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Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

U.S. CMS Upgrades

Steve Nahn

Fermilab Institutional Review

February 10-13 2015

Long History of CMS Construction at Fermilab

DOE/NSF Baseline Review
of the CMS Detector Project
5/22/98

16 years

DOE Critical Decision 2 and 3 Review
of the LHC CMS Detector Upgrade Project
8/06/14

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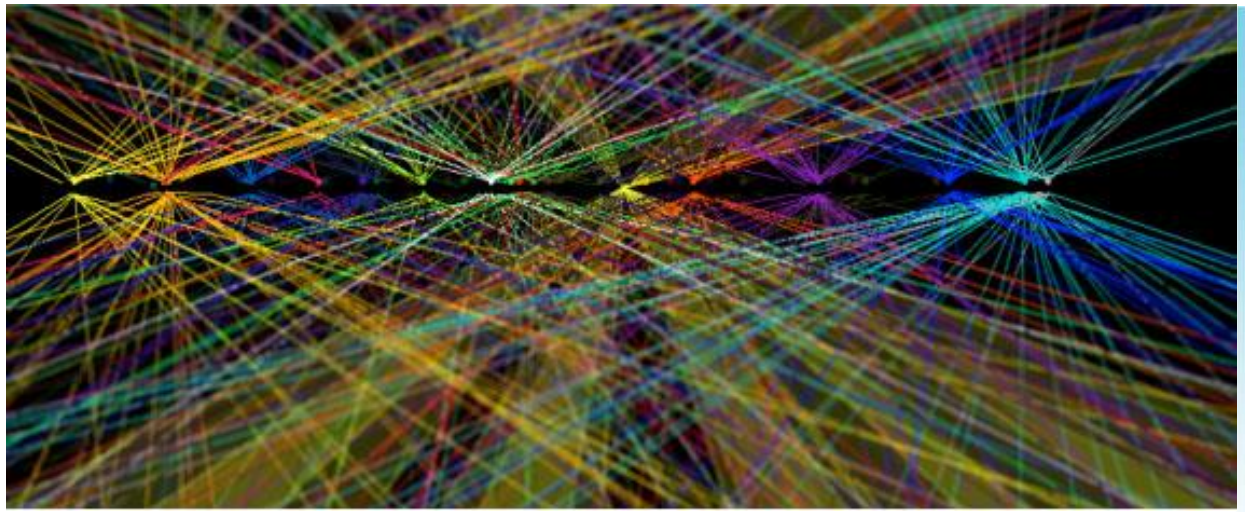
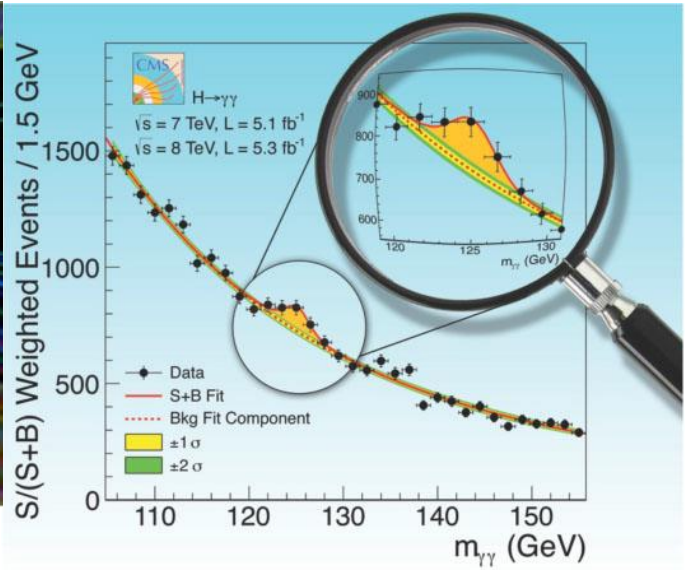
Motivation

P5 Recommendation 10: Complete the LHC phase-1 upgrades and continue the strong collaboration in the LHC with the phase-2 (HL-LHC) upgrades of the accelerator and both general-purpose experiments (ATLAS and CMS). The LHC upgrades constitute our highest-priority near-term large project.



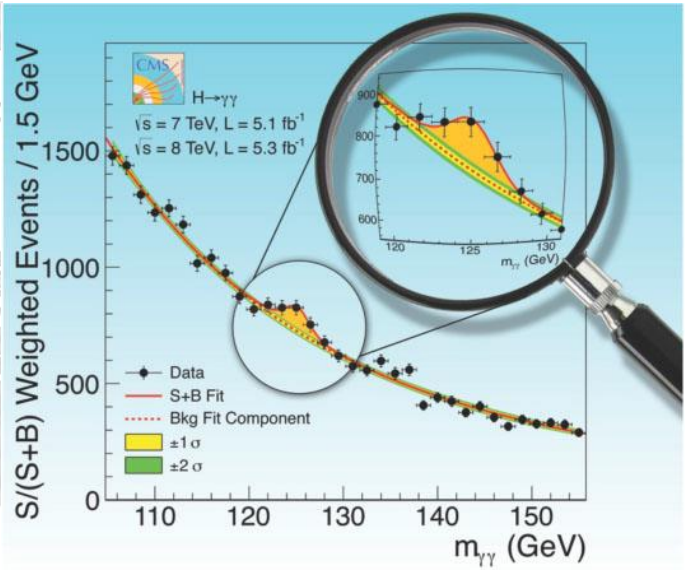


Physics Case for Upgrades

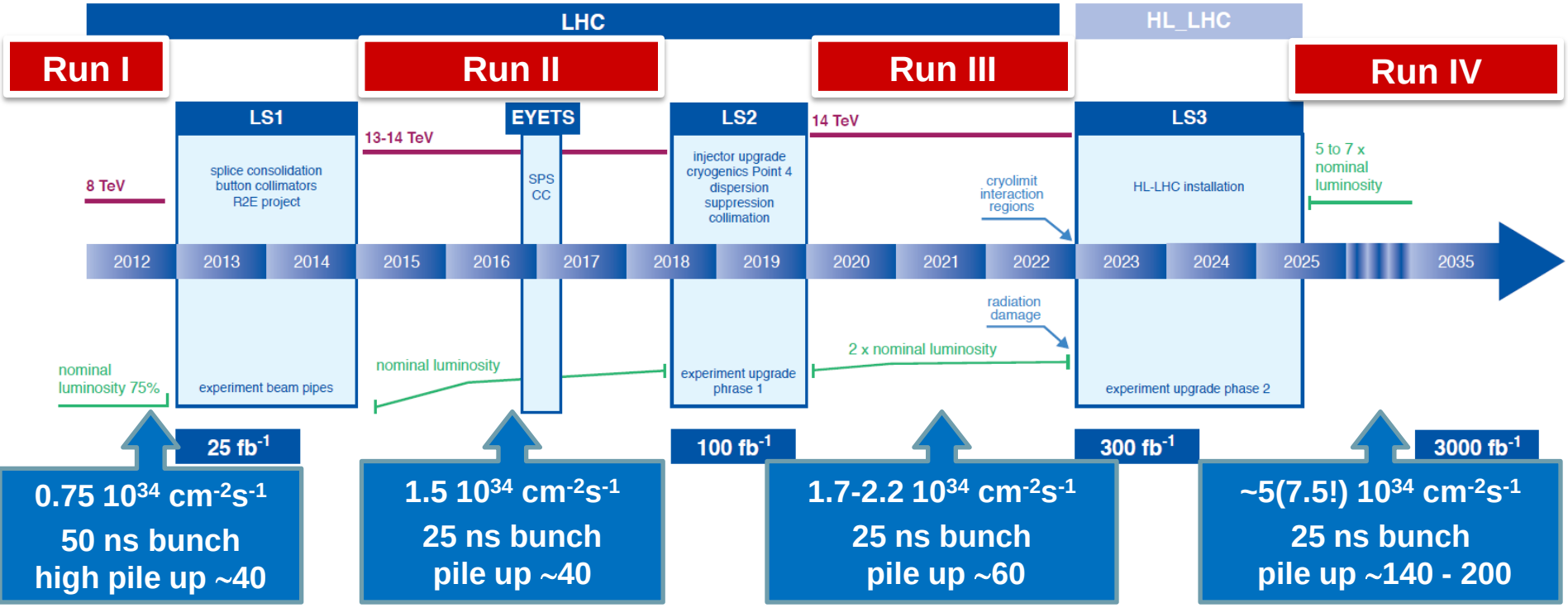
- CMS Run 1 was an unqualified success
  - > 300 publications and counting
  - One Higgs Boson, $m_{\mathrm{H}} = 125.02\,^{+0.26}_{-0.27}(\mathrm{stat.})\,^{+0.14}_{-0.15}(\mathrm{syst.})\ \mathrm{GeV}$
    - Sets the stage for Run 2
  - What are the rest of the Higgs Properties?
  - What makes it so light?

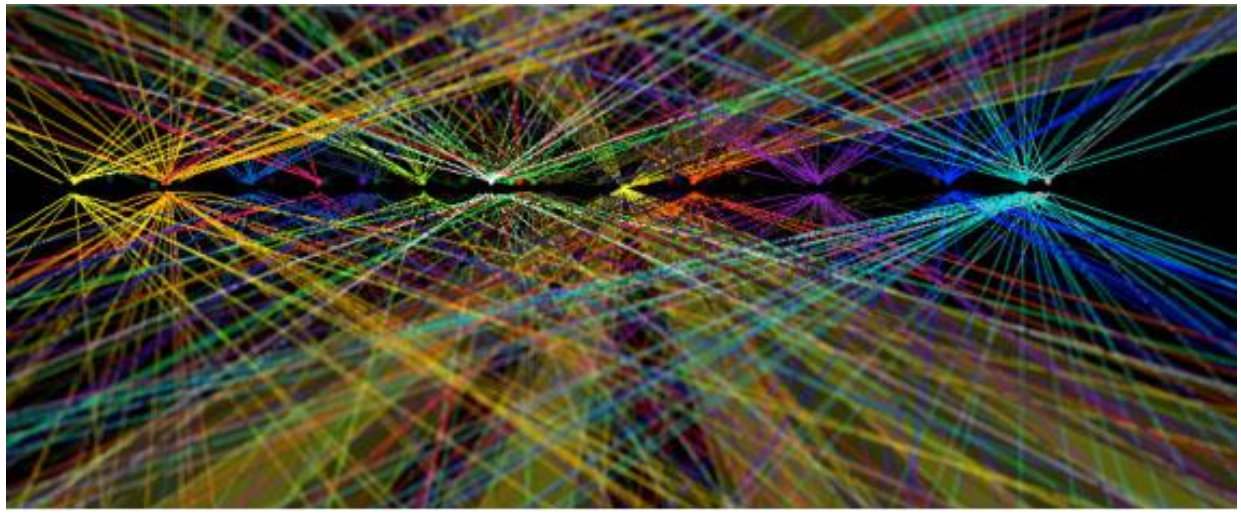
New Physics at higher Energies found with higher Luminosity

- Principle of Requirements
  - Achieve same or better efficiency, resolution, background rejection, trigger thresholds as in Run 1
  - Leverages initial U.S. investment with potentially enormous payoff



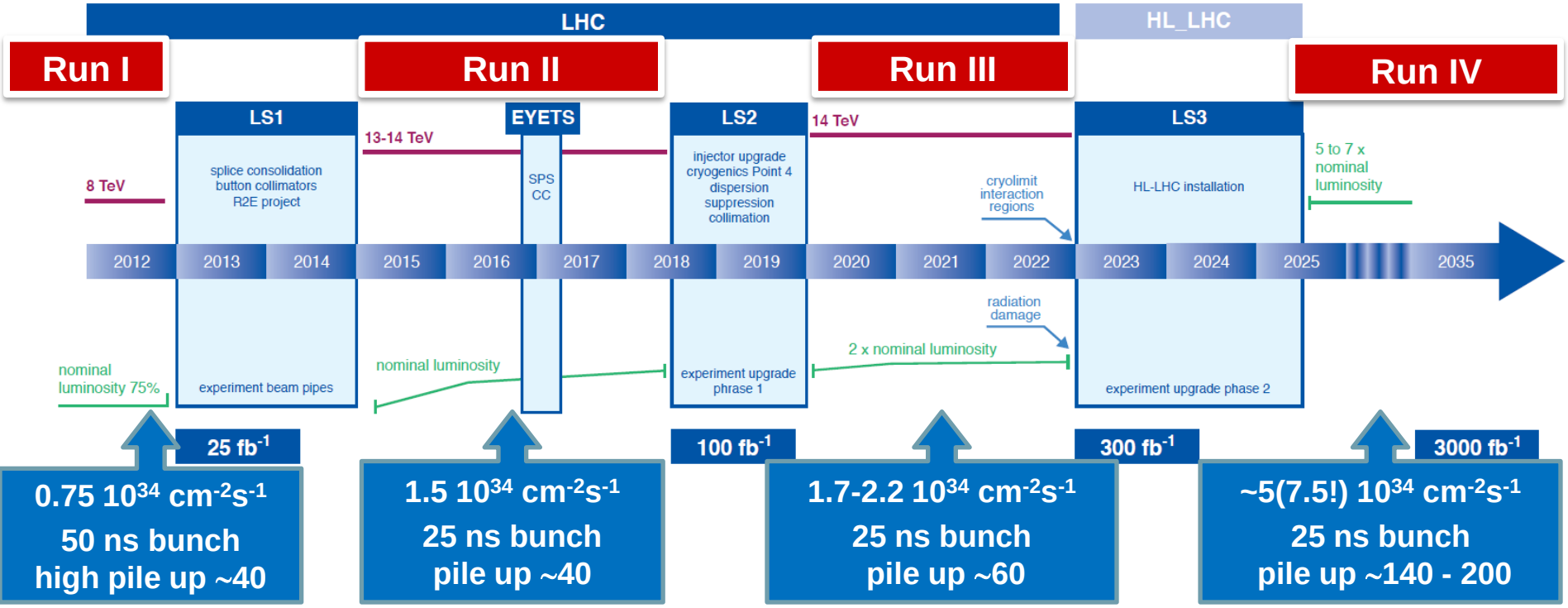
Challenge of LHC Run 2 and beyond





- Criteria for Upgrades
  - Maintain low trigger thresholds with increased event rate
  - Operate with increasingly higher pileup
  - Survive doses ≤ 500 fb-1 before LS3, up to 3 ab-1 by end of HL-LHC

The Upgrade Plan



Phase 1 Upgrades – CD-3 Approved

- New L1 Muon and Calorimeter triggers
  - Running in 2016
- New forward pixel detector
  - Installed in 2016-2017 EYETS
- HCAL upgrade: photodetectors and electronics
  - HF Install 2015-2016 shutdown
  - HB/HE Install LS2 (2018) or earlier

Phase 2 Upgrades: Technical Proposal this fall

- Tracker Replacement, Track Trigger
- Endcap Calorimeter replacement
- Barrel ECAL Electronics
- Trigger/DAQ
- Tracker & possible endcap Calorimeter, Muon extension $|\eta|=3$ to $|\eta|\sim4$

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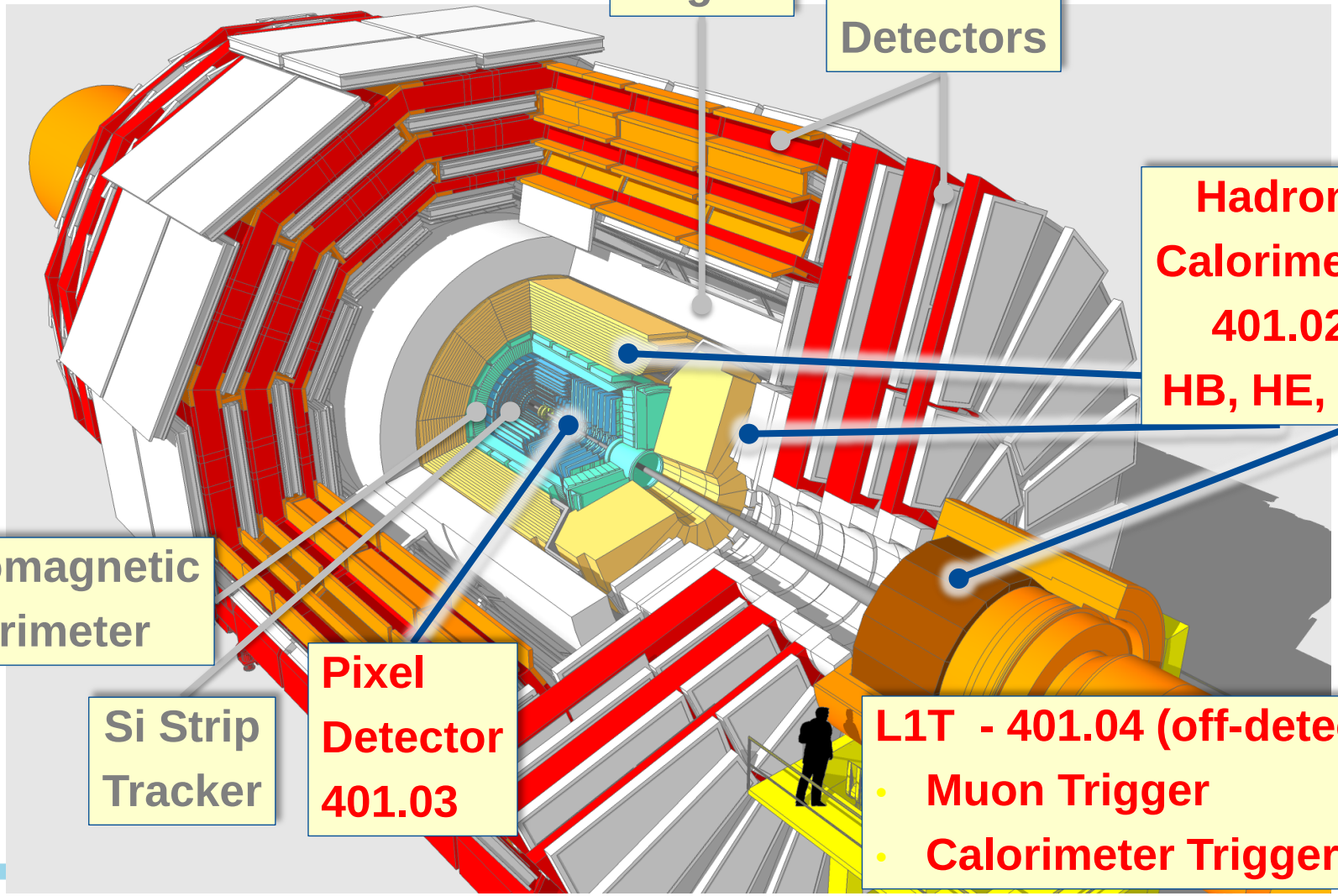
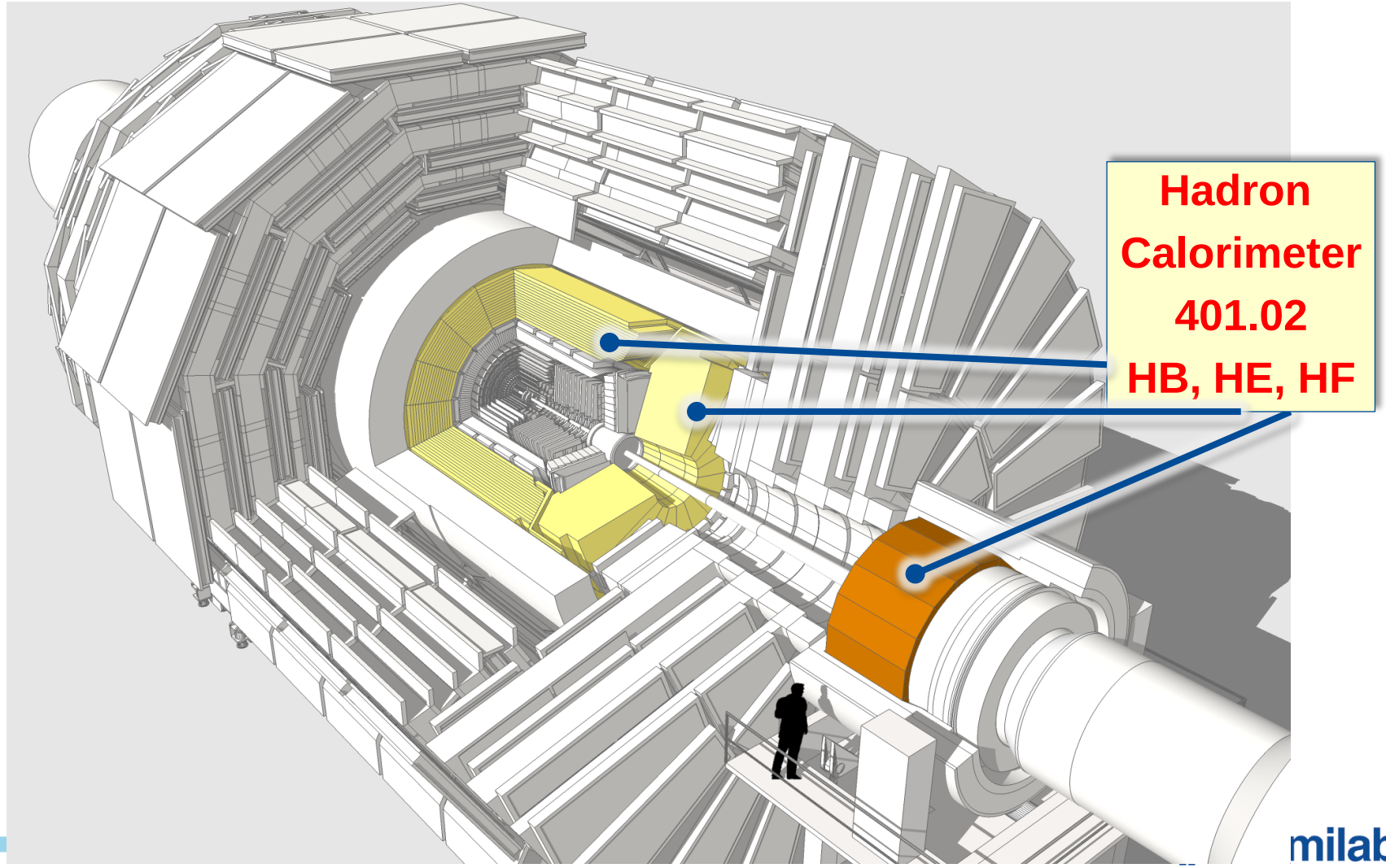
U.S. CMS Detector Phase 1 Upgrades

- 42.9 M TPC, ~ 3:1 DOE:NSF
- 30 US CMS Institutes



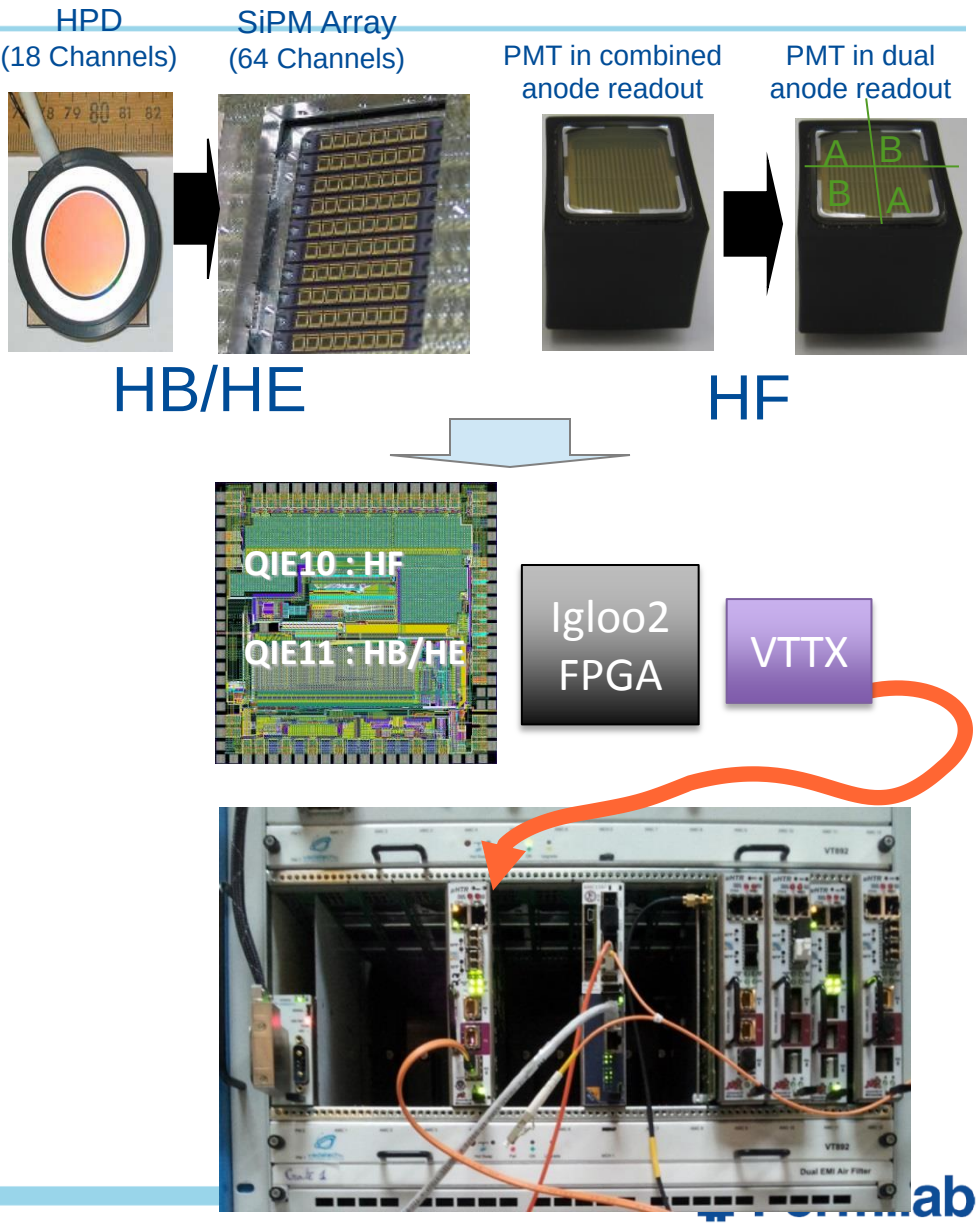
Hadron Calorimeter (HCAL) Upgrades

New “frontend” photodetector: higher granularity, timing info
and “backend” electronics increased bandwidth



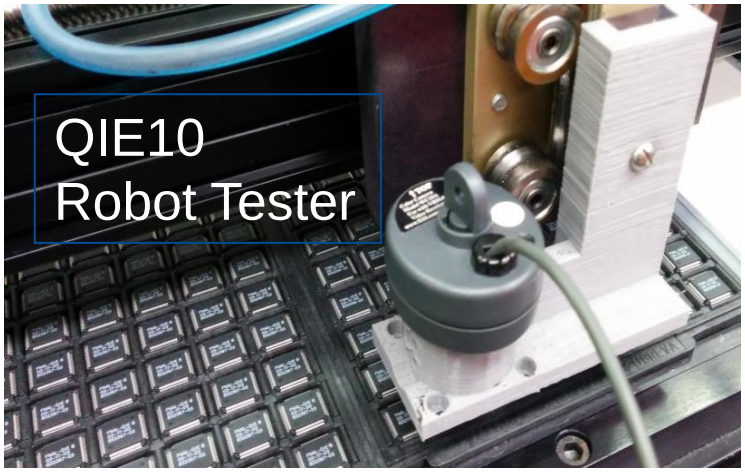
HCAL Implementation

- Front End photodetectors
  - HB/HE HPD→SiPMs Factor of ~3 increase in photon-detection efficiency
  - HF, switch from single-anode to dual-anode readout of PMTs
- New charge-integrating ADC (QIE10/11) with larger dynamic range and TDC
- Data link @ 4.8 Gbps
  - Larger dynamic range and TDC results in increase of channel count/data volume with same optical fiber plant
- Backend Electronics
  - Leading the μTCA revolution
  - Handle increased bandwidth, feed L1T



Status in pictures: HCAL

Frontend



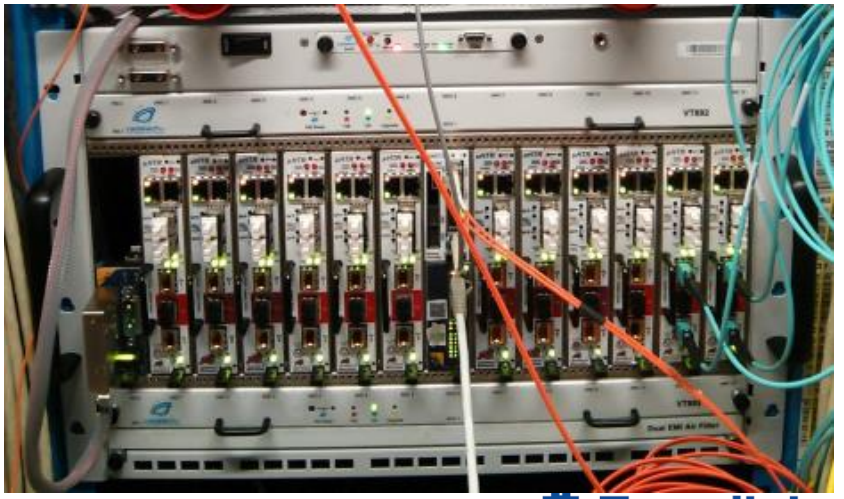
Pre-production
QIE Cards
- Works so far

Backend

μHTR

AMC13

Full crates



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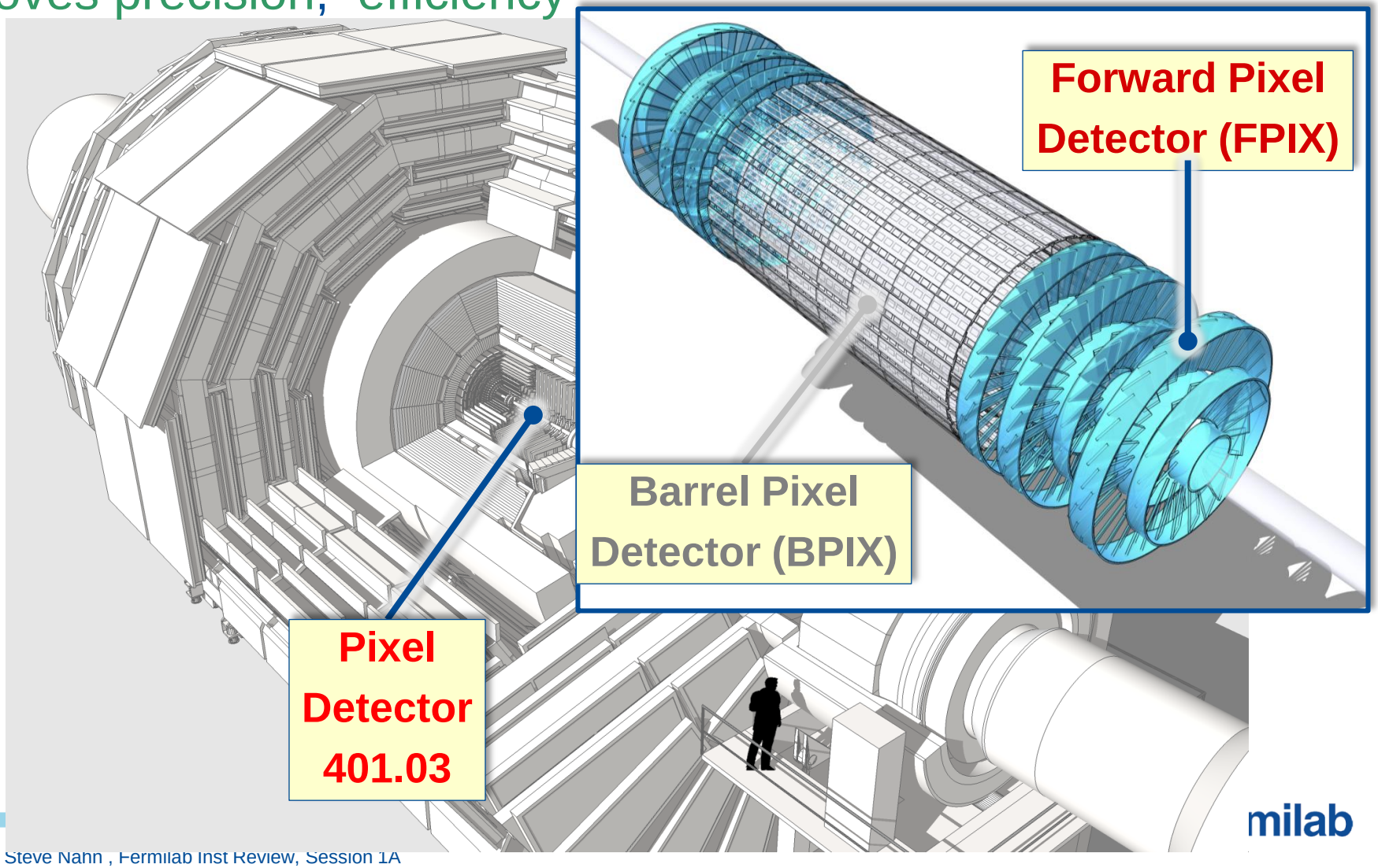
HCAL – FNAL Connections

- Engineering done on 14th floor of Wilson Hall
  - Successful QIE family of ASICs
  - Readout Cards, Front end Crates, System Integration
  - Electronics and Mechanics Teststands

- Testbeam Facility
  - Validates designs, provides system testbed
- LPC
  - Facilitates combining apparatus and analysis work, particularly for young scientists

Forward Pixel (FPIX) Upgrades

New 3 layer endcap detector: lighter, with better readout improves precision, efficiency



FPIX Cartoon Construction

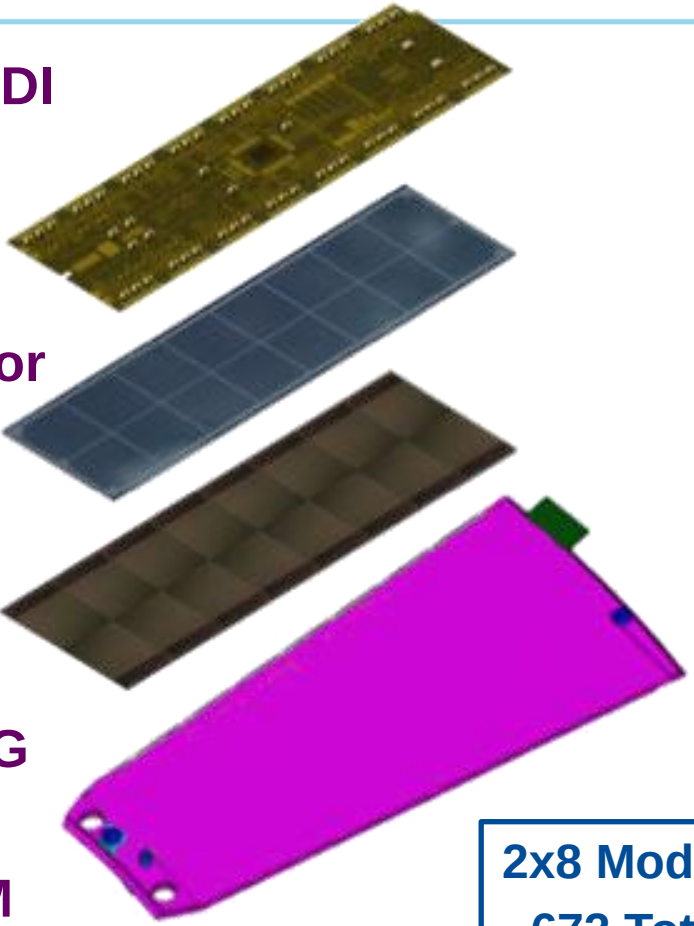
HDI

Sensor

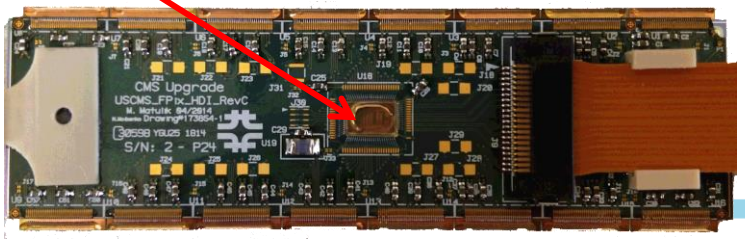
ROC (2x8)

TPG

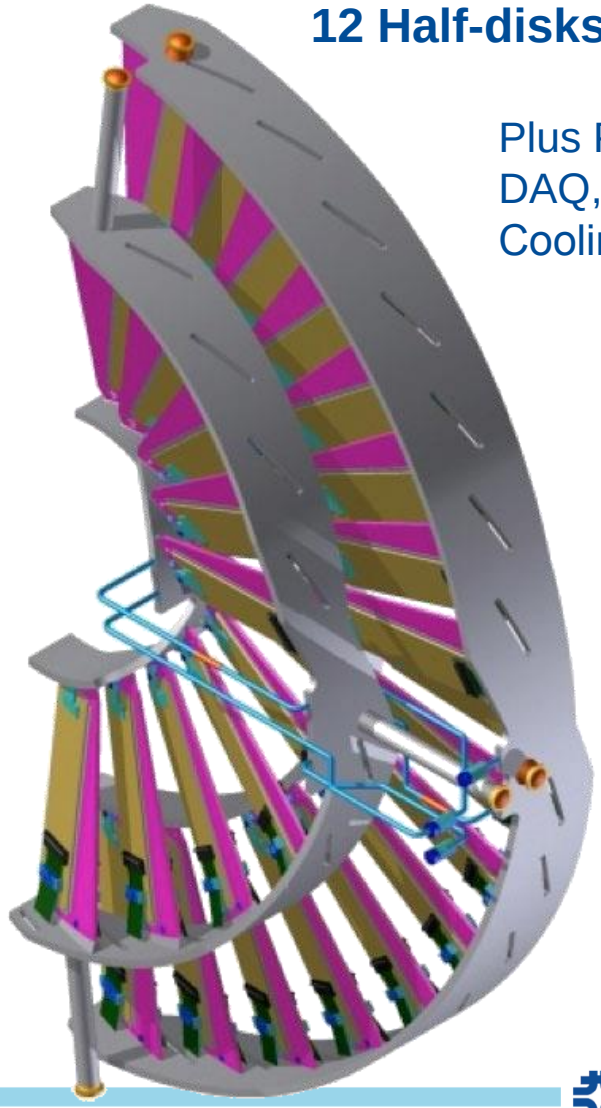
TBM



2x8 Module
672 Total



Outer and inner half-disks
12 Half-disks



Plus Periphery,
DAQ, Power,
Cooling, Software…

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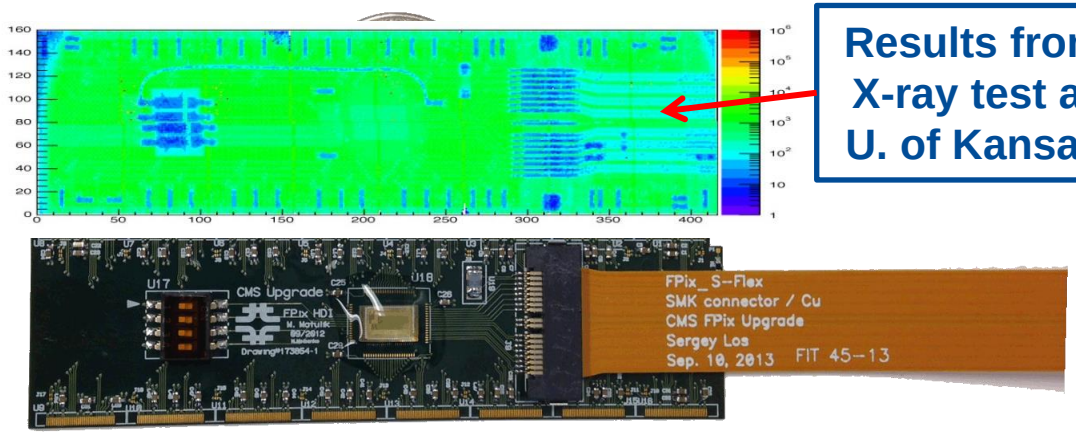
FPIX Components status in pictures

Module Assembly: The Movie

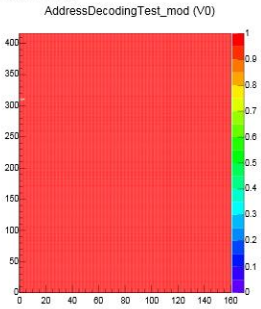


Results from X-ray test at U. of Kansas

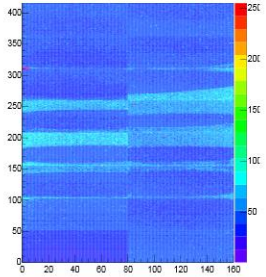
Module manufacturing

Test results of N00601:

Pixel alive:

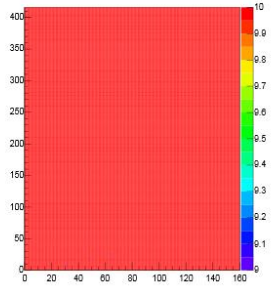


Bump bond test:

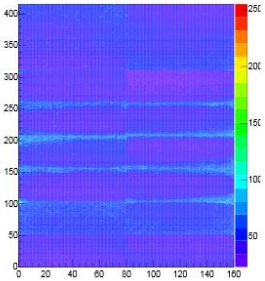


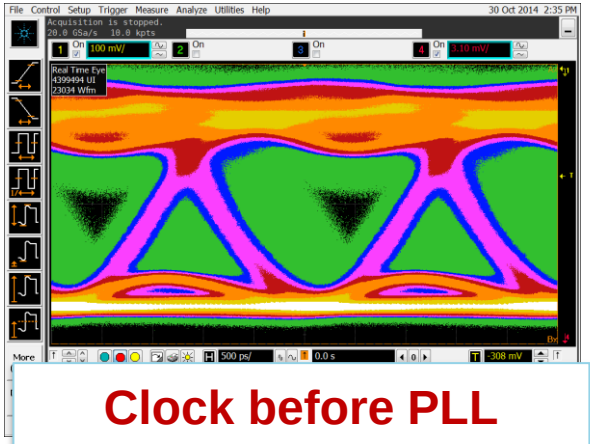
Test results of N00602:

Pixel alive:

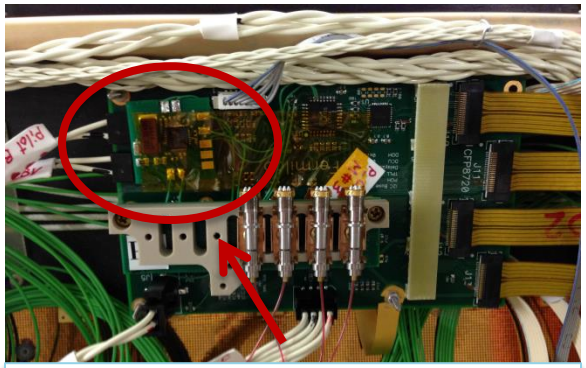


Bump bond test:

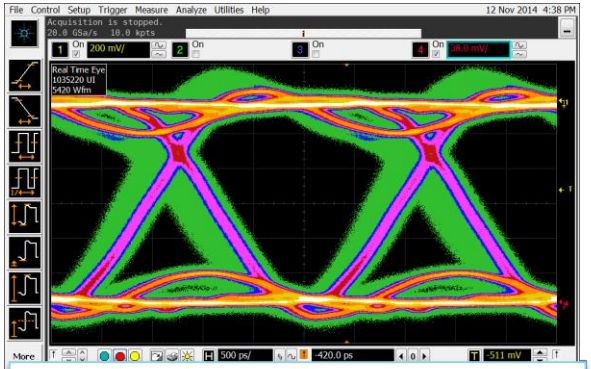




Clock before PLL



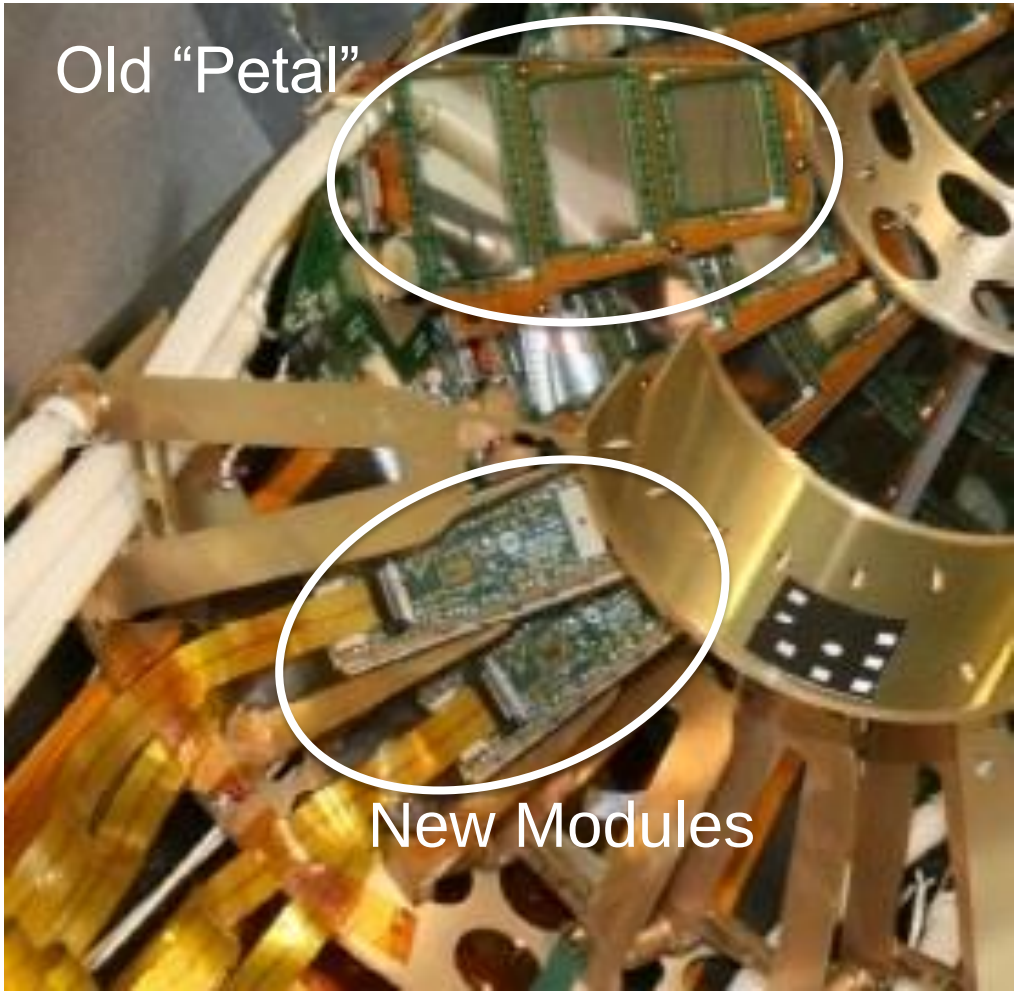
Additional PLL circuit



Clock after PLL

Status in picture: Pilot Detector installed, working

- "Pilot" = Prototype modules installed in CMS detector
  - Independent of current detector
  - Extremely valuable lessons in fabrication and installation processes
  - Allows control and calibration software development
  - First look at operating these modules with beam in 2015



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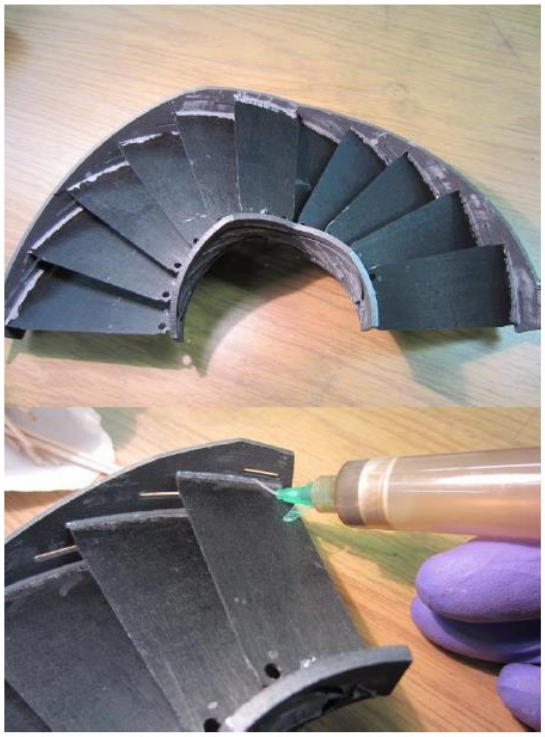
Hot off the press: Inner Half Disk Prototype

LHC CMS Detector Upgrade Project

Inner HD Prototype

- Inner HD prototype has been completed!
  - Starting to glue dummy Si, heater, and RTDs this week, testing and modifying installation tools, and start process of thermal test, thermal cycling, and retest



W. Johns/M. Verzocchi - 6 February 2015 USCMS Upgrade Technical Board 3

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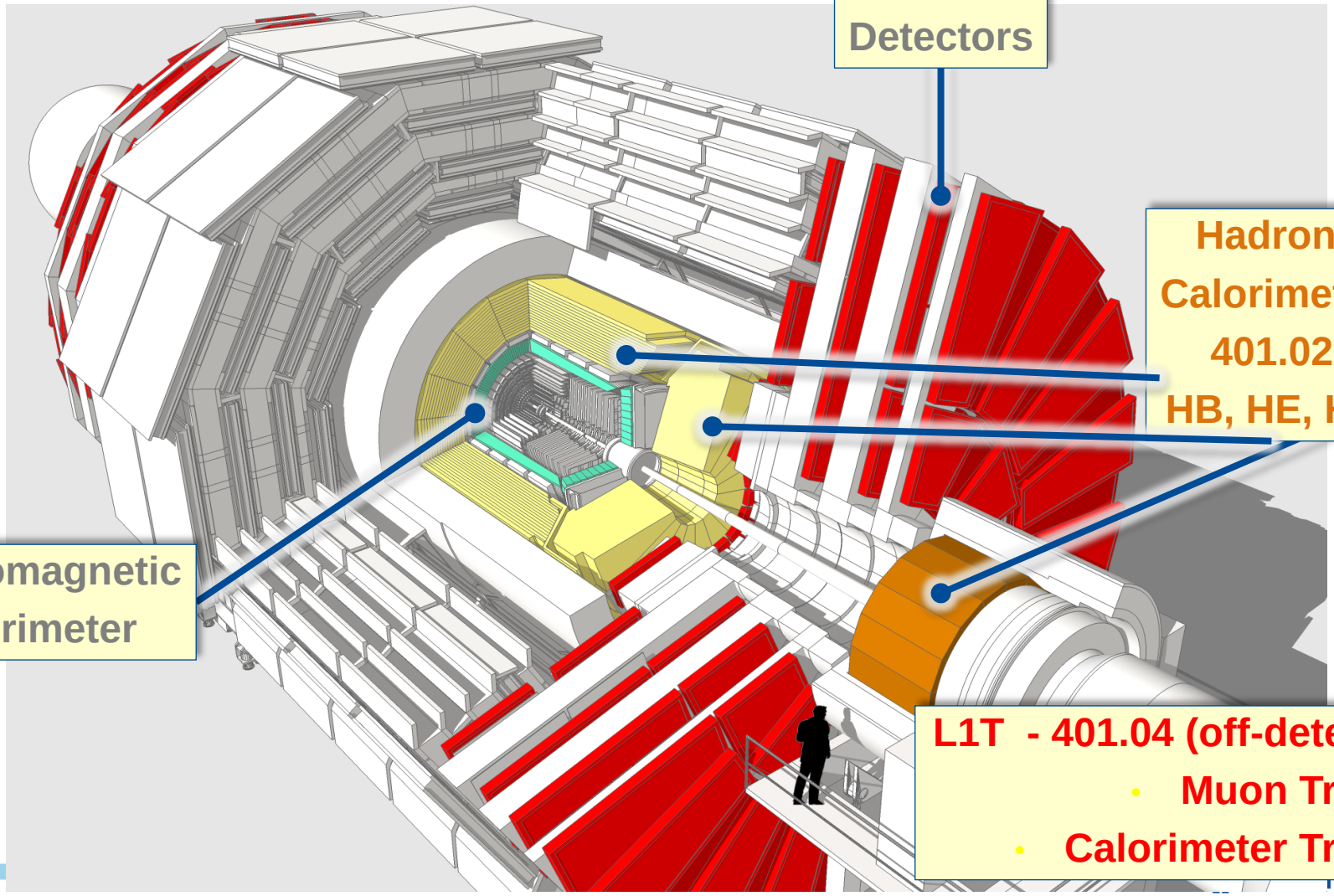
FPIX - FNAL Connections

- SiDet – home of FPIX production
  - Expertise and equipment to design and fabricate mechanics, cooling, module testing, assembly, and installation

- Computing Division
  - Developing Rad hard laser transmitters (POH)
- Test Beams
  - CMS FPIX/(BPIX) Component tests

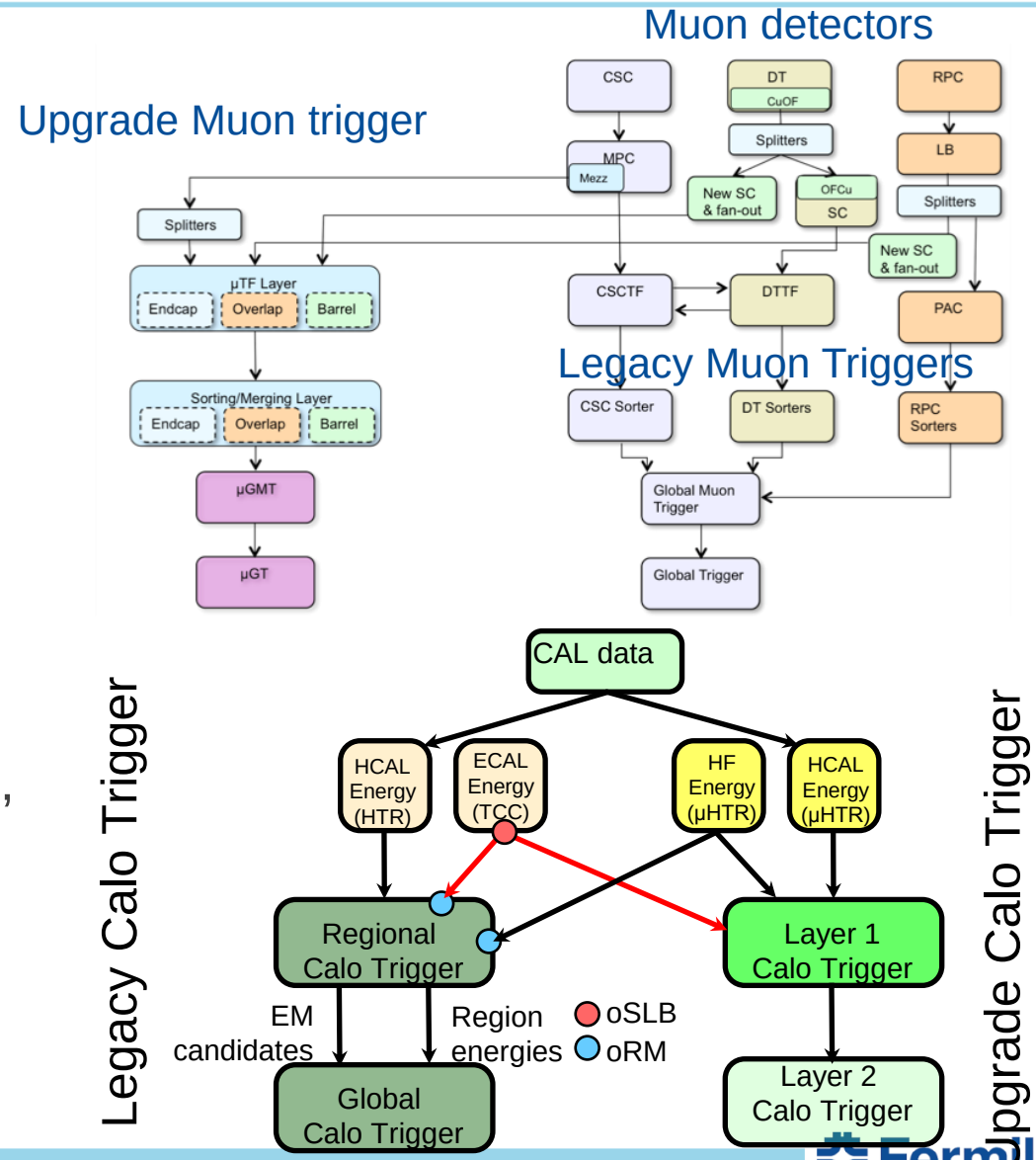
L1 Trigger Upgrades

Modern electronics system: more sophisticated filtering



Concurrent Operations and Commissioning

- Guarantees no loss in operation during LHC Running
- Optimal solution for benchmarking the new system vs current one
- Evolutionary approach
  - Legacy: Now
  - Stage 1: Target: 2015
    - Pileup subtraction, better lepton isolation, taus
    - FNAL PPD/CD plays role through Ops program
  - Stage 2: Target: 2016



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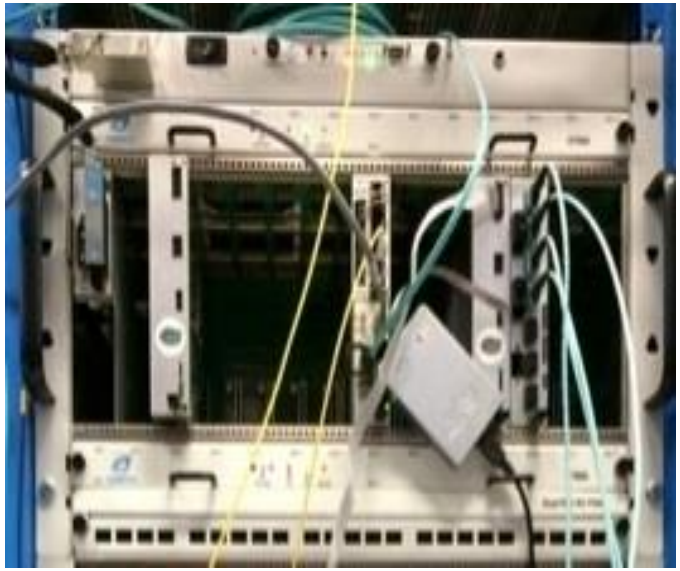
L1T: Production and Interface testing

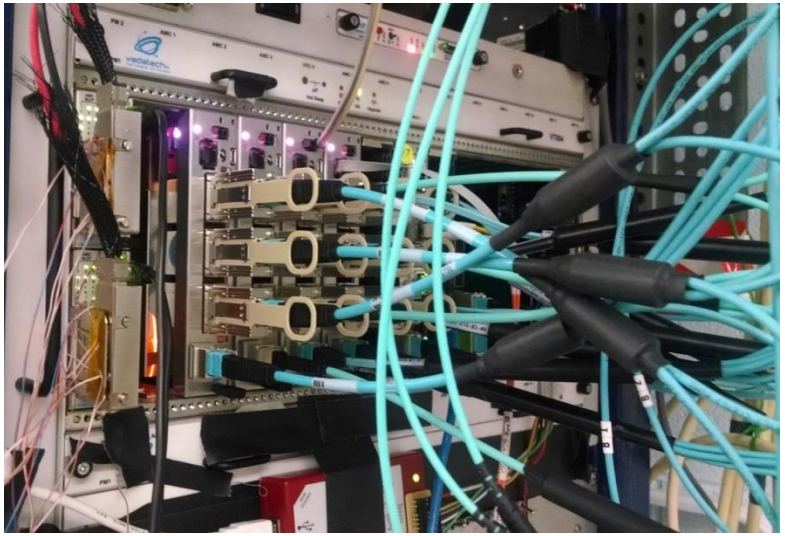
Muons



Testing Interfaces & Algorithms,

Seeing Real Muons @P5

Calorimeter



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Hot off the press: Stage 1

LHC CMS Detector Upgrade Project

Calorimeter Trigger Stage 1 development map

- J. Berryhill

Upcoming "shippable product increments" →

MP7 IS + jet algo **In progress**	**MP7 IS + jet+egamma algo** **Test week 7+**	**MP7 IS + jet+egamma+sums** **Test week 7+**

Etc.

Now that we are demonstrating shipment of data throughout the system, most urgent development item is ECAL/HCAL synchronization.
Next most urgent is MP7 DAQ integration.
And algorithm feature validation in parallel

Product feature backlog (choose next feature increment/s and integrate/test/deploy ~weekly):
Egamma algos
Sum algos
Tau algos
S1/legacy switching SW
MP7-based DQM
MP7 TS configuration
CTP7 DAQ/DQM/TS

Management

401.01 LHC CMS Detector Upgrade Project Project Office

Project Manager:	Steve Nahn
Deputy Project Manager:	Aaron Dominguez
Deputy Project Manager:	Lucas Taylor

Order 413.3b Specialists

ESH&Q Coordinator:	Stefan Gruenendahl
Project Controls:	Bill Freeman
Project Finance:	Jenny Teng
Risk Manager:	Lucas Taylor
Project Electronics Engineer:	Mike Matulik
Project Mechanical Engineer:	Greg Derylo

Example 2: DOE Projects

- **Successful delivery of construction projects and facilities for science is a central part of the DOE science mission**
  - In particular, Office of Science practice (critical decision [CD] process and Lehman reviews) considered gold-standard in DOE
    - *"Failure is not an option"*
  - SC has *earned* the authority to manage projects flexibly. This authority is only protected by unblemished project execution and is recognized as essential to SC success. This explains why so much attention is paid to project execution.
  - Therefore, we have close Federal oversight and coordination with contractor project managers. *Experienced personnel required.*
- **Extent of oversight tailored to total project cost**
  - Larger projects automatically get higher visibility in DOE due to layered approval levels
- **Complex dance between different project and budget requirements and timelines**
  - DOE Budget Requests *require* appropriate CD's are passed before requesting/spending money
  - Project execution not well suited to university grant funding mechanisms
- **For all these reasons, DOE Labs have a critical role in project management and construction**
  - Universities also play important roles, but must understand and adapt to requirements of DOE project system

14

HEPAP 12/08/14 G. Crawford - DOE

401.02 HCAL

L2 Manager:	Jeremy Mans
Deputy L2 Manager:	Frank Chlebana

401.02.03 HF Front End

L3 Managers: Ulrich Heintz

401.02.04 HB/HE Front End

L3 Manager: James Hirschauer

401.02.05 HCAL Back End

L3 Manager: Yuichi Kubota

401.03 FPIX

L2 Manager:	Will Johns
Deputy L2 Manager:	Marco Verzocchi

401.03.03 FPIX Components

L3 Manager: Harry Cheung

401.03.04 FPIX Assembly & Testing

L3 Managers: Cecilia Gerber, Petra Merkel

401.03.05 FPIX Pilot System

L3 Manager: Karl Ecklund

401.04 Trigger

L2 Manager:	Wesley Smith
Deputy L2 Manager:	Darin Acosta

401.04.03 Muon Trigger

L3 Manager: Ivan Furic

401.04.04 Calorimeter Trigger

L3 Manager: Sridhara Dasu

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Phase 1 Outlook Overall

- DOE Approved for Critical Decision 2 (project baseline) and Critical Decision 3 (ready for fabrication) Nov 12, 2014
  - Performance Evaluation and Measurement Plan (PEMP) Notable Outcome for FY15
  - Reviews in January, March, May, July, August, December
- Currently: Launched Production on near term components
  - L1 trigger ready for 2016
    - Stage 1: Interim enhancements using early boards
  - HCAL backend needed to feed trigger: also by 2016
  - FPIX, HCAL front ends have dedicated installations predicated on windows of opportunity
    - Staged to have the best possible detector at all times
- Extensive use of advanced prototypes produces lessons learned ahead of fabrication, installation, and operations
  - Provide procedures and tools ahead of the game
- Fermilab provides the backbone through the CMS group working in conjunction with the University collaborators, exploiting the facilities and resources unique to the Lab

Phase 2 (HL-LHC) – details tomorrow

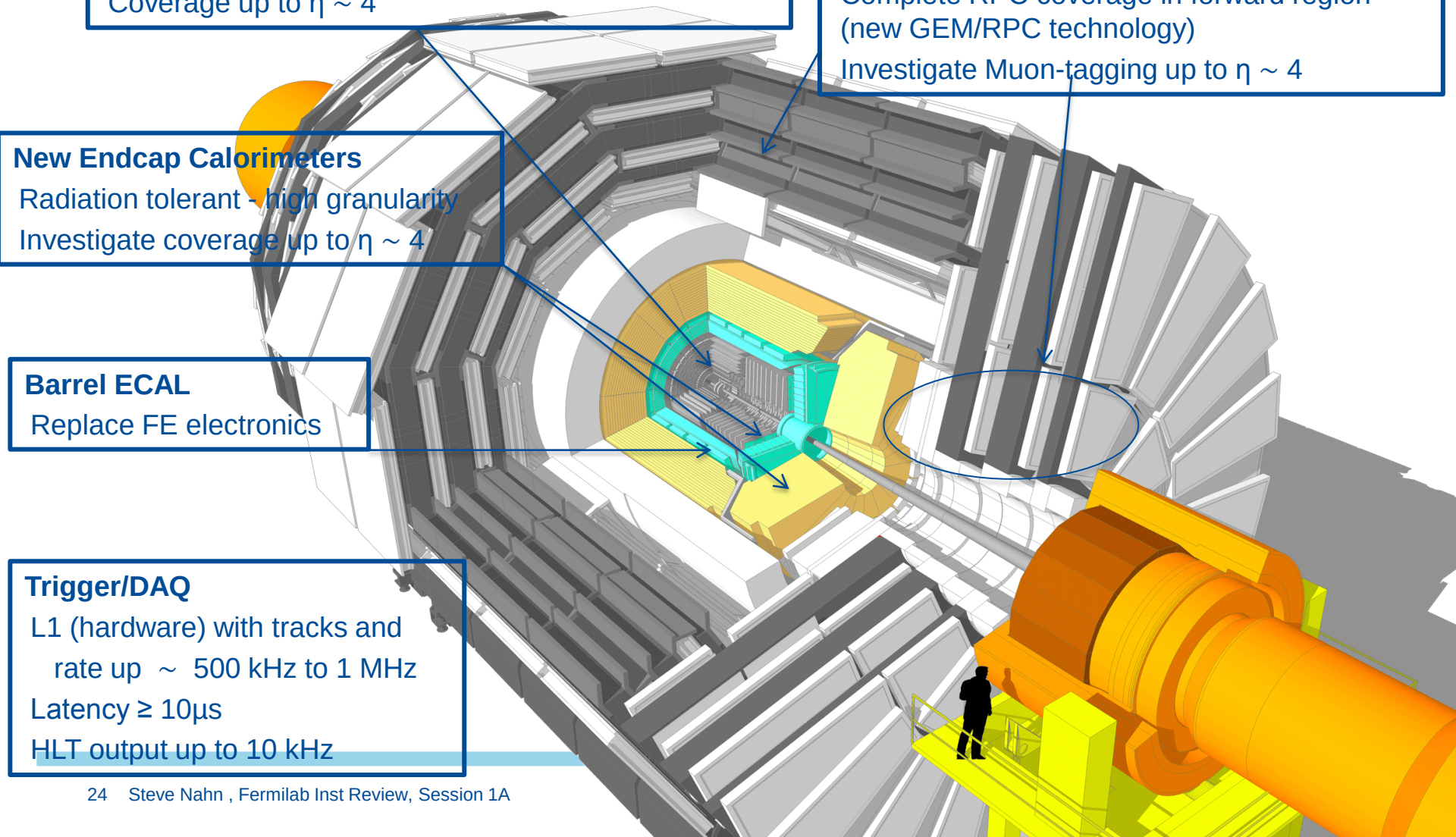
New Tracker
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to η ~ 4

Muons
- Replace DT FE electronics
- Complete RPC coverage in forward region (new GEM/RPC technology)
- Investigate Muon-tagging up to η ~ 4

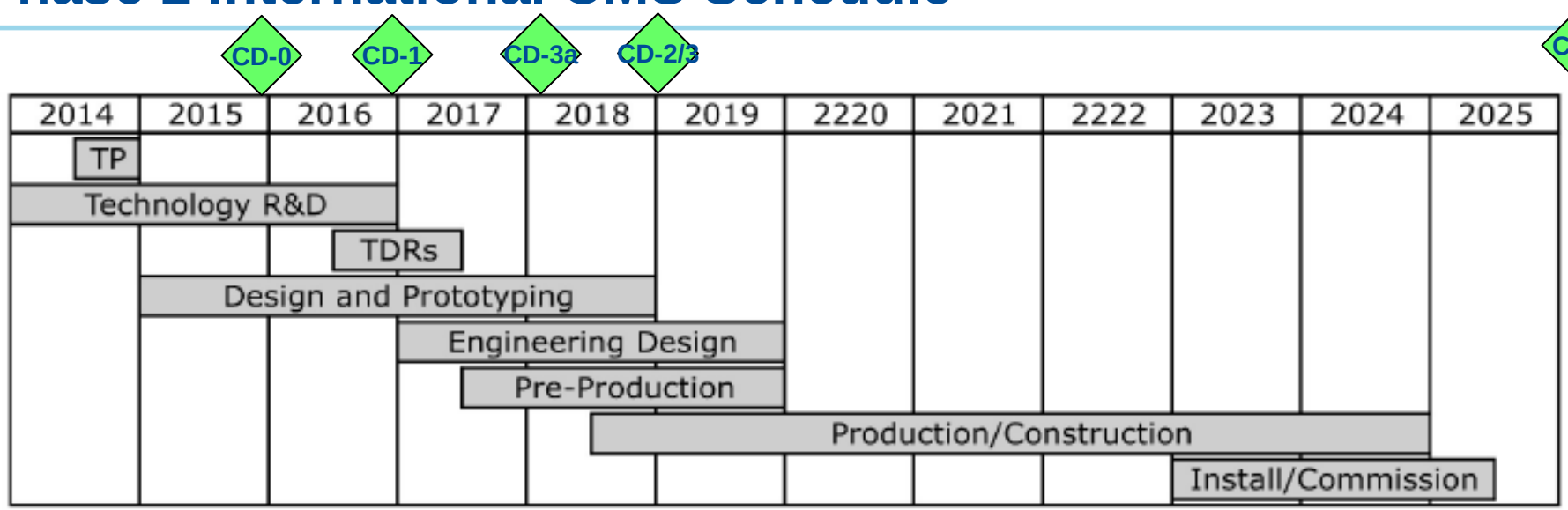
New Endcap Calorimeters
- Radiation tolerant - high granularity
- Investigate coverage up to η ~ 4

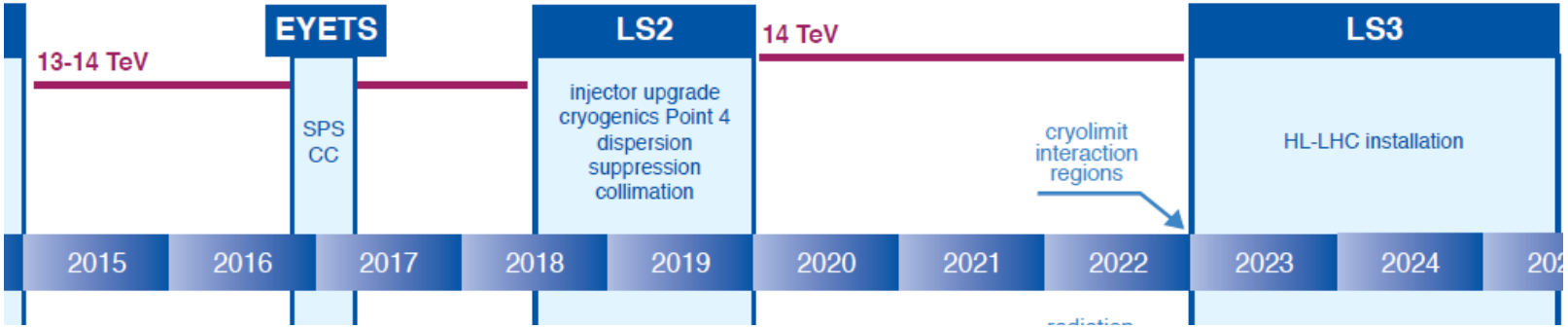
Barrel ECAL
- Replace FE electronics

Trigger/DAQ
- L1 (hardware) with tracks and rate up ~ 500 kHz to 1 MHz
- Latency ≥ 10μs
- HLT output up to 10 kHz



Phase 2 International CMS Schedule





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USCMS Phase 2 Project Rapid Developments

- R&D in all areas of interest ongoing through Ops Program
  - FNAL has strong involvement in DAQ/L1T, HCAL, FPIX
- V. O'Dell recently appointed Phase 2 Manager to bolster the effort in line with P5 recommendations
- U.S. CMS Upgrades Meeting 2/27-3/2: Catalyst
  - Recruited group of past and future experts in each area of interest
    - Charged with developing the physics case/cost/schedule
  - Developing our management structure
    - Goal: WBS defined at least to level 2
  - Positioning to use official project tools from the start
    - Leveraging expertise and lessons learned from the Phase I Project
- FNAL will play a similar role in Phase 2 as it did in the construction project and as it is doing in Phase 1

Take Home messages

- The US CMS Upgrades are Mission Critical for HEP
  - Ensures further exploitation of the rich physics opportunities of the LHC for the next 10-30 years
  - Focused on high-impact improvements within envelope of budget and schedule constraints
- Fermilab is the nexus of these activities
  - Provides leadership, scientific and technical manpower, expertise, capabilities, and support and services for executing the technical and managerial aspects of the Upgrades
  - Correlates well with other CMS endeavors, incorporating Fermilab resources and facilities and the University community

Backup Slides

Technical Proposal: Status

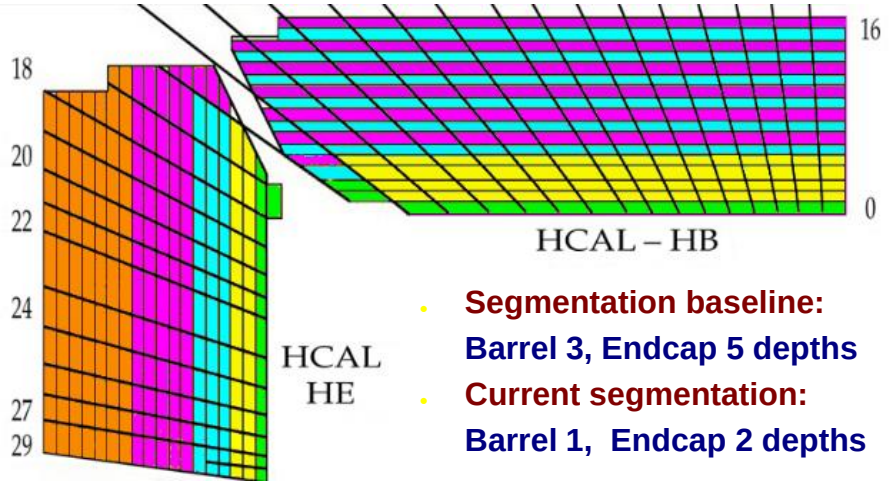
- Guidance from LHCC: select calorimeter option before submitting the Technical Proposal
- CMS has set up a review committee / schedule to do that
  - Review panel consisting of calorimeter experts from the collaboration
  - RP members: A. Ball, P. Bloch (chair), J. Butler, D.Contardo, J.L. Faure, K. Gill, M. Hansen
  - J. Mans, D. Petyt, P. Rumerio, J. Spalding, P. Sphicas, J. Varela, F. Wuerthwein
- The review process has consisted of both CMS wide meetings and meetings between the review committee and proponents
  - Many detailed questions by collaboration and review committee – the collaboration has been truly engaged in this
- Report from review committee due early Feb.
  - Decision will be made during CMS upgrade week Feb 9-13
- Technical proposal will then be completed and given to LHCC in Feb / Mar
- Upgrade scope document will be submitted to RRB in October
  - Targeting nominal funding, -12.5%, -25%

L1 Trigger

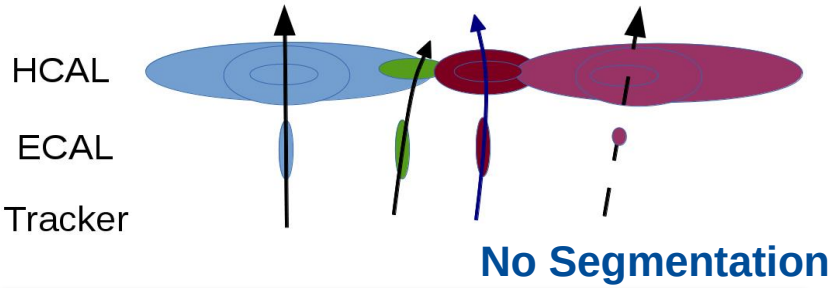
- Challenge: Increase in rates from higher $\mathcal{L}_{inst}$ and pileup
- Constraints:
  - ~23 interactions every 25 ns producing 0.5 MB
  - L1A rate limited by readout to 100 kHz and 4 μs latency
- Strategy: improved and more sophisticated algorithms
  - e/μ/γ isolation, τ id, μ p_T resolution, pileup subtraction
- Implementation: Increase system flexibility with high bandwidth optical links and large FPGAs using μTCA standard (CMS-wide choice)
  - Calorimetry: Two-layer trigger with tower-level precision and PU subtraction
  - Muons: combining all CSC, DT and RPCs in track-finding

Depth Segmentation

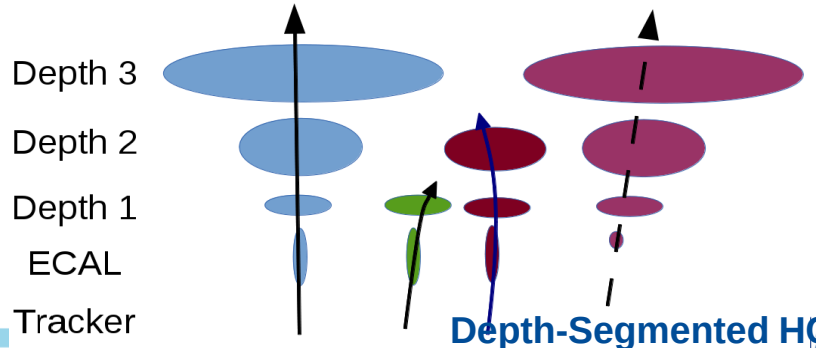
- CMS uses particle flow
  - Suppresses pileup and improves jet and MET resolution
  - Requires accurately associating energy deposits with tracks
- Depth segmentation allows better separation of hadronic deposits and better matching to tracks
- Radiation damage is depth dependent: better granularity of correction term
- Timing information provides new handle on pileup



- **Segmentation baseline:**
  Barrel 3, Endcap 5 depths
- **Current segmentation:**
  Barrel 1, Endcap 2 depths



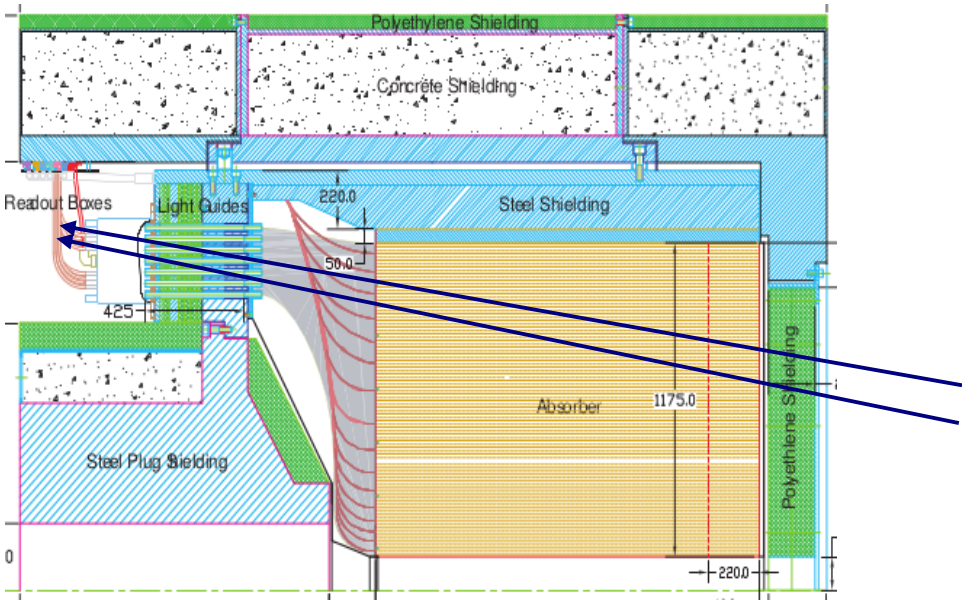
No Segmentation

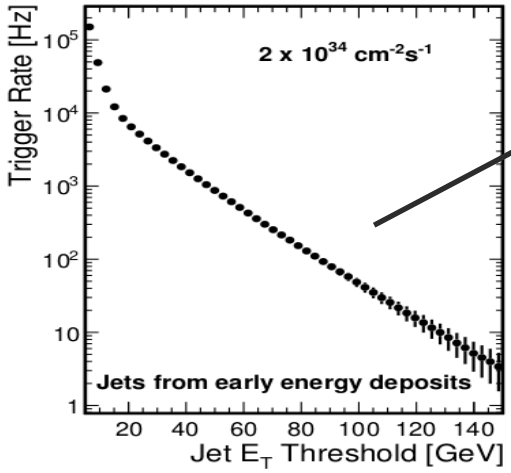


Depth-Segmented HCAL

Forward Calorimeter Requirements

- The Forward Hadron Calorimeter (HF) is important for VBF Higgs production “tagging jets”
- Particles (muons from decay-in-flight, punch-through particles) passing through the HF PMTs produce spurious signals in the PMTs
  - Signals from backgrounds appear earlier (by ~4 ns) than signals from showers in the calorimeter
  - Signals from backgrounds often affect only a small portion of a PMT
- Requirement: Reject background signals separated by at least 2 ns in time from nominal, and recover channel performance when just a small portion of the PMT is affected.





Fake jets from early energy deposits as observed in 2012

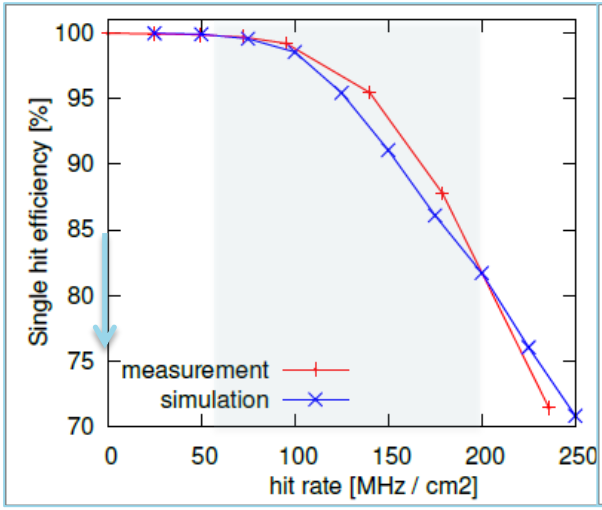
Fermilab

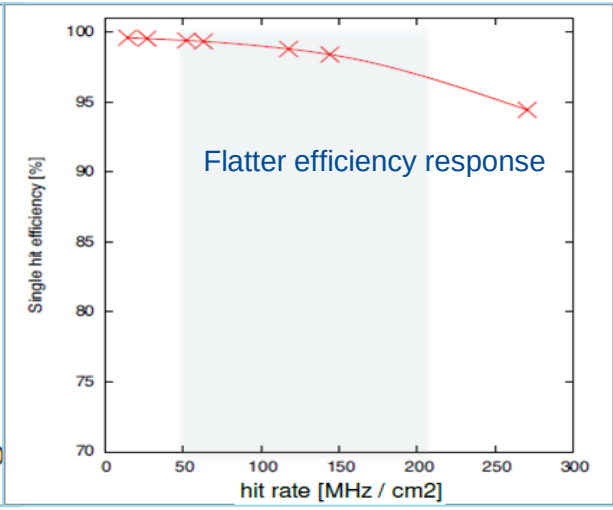
Examples of improvement: FPIX

Current Pixel Detector

Upgrade Pixel Detector

- Current device loses efficiency rapidly with increasing fluence

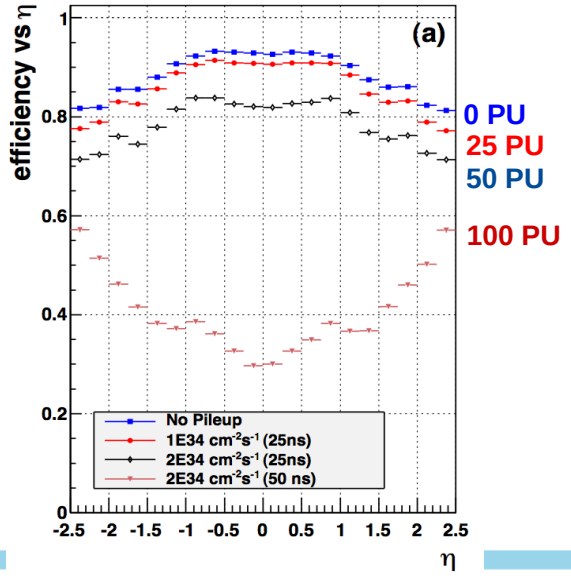


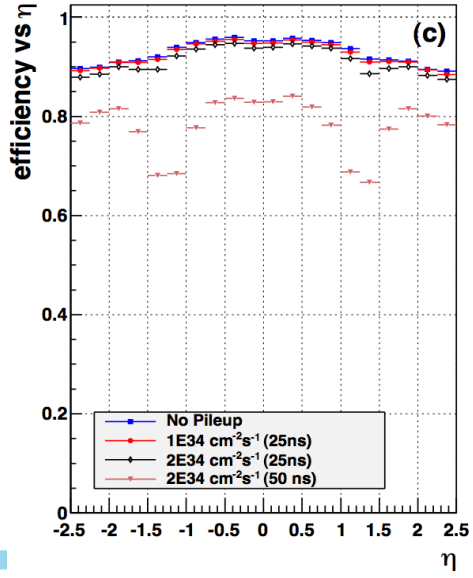


- Increased layers and less material increase efficiency
  - Effect varies with different pileup conditions

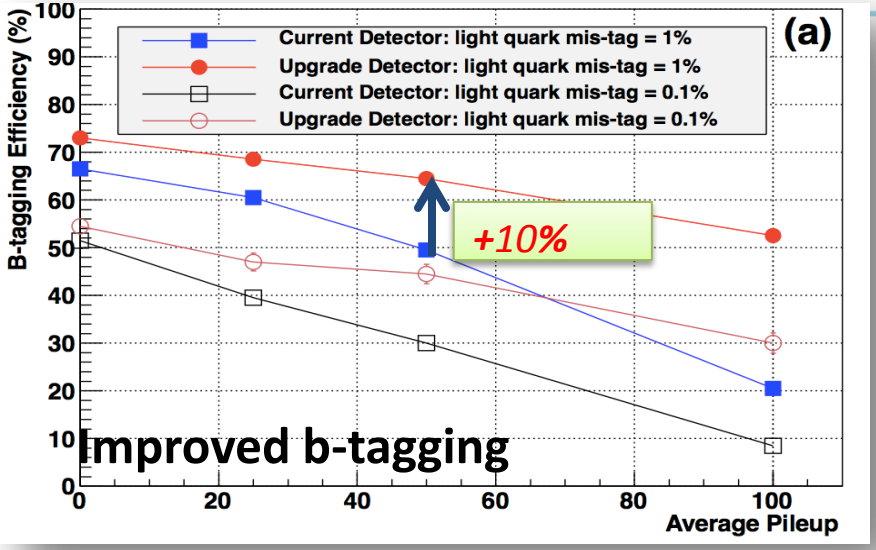
current detector

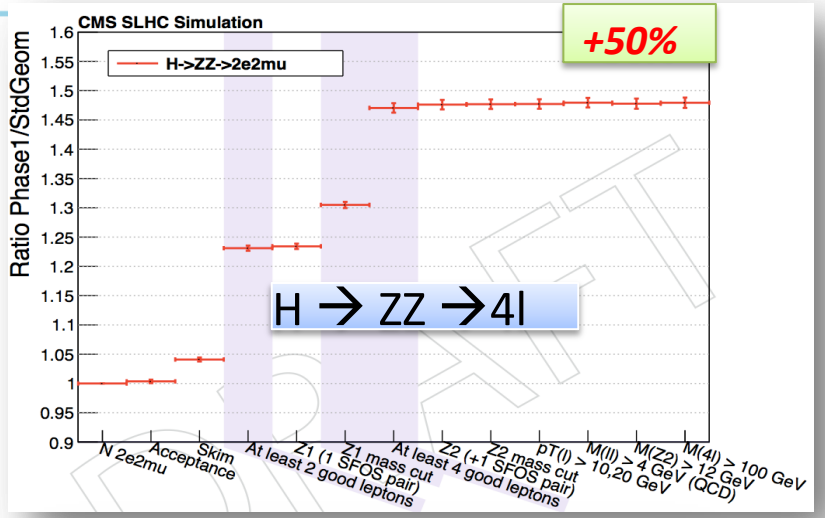
upgrade detector

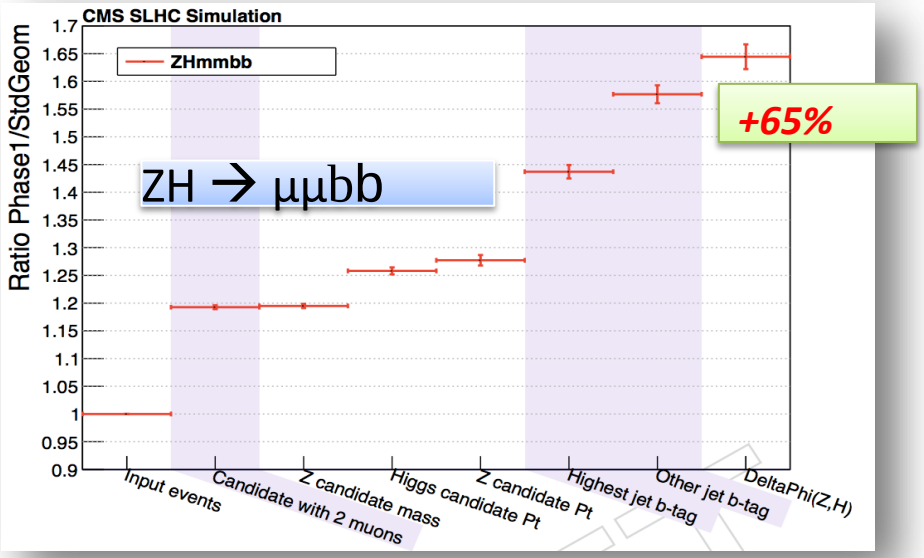


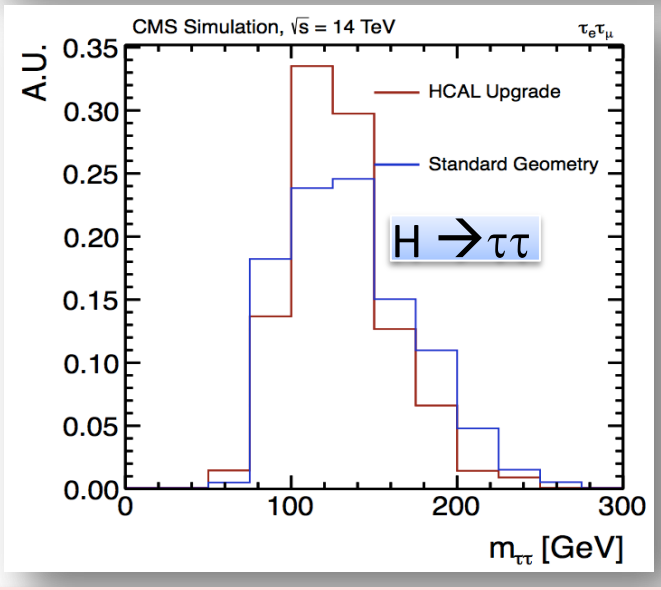


Performance Examples: FPIX









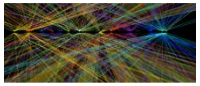
Improved $m_{\tau\tau}$ resolution

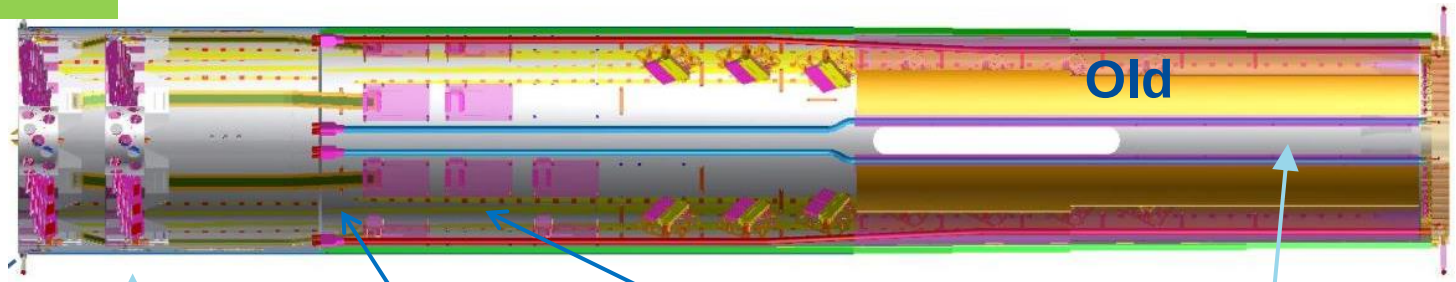
Fermilab

Half Cylinder Comparison

Half Disks: 2 → 3

Increased robustness, better efficiency, less fake tracks





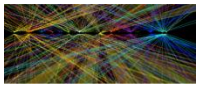
Half Disk and module design uses carbon (less material), replaces Al/Be

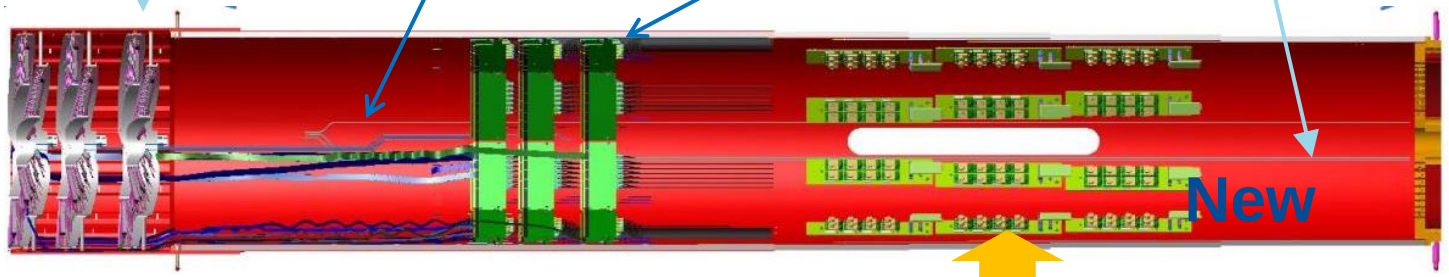
Support Electronics:

Boards out of tracking volume & new low mass flex cable

Cooling → CO_2

Reduction in mass.





Adding DC-DC converters:

Cables to Half Cyl. same, power needs x2

L1 Trigger upgrade studies

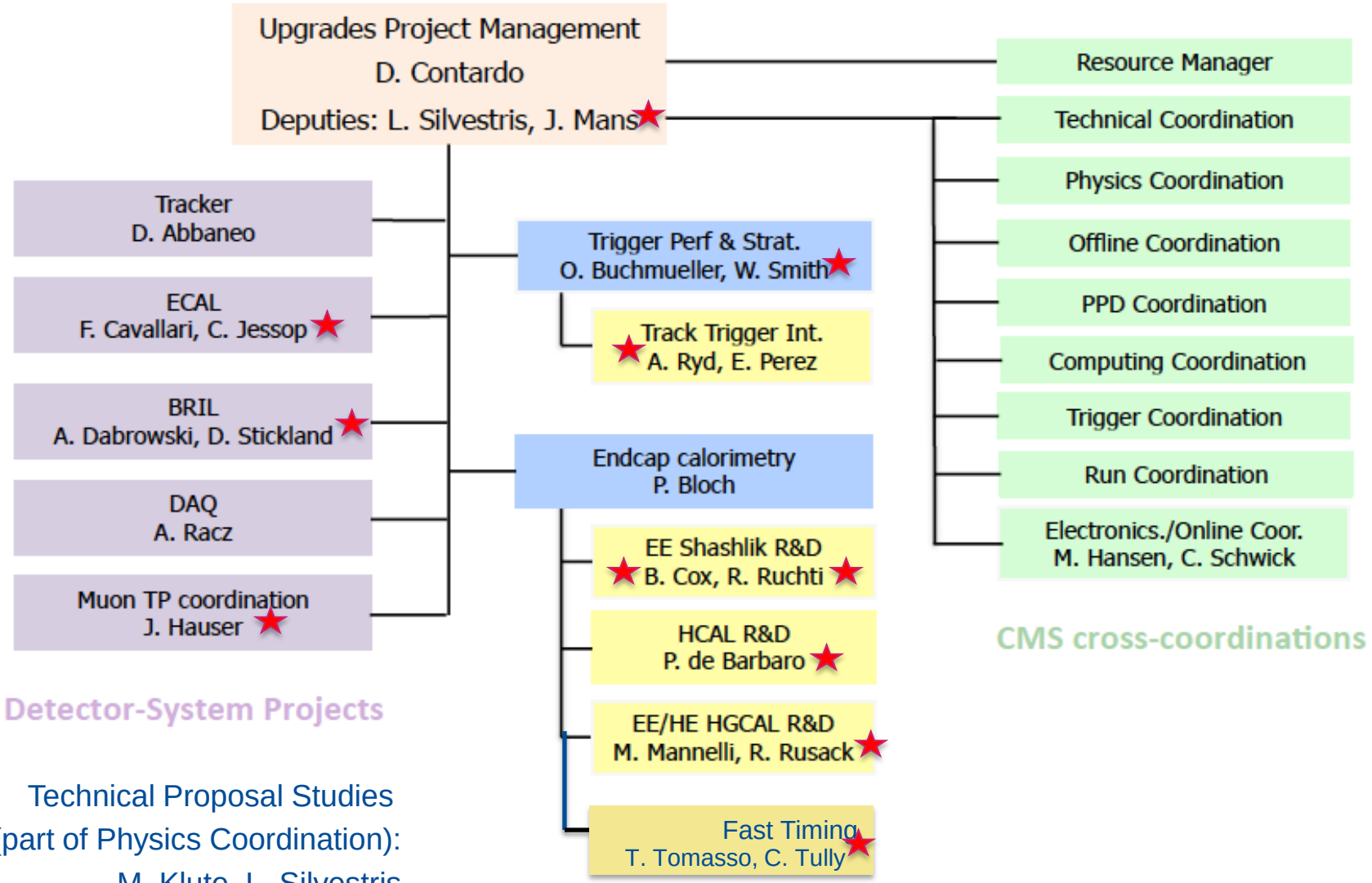
- **Level-1 trigger rate** limited to **100kHz**, 4μs latency by detector readout.
- Mitigate through improved:
  - **muon triggers**: improved μ p_T resolution w/ full information from 3 systems in track finding, more processing
  - **calorimeter triggers**: finer granularity, more processing means better e/γ/μ isolation & jet/τ resolution w/ PU subtraction
- Increased system flexibility and algorithm sophistication
- Build/commission in parallel with current system – staged installation, will benefit already at start of Run 2

Larger FPGAs, finer granularity input, high speed optical links

Trigger efficiency @ 2e34 $cm^{-2}s^{-1}$

Channel	Current	Upgrade
W(eν),H(bb)	37.5%	71.5%
W(μν),H(bb)	69.6%	97.9%
VBF H(ττ(μτ))	19.4%	48.4%
VBF H(ττ(ετ))	14.0%	39.0%
VBF H(ττ(ττ))	14.9%	50.1%
H(WW(eeνν))	74.2%	95.3%
H(WW(μμνν))	89.3%	99.9%
H(WW(eμνν))	86.9%	99.3%
H(WW(μeνν))	90.7%	99.7%

International CMS Phase 2



Technical Proposal Studies
(part of Physics Coordination):
M. Klute, L. Silvestris

US CMS Upgrades Schedule