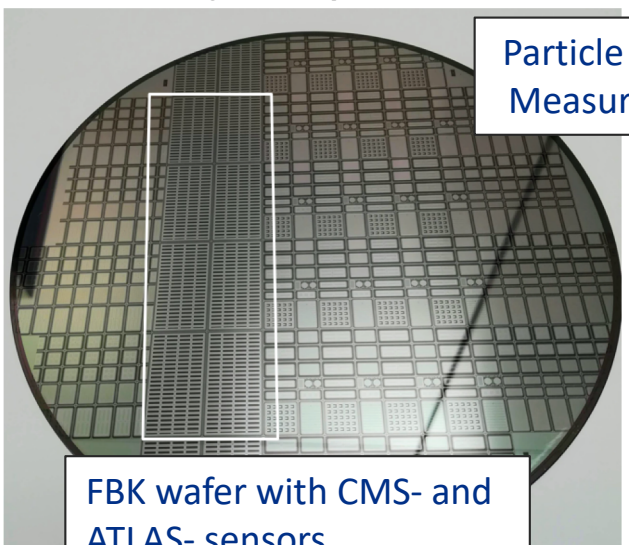
- Active element: silicon sensors with specially doped region that produces high electric field → produces avalanche signal with 10-30 gain (LGAD)
  - Large community: RD50 collaboration, several manufacturers: CNM, FBK, Hamamatsu
  - Demonstrated time resolution ~30 ps up to 1×10^{15} n_{eq}/cm^2, and about 40 psec up to 2×10^{15} n_{eq}/cm^2 high uniformity
- The ETL detector ensures at least two measurements per track, to achieve better than 35 ps resolution
  - Designed to be accessible for repairs and replacements of faulty components



Exploded module view

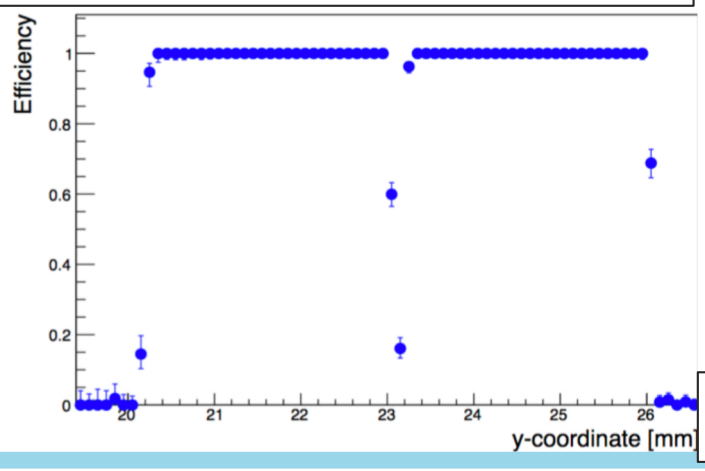


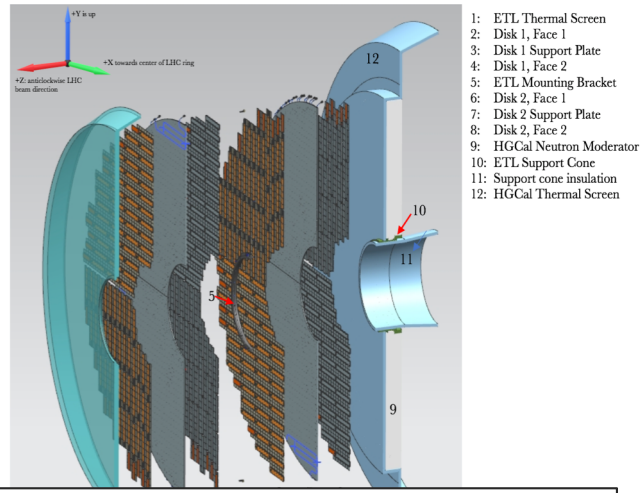
Time resolution measured in Fermilab test beam



FBK wafer with CMS- and ATLAS- sensors

Particle detection efficiency across sensor surface
Measurements performed at Fermilab test beam

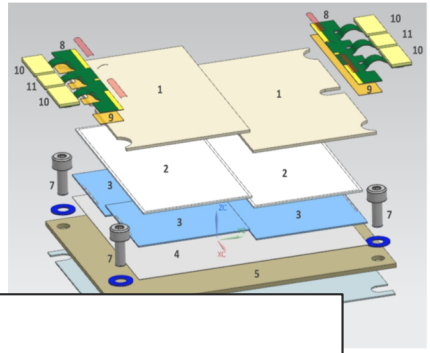




Cross-sectional view of the endcap timing layer (ETL) along the beam axis.

Endcap Timing Layer

- Active element: silicon sensors with specially doped region that produces high electric field → produces avalanche signal with 10-30 gain (LGAD)

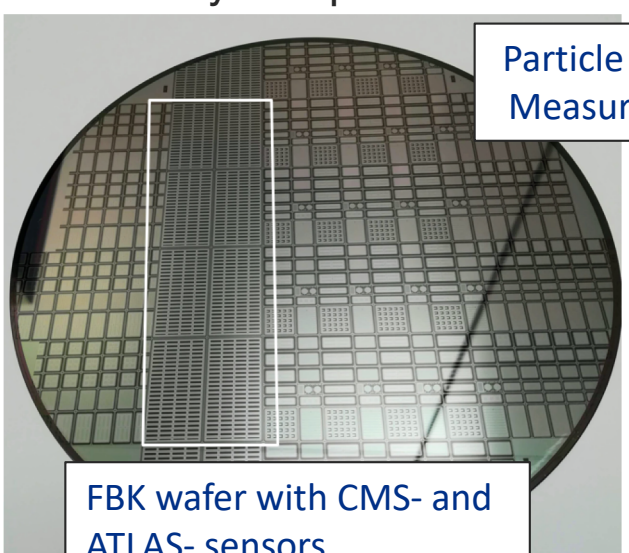


U.S. ETL deliverables

R&D / prototyping assembly procedures. Deliver 50% of assembled ETL modules, tested and graded, to CERN.

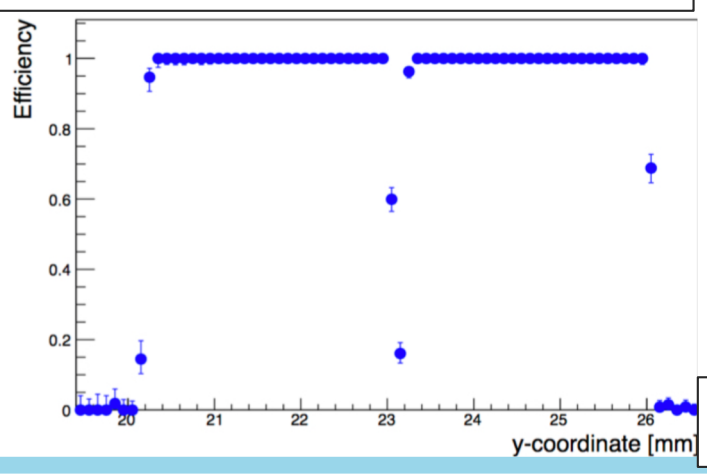
Design and prototyping of the ETL FE ASIC. Deliver 50% of the production ASICs

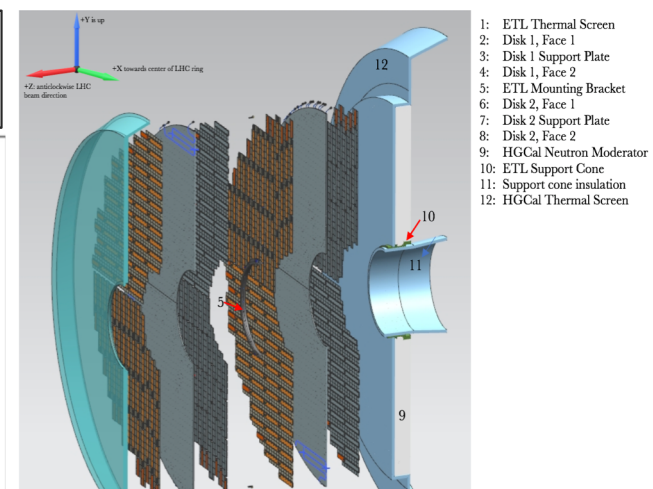
Time resolution measured in Fermilab test beam



FBK wafer with CMS- and ATLAS- sensors

Particle detection efficiency across sensor surface
Measurements performed at Fermilab test beam



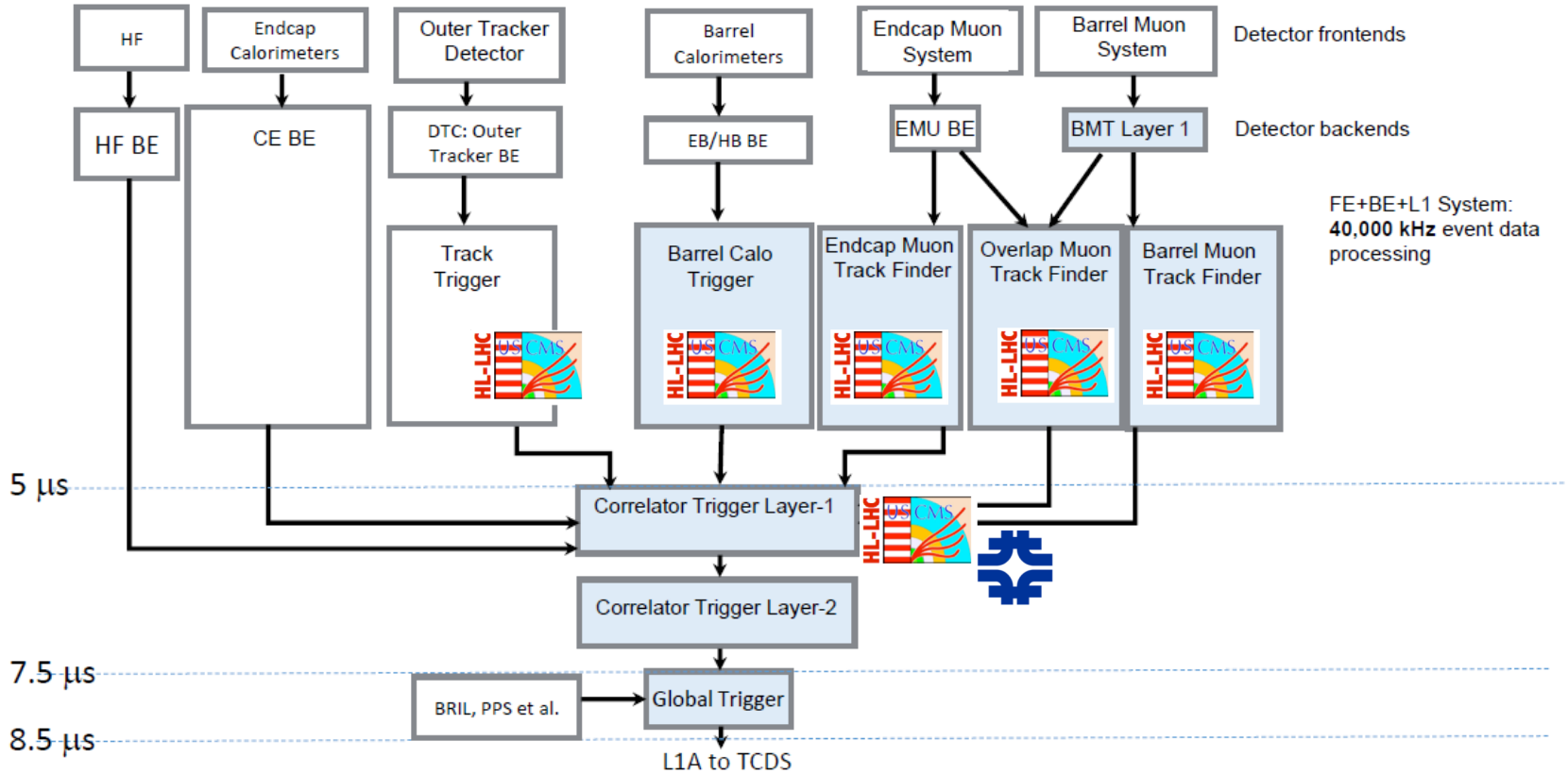


Cross-sectional view of the endcap timing layer (ETL) along the beam axis.

ETL ASIC status

- Have built a strong design team (SMU/Fermilab) that is making rapid technical progress.
  - Front-end design, implementation and optimization done (June – Dec 2018)
    - Critical front-end (preamp + discriminator) done with good post-layout simulation performance. First single channel mini-ASIC design submitted in Dec 2018, expected in March 2019.
  - TDC design study done (July – Dec 2018)
    - TDC design optimization and implementation started (complete April 2019)
  - Clock distribution implementation study for full size chip started (Dec 2018 -)
- Future Milestones:
  - Prototype 1 submission: Q2 CY2019 (4x4 pixel matrix, ETROC1)
    - Full chain: preamp+disc + TOA/TOT TDC with e-link
    - Bump-bondable to LGAD sensor -- test and evaluate the performance of the full-chain
  - Prototype 2 submission: Q3 CY2020 (8x8, ETROC2)
    - Supporting circuitry: PLL, phase shifter, fast/slow control, I/O, L1 buffer, clock distribution…
  - Pre-production submission: Q1 CY2022 (16x16 full size)
    - Scale to full-size with clock distribution

Trigger / DAQ



U.S. (Fermilab) leads the international CMS Trigger effort

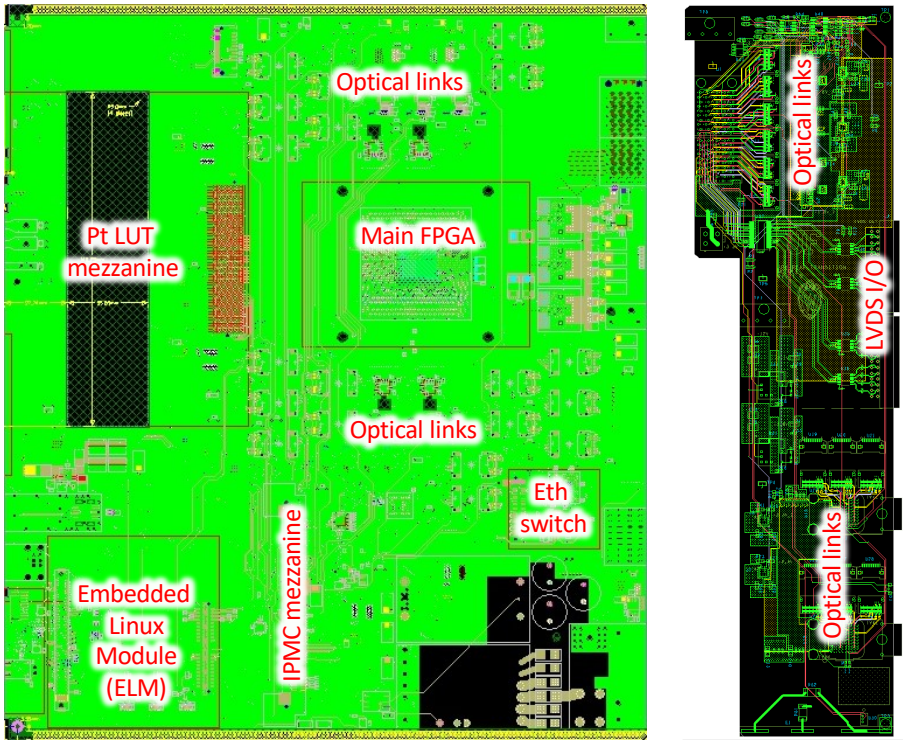
DOE: Barrel Calorimeter Trigger, Correlator Trigger

NSF: Track Trigger, Muon Trigger

A lot of synergy between DOE/NSF deliverables – for muon / calo / correlator triggers, common base hardware (APx – FPGA ATCA board)

Trigger / DAQ

- Main board + RTM
- **Large UltraScale+ FPGA**
  - Typically targeting Xilinx VU9P
- Embedded Linux mezzanine for control functions (Xilinx Zynq)
- IPMC mezzanine (another Zynq+Linux)
- Gigabit Ethernet as main control interface
  - Option for 10G Ethernet
- **~100 optical links** total
  - RX+TX each
  - **Up to 28 Gb/s each**
  - On main board with FPGA for cleanest high-speed signal path and widest airflow



Main board screenshot from T. Gorski

Current Status:

1st prototype APd1 (development board) being assembled now

Testing will start this month

Firmware development using HLS shows that we can run Particle Flow/PUPPI algorithms on the trigger boards within necessary latency and resource limitations

We will test the firmware on actual hardware in the next months!

Fermilab: building on strengths and facilities

- Silicon Detector Facility and silicon expertise
  - Critical for: building, assembling and testing Endcap Calorimeter cassettes and Outer Tracker Modules, design, assembly and testing of the Outer Tracker Flat Barrel, Endcap Timing Layer construction
    - Size of facility, high capacity dual-phase CO_2 cold plant
    - Facilities for custom fabrication of Carbon Fiber support
    - Equipment/personnel for precision mounting tasks and alignment survey
- ASIC engineering
  - Designing data concentrator chip for Endcap Calorimeter, readout chip for Endcap Timing
- Scintillator / SiPM expertise (Endcap Calorimeter)
- Firmware engineering / algorithm development

Fermilab: building on strengths and facilities

- Test beams
  - ***There will be no test beams at CERN in 2019/2020***
  - Fermilab has a world class test beam facility: We have taken the lead in test beams in the past due to having both the facilities and the personnel knowledge base.
- Irradiation Test Area (ITA)
  - Proposal for irradiation facility at MTEST (see talk from Mandy)
  - Shielding studies have launched – viewed favorably by DOE – this is an exciting new capability for Fermilab that will be used by CMS/ATLAS and others
  - CMS plans to start using it in April to irradiate test sensors for the Outer Tracker – this is a key step in international CMS testing and qualification plans
  - MTEST cleanup is critical path for this!

U.S. CMS Reviews

- U.S. CMS project is funded by both DOE (MIE) and NSF (MREFC)
  - For the NSF, funding is through an MREFC
    - Joint US ATLAS / US CMS MREFC (total of $150M)
    - MREFCs are approved by NSF Associate Lab Directors and the National Science Board. The ”gate” reviews are:
      - Conceptual Design Review (MREFC cost/schedule range) March, 2016) (check dates)
      - Preliminary Design Review (MREFC baseline) Dec, 2017 – NSB approval in Feb. 2018
      - Final Design Review (MREFC start construction) Sep, 2019 – NSB approval in Feb 2020
  - For the DOE funding for US CMS is through a normal O413.3B project ($162M)
    - CD-0 (Mission Need) granted 2016
    - CD-1 (Approve Cost and Schedule Range) June 2018/2019
    - CD-3a (Approve Long Lead Procurements) Fall, 2019
    - CD-2/CD-3 (Project Baseline / Start Construction) Fall 2020.
    - CD-4 (Project Closeout) Fall 2027

CD-1 Review (June, 2018)

- The upshot: Outer Tracker, Endcap Calorimeter, Trigger/DAQ were all recommended to proceed to CD-1 (>90% of the project by cost)
- The MIP Timing Detector was a late addition to the CMS suite of upgrades, and as such was not as mature as the other projects
  - i.e. does not yet have a TDR – was only approved to move to TDR last year
  - As a result, U.S. planning was not yet at a CD-1 level of maturity
  - The project has made huge progress since last June
- As a response to the CD-1 review, we have:
  - Strengthened the Project Office to respond to CD-1 recommendations
  - Firmed up the U.S. plans for the MIP Timing Detector, Appointed Project Management down to Level 4, Held a technical review of the MTD in November (which was quite positive), Preparing for a Fermilab Office of Project Support Services review of cost and schedule in January
- We will be addressing CD-1 again this year
  - March 19-21 for a Fermilab Director's Review (chaired by Mike Lindgren)
  - June 11-13 for the DOE Independent Project review

MTD PEMP Notable

- Additionally, the MTD was a topic for a Fermilab PEMP notable
  - "By December 2018 have a viable plan for the inclusion of the MIP Timing Detector (MTD) in the HL-LHC CMS project, within the funding constraints provided by the program, consistent with the larger international plan for the final design choice, and have the subproject fully staffed with people who have demonstrated both project management and technical expertise or drop the MTD from the project baseline".
  - We held a DOE briefing on December 3, and successfully demonstrated that the MTD satisfied all of the elements of the PEMP notable (https://indico.fnal.gov/event/19218/)
  - The MTD is now included in the project baseline

From: Procario, Michael [mailto:Michael.Procario@science.doe.gov]
Sent: Tuesday, December 04, 2018 4:01 PM
To: Nigel S. Lockyer <lockyer@fnal.gov>
Cc: Siegrist, Jim <Jim.Siegrist@science.doe.gov>; Robert S Tschirhart <tsch@fnal.gov>; Erik E Gottschalk <erik@fnal.gov>; Caradonna, Robert (BHSO) <Robert.Caradonna@science.doe.gov>; Rolli, Simona <Simona.Rolli@science.doe.gov>; Alan Harris <alan.harris@science.doe.gov>
Subject: HL-LHC CMS

I am writing to acknowledge that the lab has met the FY 2019 notable shown below.

"By December 2018 have a viable plan for the inclusion of the MIP Timing Detector (MTD) in the HL-LHC CMS project, within the funding constraints provided by the program, consistent with the larger international plan for the final design choice, and have the subproject fully staffed with people who have demonstrated bot project management and technical expertise or drop the MTD from the project baseline".

This decision is based on the briefing given to me, Simona Rolli, Robert Caradonna, and Alan Harris of DOE on December 3, 2018 and the material provided at https://indico.fnal.gov/event/19218/.

Mike Procario

MTD Technical Review (November, 2018)

Some excerpts from the final report:

1. Are the physics requirements clearly stated and documented? Have the requirements been translated into technical performance requirements and specifications? **Resounding YES. If the physics goal of 30ps timing is not met, there is still significant benefit to the physics output of the detector up to 60ps resolution and thus should be**

4. Are the risks (technical, cost, and schedule) of the selected base design approach and alternatives understood and documented, and are appropriate steps being taken to manage and mitigate these risks? **Committee was impressed with maturity of thought that has gone into understanding the risks as well as potential mitigating steps.**

Are the required resources for delivering the project understood and likely to be available both for the design and construction phases? **The team being assembled for MTD is top notch and mostly completely orthogonal to the rest of the CMS upgrades. Thus the MTD project does not present a resource threat to the other upgrades nor is it dependent on people committed to the other projects.**

Of course, we have some recommendations to address before CD-1

Conclusions

- U.S. CMS contributions are critical to CMS HL-LHC upgrades, and Fermilab is critical to U.S. CMS contributions
- We are making significant technical progress in all areas of the update
- Critical items from the lab that we need to continue our success are:
  - ASIC engineering. This is being addressed, however we believe another new hire would help ensure success of FNAL ASIC commitments. CMS depends on the success of the FNAL ASIC group.
  - Irradiation Test Area – we really need this by April, 2019. This implies cleanup of MTEST needs to start now.
  - Lab scientists are key to the success of CMS and the HL-LHC detector upgrades and strong support for the CMS research program is critical.

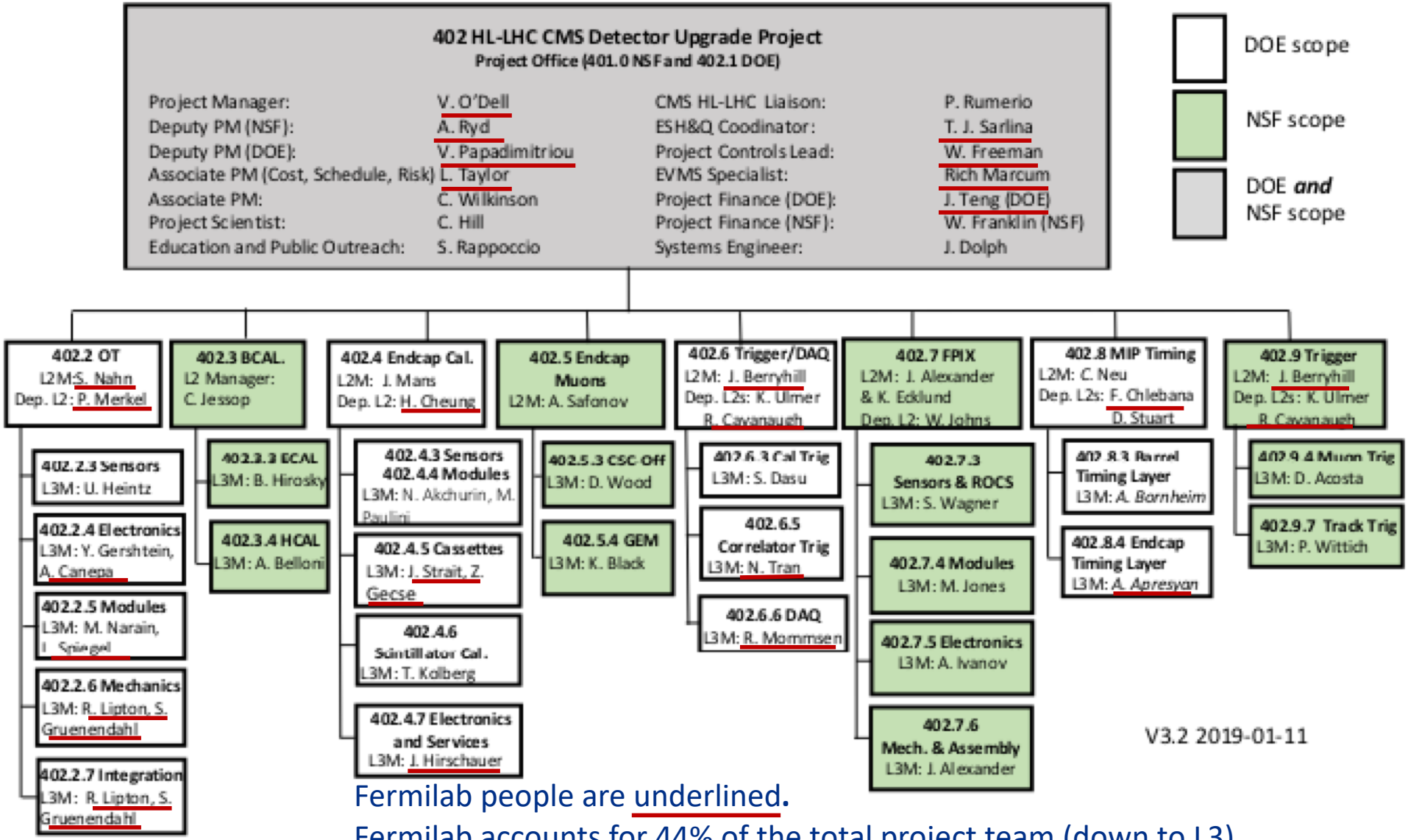
CMS HL-LHC upgrades

backup

Fermilab Deliverables for HL-LHC CMS Upgrades

- Outer Tracker:
  - 2700 total combination of PS/2S modules (includes preproduction & spares) (~17% of the total modules for the OT).
  - Flat barrel (mechanical structure + PS modules coming from above production)
  - Bump bonding of all MaPSAs (pixel side of PS modules) – oversight and QC
- Endcap Calorimeter
  - Design and assemble 375 Cassettes (corresponding to 1st 15 layers of hadronic section + test wedge), test, ship to CERN
  - Assemble tile modules for 1st 15 layers
  - Design and provide concentrator ASICs for the whole EC project (ECON)
- MIP Timing Detector
  - Endcap Timing Layer – design FE ASIC, supply 50% of the final ASICs
  - Develop module assembly procedures, share module assembly of 50% of the ETL modules with Nebraska (exact share is unclear right now).
- Trigger/DAQ
  - DAQ Storage Manager, trigger algorithms/ firmware/board testing

U. S. CMS HL-LHC Upgrade Organization

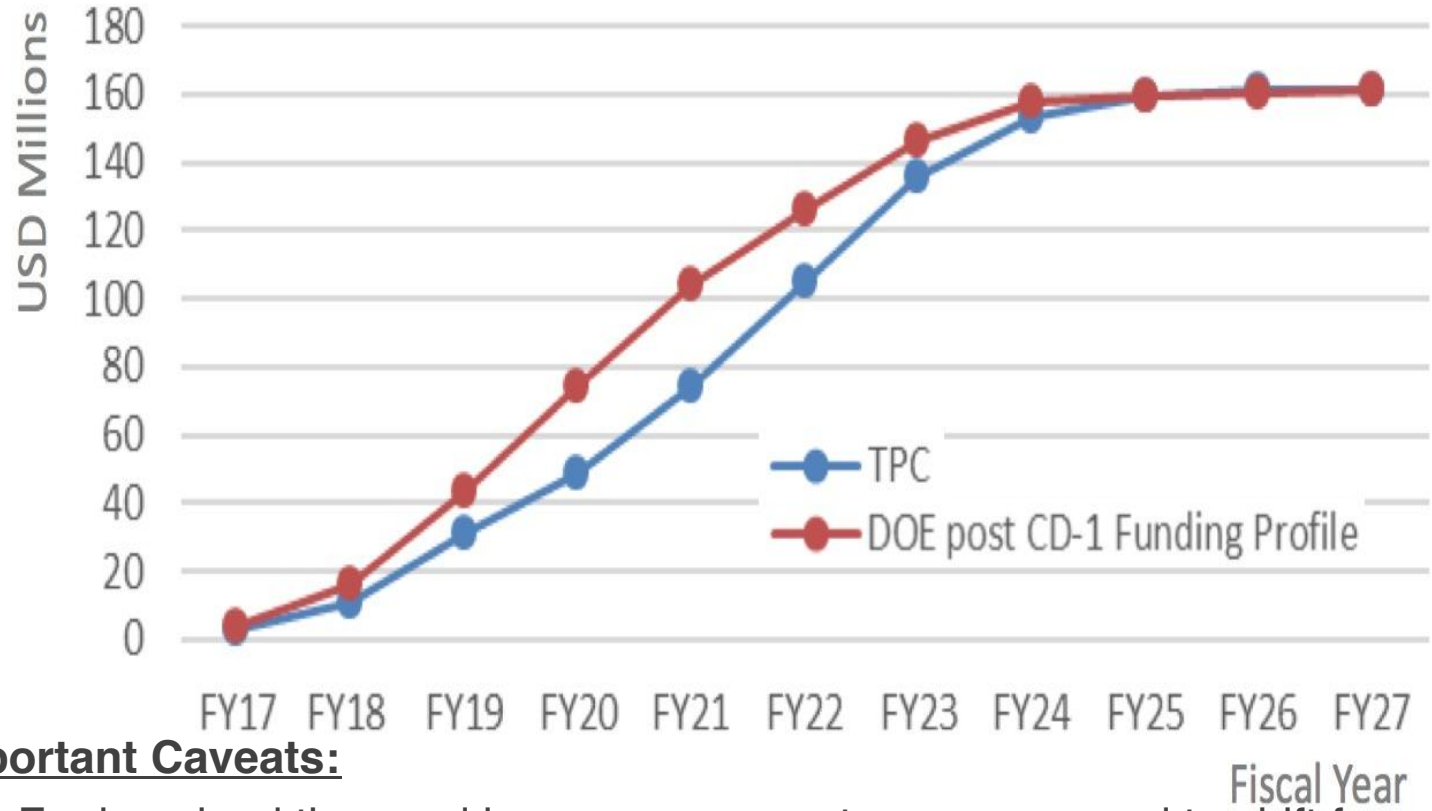


Fermilab people are underlined.

Fermilab accounts for 44% of the total project team (down to L3).

Working towards the CD-1 DOE profile

Project profile vs. DOE funding



- **Important Caveats:**
  - For long lead time and large procurements, we may need to shift forward by 3-6 months, especially e.g. large Si purchases through CERN for OT/EC
  - **This is not the final DOE funding profile**
    - Funding for FY17-FY19 is "fixed", from FY20 onwards this could change
    - We have run several scenarios for funding from DOE – we believe we are ok profile wise
    - We will get a CD-1 funding profile to use for the Fermilab Director's Review

CERN/CMS Project Approval Process

Four step definition/review process:

1. Technical Proposal defines the overall scope and cost for the entire upgrade program, with the possibility to maintain different options which may depend on technical issues and/or on funding availability.
2. The detailed technical design reports (TDR) for subsystems are reviewed individually, with the requirement that each fits in the overall approved plan for scope and cost (Project Baseline).
3. The final design and construction readiness of the major detector components are reviewed, as well as the installation plan (Start of Construction).
4. Operations readiness reviews held to evaluate the capability of the completed detectors to provide the expected performance and mark the end of the construction project. (Start of Operations or Project Completion).

We are here*

*Exceptions: MIP Timing Detector (Has TP, TDR submission March, 2019)

Trigger/DAQ will have final TDRs in 2019/2020 (benefit from latest tech.)

The U.S. in International CMS HL-LHC Upgrade

Upgrade Support Project Office

UTC, UEOC, URM, UPO, UPSG

Upgrade Project Coordinator and deputies
Frank Hartmann, Didier Contardo, Paolo Rumerio

Cent. Coord. Contacts
- Off./Comp. Coord.*
- PPD Coord.
- Trigger menus Coord.
- Run Coord.

Dmitri Denisov has been named CMS Upgrade Planning Officer (UPO) Oversees Milestones, Schedules, and Risk Registry across the project.

U.S members
( ) FNAL

Cross-System Working Groups

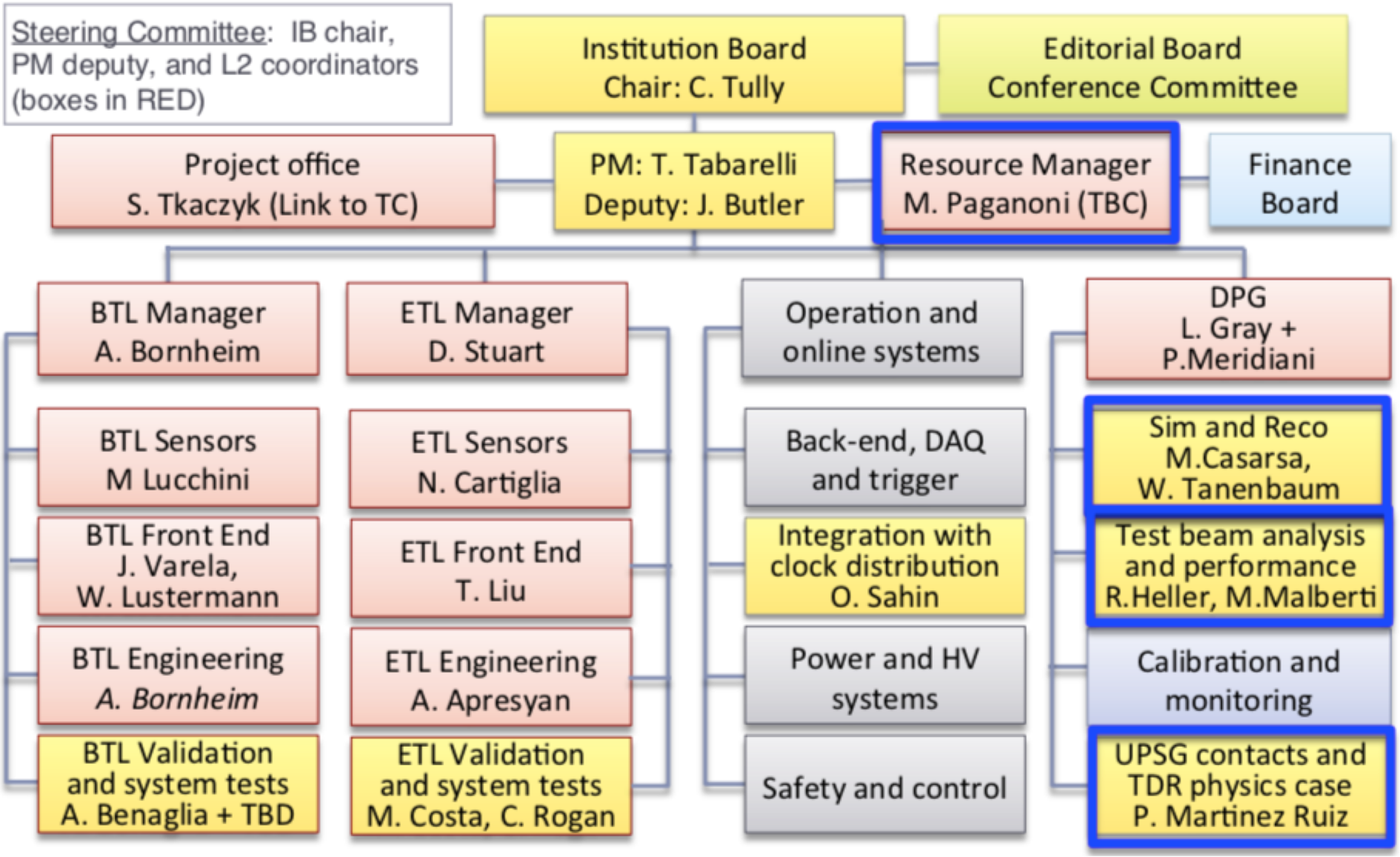
- Performance Studies*
  UPSG convener(s)
- Electronics and Online Systems**
  UEOC + convener(s)
- Detector Interfaces and Integration**
  UTC + convener(s)

* Joint with Physics Coord
** Joint with Tech. Coord

Upgrade Systems
SUC and STC

- Tracker: D. Abbaneo
- Barrel Calorimeters: C. Jessop
- Endcap Calorimeter: T.Virdee,MMannelli
- Muons: A. Korytov
- MIP Timing Det: T. Tabarelli, J. Butler
- BRIL: A. Debrowshi, D. Stickland
- L1-Trigger : J. Berryhill, A. Zabi
- DAQ/HLT : E. Meschi

International CMS MTD Management

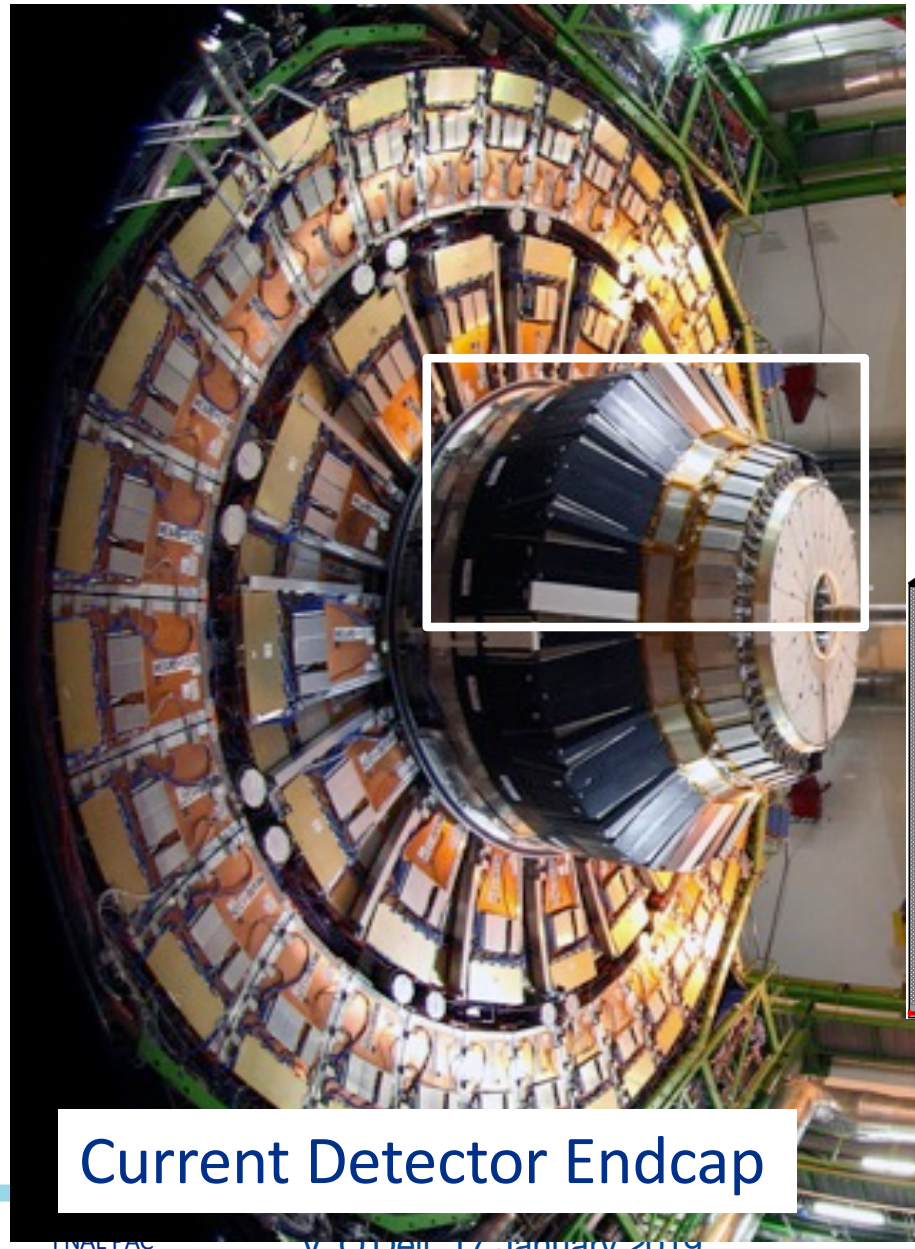


USCMS HL-LHC upgrades: Fermilab

- Fermilab major scientific contributions to the upgrade detectors are:
  - International CMS Subsystem Upgrade Coordinators in Trigger and MTD
  - International leadership roles in Endcap Calorimeter, Trigger, MTD
  - Project office (2 Scientists)
  - Tracker (6 Scientists+ 1 new hire+3 postdocs)
    - modules and mechanics
    - Test stands / test beams / integration tasks
    - MaPSA testing
  - Endcap Calorimeter (8 Scientists+1 postdoc)
    - Cassette design, assembly, testing
    - Sensor design, testing
    - Data concentrator ASIC
  - Trigger/DAQ (6 Scientists+ 2 postdoc)
    - Trigger leadership/Calorimeter Trigger / Correlator Trigger / Algorithms
  - Fast timing (MTD) (8 Scientists + 2 postdocs)
    - Front end chip, barrel mechanics design, endcap design

(#) = headcount, not FTEs.

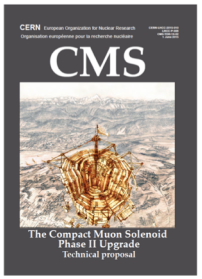
High Granularity Endcap Calorimeter

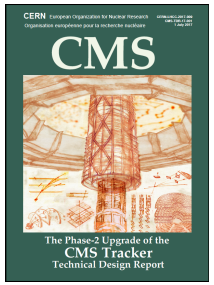


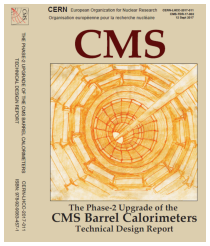
Current Detector Endcap

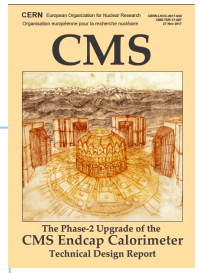
CMS HL-LHC Upgrade Endcap

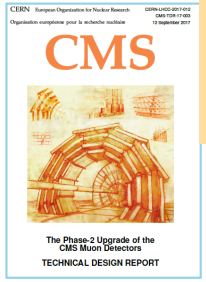
Status of the CMS HL-LHC Upgrades











Subsystems

1. Tracker: consists of Outer Tracker and Inner (Pixel) Tracker
   - **Tracker TDR**: https://cds.cern.ch/record/2272264. UCG report: https://cds.cern.ch/record/2295762
   - Approved by CERN RB Dec. 4, 2017
2. Barrel Calorimeter: consists of hadronic and electromagnetic
   - **Barrel Calorimeters (TDR):** https://cds.cern.ch/record/2283187. UCG report: https://cds.cern.ch/record/2304338
   - Approved by CERN RB March 7, 2018
3. Endcap Calorimeter: both hadronic and electromagnetic parts
   - **Endcap Calorimeter (TDR**) https://cds.cern.ch/record/2293646. UCG report: https://cds.cern.ch/record/2313441
   - Approved by CERN RB April 18, 2018
4. Muon Systems: both hadronic and electromagnetic parts
   - **Muon Systems (TDR):** https://cds.cern.ch/record/2283189. UCG report: https://cds.cern.ch/record/2304341
   - Approved by CERN RB March 7, 2018
5. L1-Trigger; DAQ
   - L1-Trigger (interim-TDR): https://cds.cern.ch/record/2283192. **TDR Q1 2020**
   - DAQ/HLT (Interim-TDR): https://cds.cern.ch/record/2283193 . **TDR Q2 2021**
   - Both iTDRs approved by RB Dec. 4, 2017
6. MIP Timing Detector
   - MIP Timing (Technical Proposal) : https://cds.cern.ch/record/2296612 . **TDR Q1 2019**
   - TP approved by CERN RB March 7, 2018

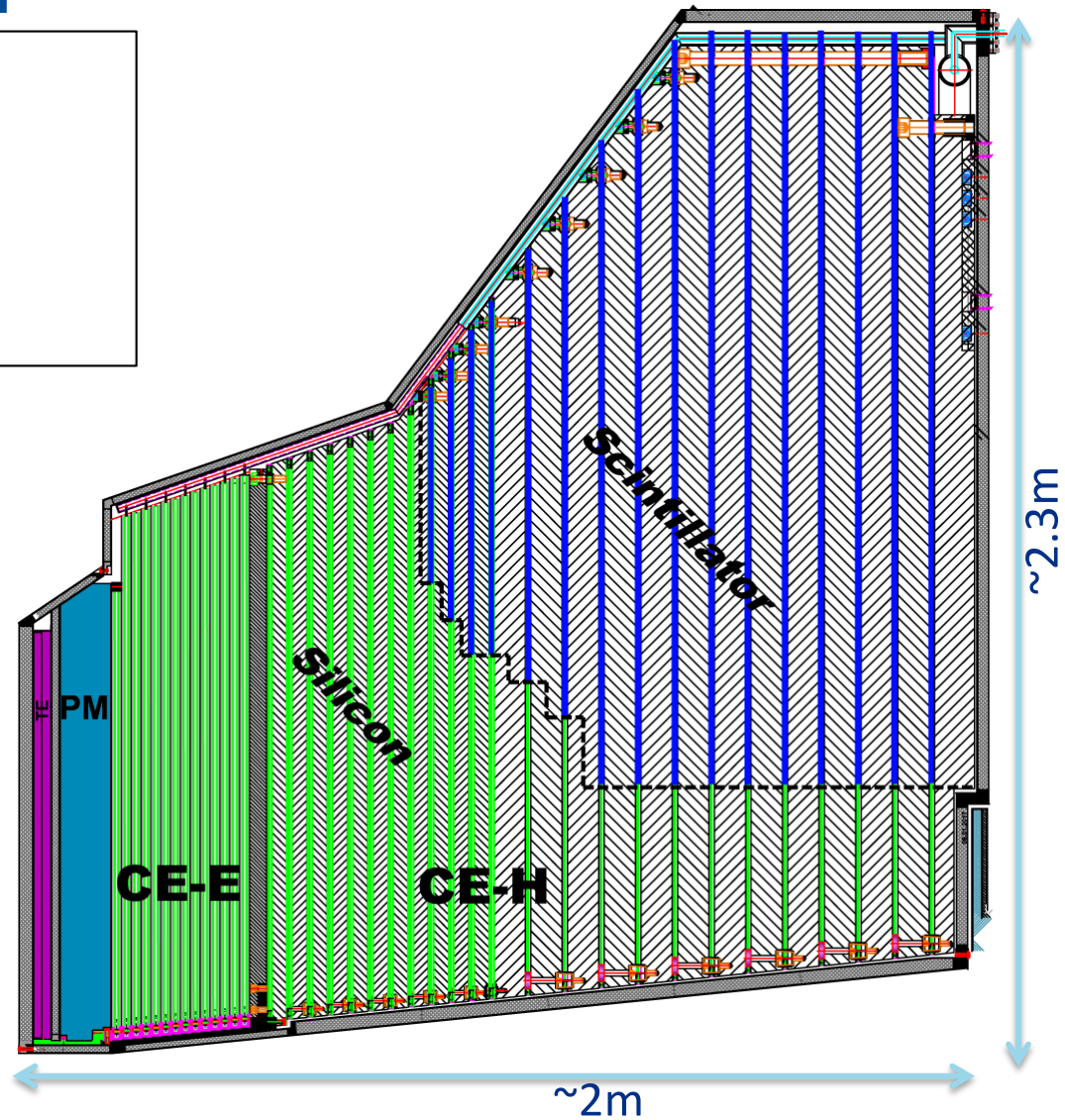
High Granularity Endcap Calorimeter

Active Elements:

- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- Scintillating tiles with SiPM readout in low-radiation regions of CE-H

Key Parameters:

- HGCAL covers $1.5 < \eta < 3.0$
- **Full system maintained at -30°C**
- **~600m²** of silicon sensors
- **~450m²** of scintillators
- 6M Si channels, 0.5 or 1.1 cm² cell size, 350k scint-tile channels ($\eta-\phi$)
  - Data readout from all layers
  - Trigger readout from alternate layers in CE-E and all in CE-H
- ~28000 Si modules (incl. spares)



Electromagnetic calorimeter (**CE-E**): **Si**, Cu/CuW/Pb absorbers, 28 layers, 26 X_0 & ~2λ
Hadronic calorimeter (**CE-H**): **Si** & **scintillator**, steel absorbers, 22 layers, ~8λ

CERN/LHCC Management, Oversight, and Review

- Project approvals:
  - The LHC Committee (LHCC) reviews and approves TDRs for scientific and technical merit
  - The Upgrade Cost Group (UCG) reviews cost, schedule, and risk
  - When the LHCC and UCG reviews are passed, the Research Board (RB) approves the project
  - When the ensemble of projects is approved it is sent as a package to the Resource Review Board (RRB) to approve final financial obligations
- Project monitoring
  - The LHCC Phase 2 Upgrade Group has been formed and will review the approved projects annually
  - 1st such review for CMS is May 20-21, 2019

US CMS Software and Computing During LS2

- Significant upgrade of computing facilities and capabilities needed, to meet Run 2 analysis and Run 3 data processing needs
  - maintain & replace aging hardware, increase computing capacity as needed, and use HPC resources
    - external resources that might only be available periodically will enter the computing cost equation, such as DOE and NSF HPC resources, commercial clouds, and opportunistically shared resources
    - re-direction of work to the most cost-effective available resource, through Fermilab HEPcloud
  - Already now significant use of DOE and NSF HPC centers:
    - CMS was awarded 82M hours at NERSC for 2019, and NSF XSEDE allocations are actively used and ready for renewal, requesting resources at HPC centers to handle ~5% of CMS's simulation needs for the year
- Software development to upgrade aging computing services (data / workflow management etc) to improve infrastructure performance
  - Example is work on data management and data access systems, that need significant upgrades
  - Run3 will be serving as a "dress rehearsal" for HL-LHC
- Ramping up R&D towards software and computing upgrades for HL-LHC
  - US CMS efforts at Fermilab and Universities are part of an emerging global work plan
  - WLCG "strategy" document prioritizes a program of work, focusing on some of the topics covered by the Community White Paper
  - Driven by US leadership, CMS is making significant progress, with a number of concrete examples
  - e.g. nanoAOD and push towards use of common software solutions