CMS Hardware Upgrades

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on behalf of CMS Collaboration

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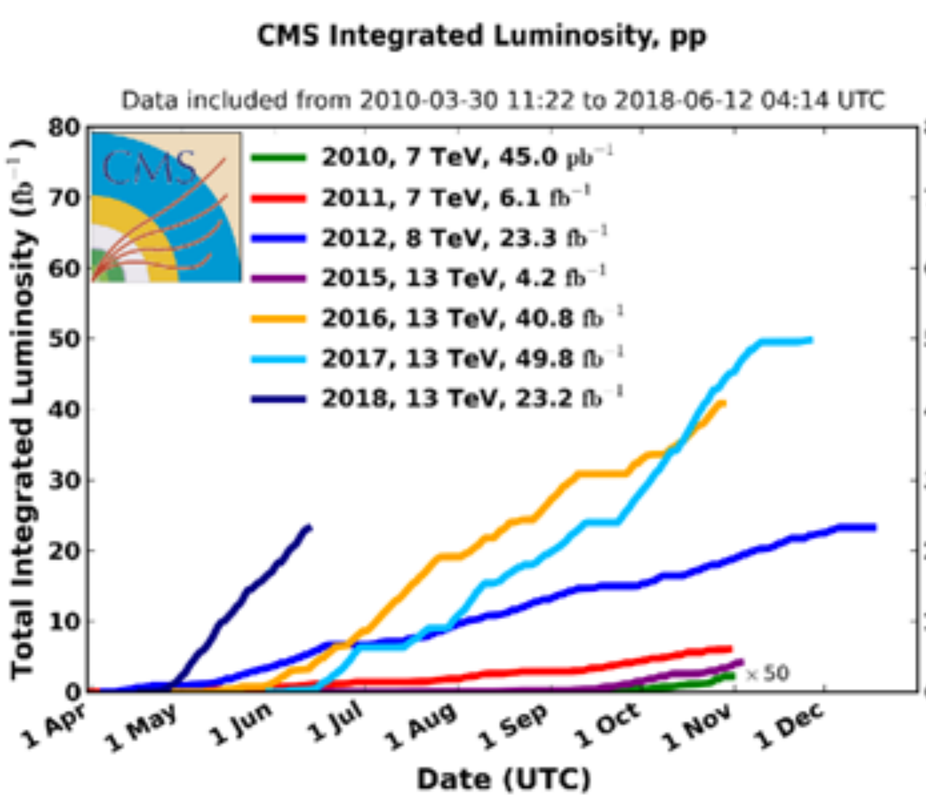
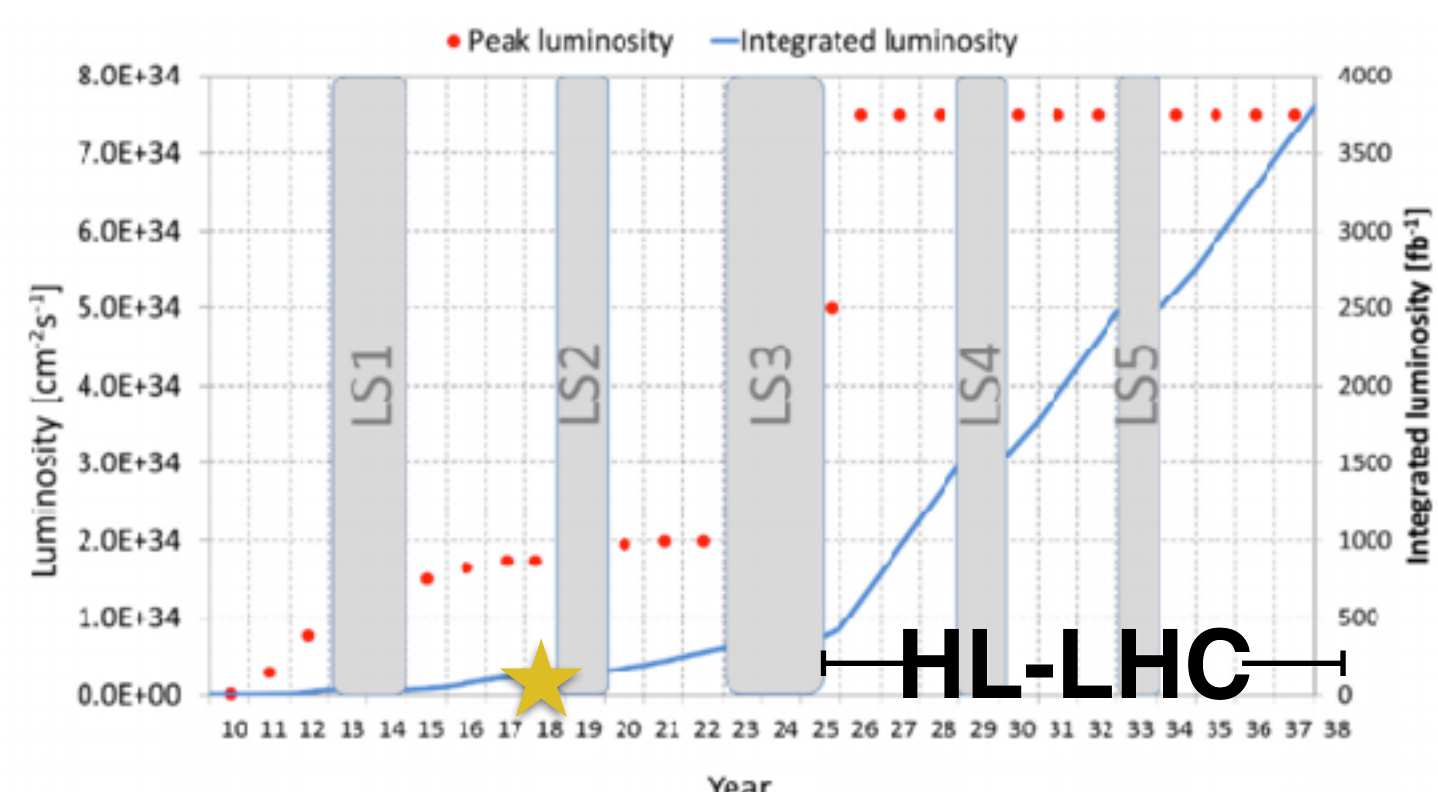
LHC Run Schedule

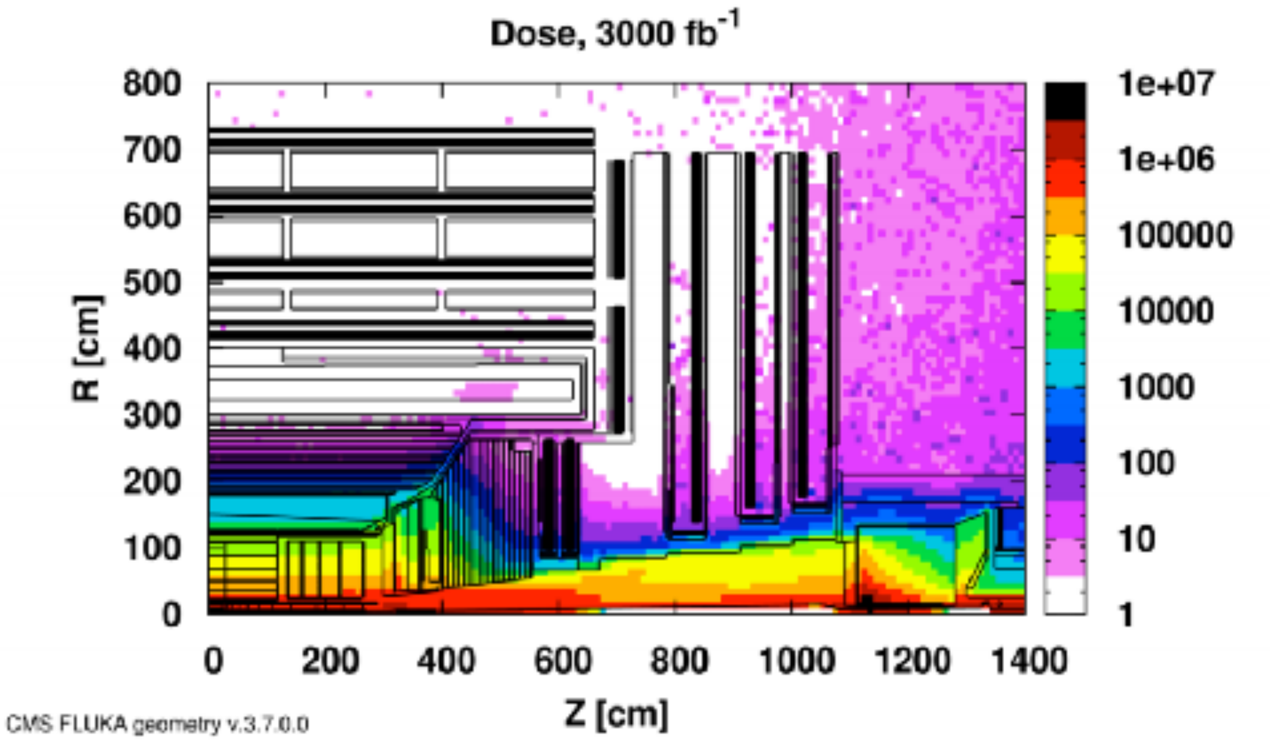
- LHC has been performing beyond expectation
  - Performance has been improving year over year
  - Already exceeded the design instantaneous luminosity (1×10^{34} $cm^{-2}s^{-1}$)
- High Luminosity LHC (HL-LHC) Upgrades will allow higher rates
  - $5\text{-}7.5 \times 10^{34}$ $cm^{-2}s^{-1}$
  - Total integrated luminosity of 3000 fb^{-1} through end of HL-LHC



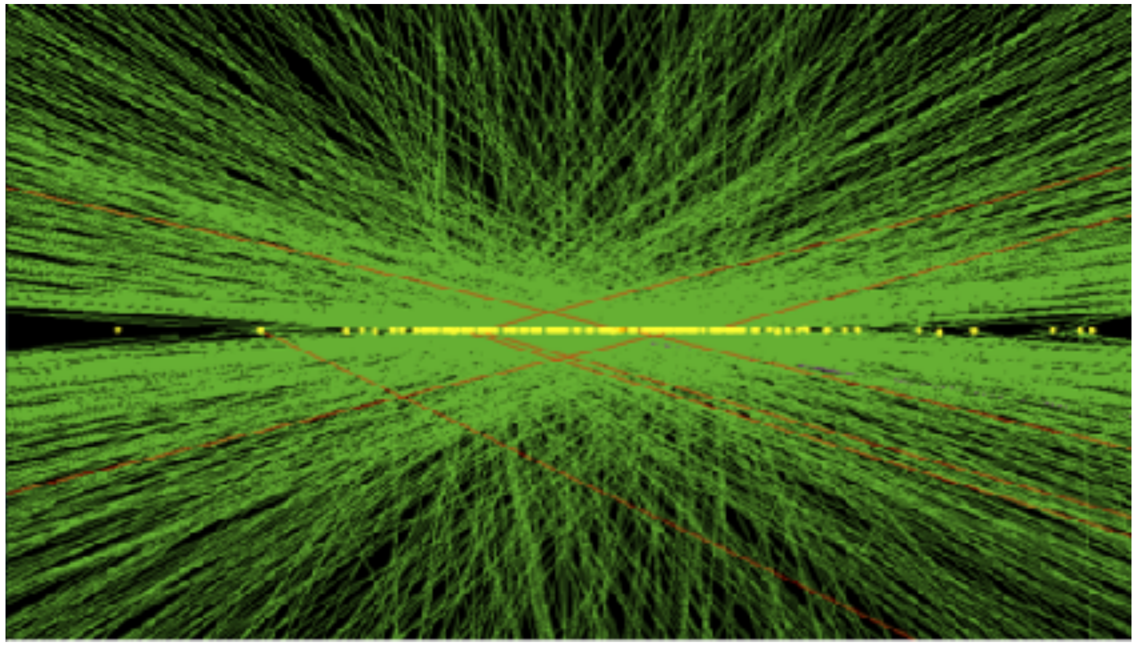


Upgrade Motivations

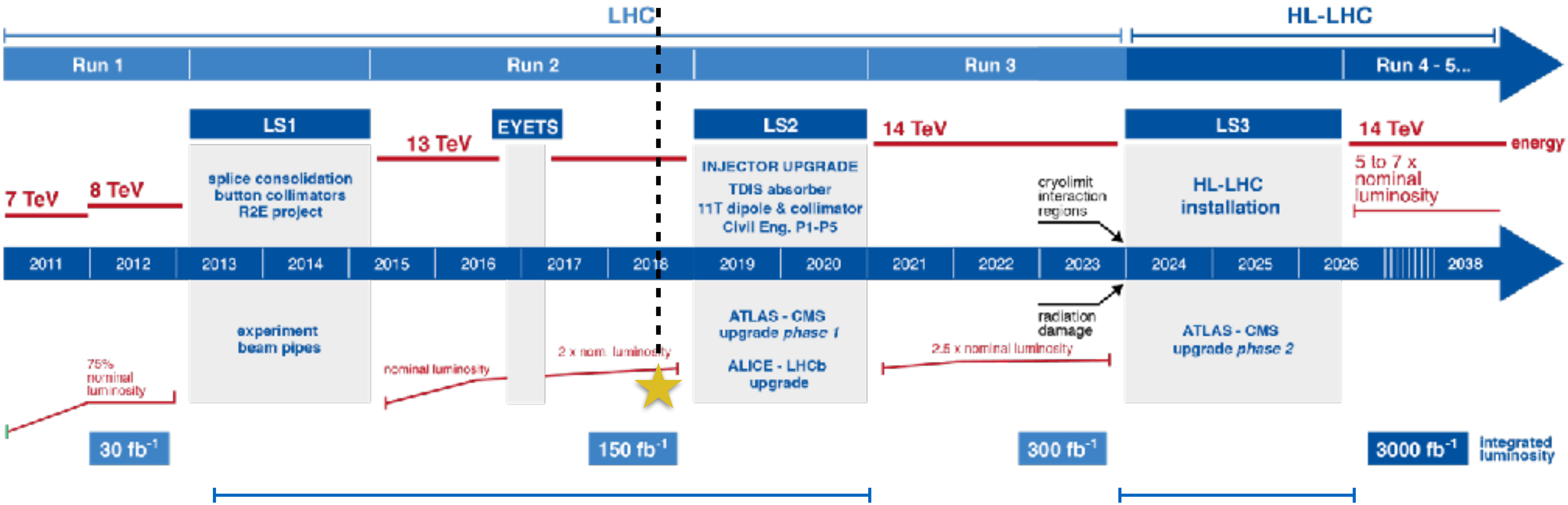
- High luminosity = more interactions per bunch crossing (pileup)
- Improvements to the LHC operating conditions require upgrades in order to maintain detector performance
  - High pileup : kills detection efficiency
  - High radiation : kills detectors



200 Pileup event



CMS Upgrade Timeline



Phase-1 Upgrades

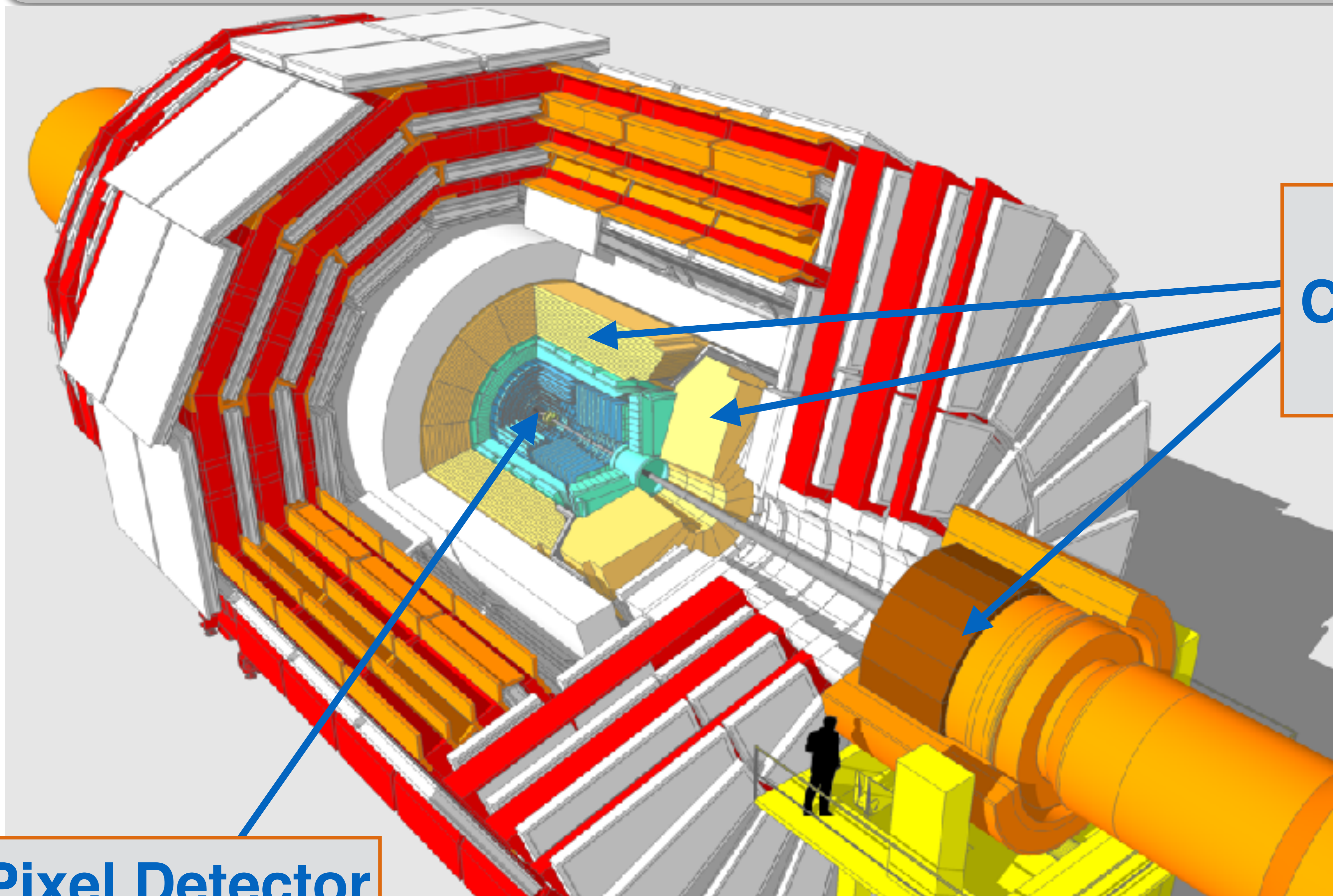
Improvements to specific subsystems to keep CMS running smoothly through 2023

Phase-2 Upgrades

Upgrades of most of CMS to cope with HL-LHC running environment

Phase-1 Upgrades

Phase-1 Upgrades

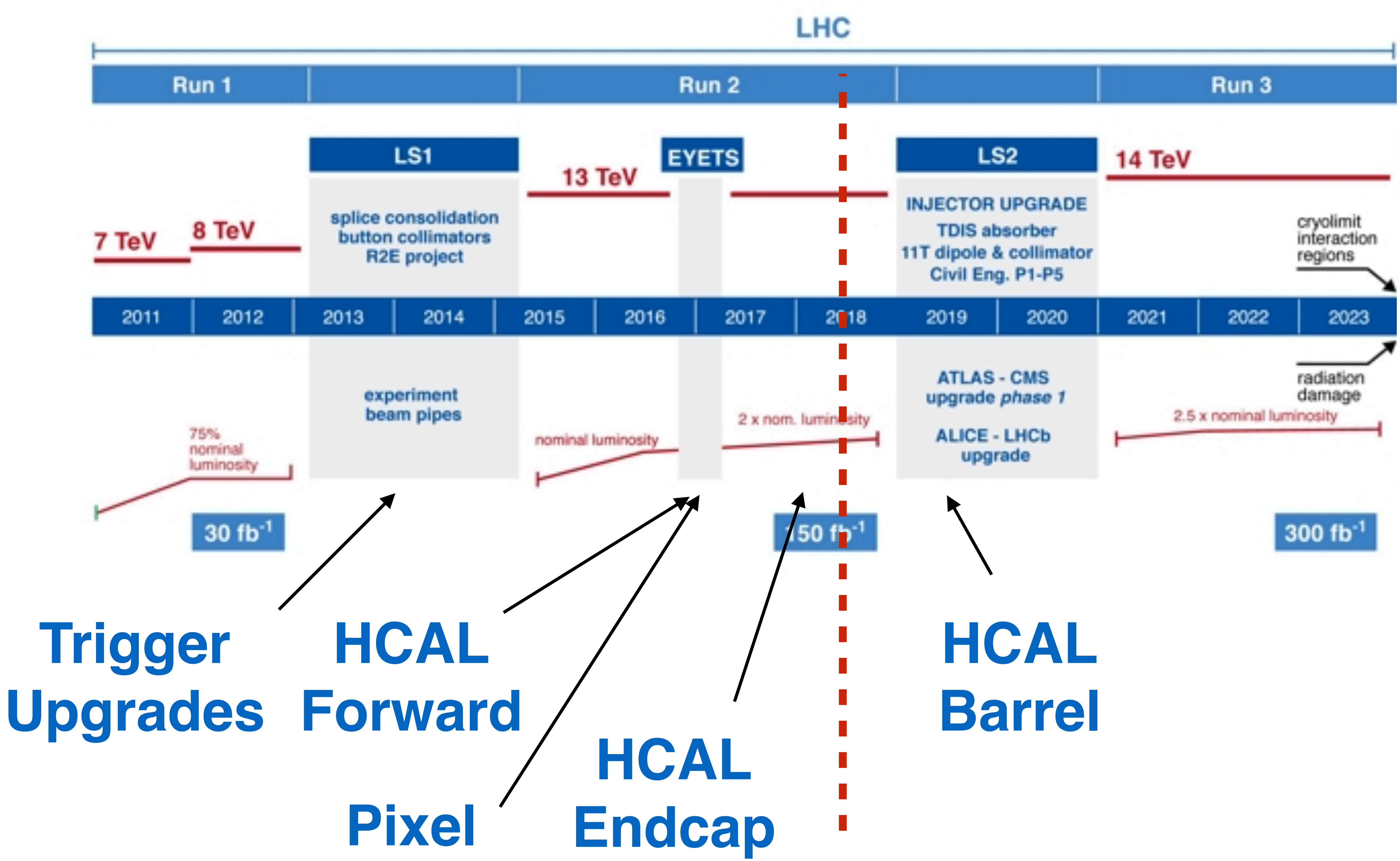


Hadron Calorimeter (HCAL)

Pixel Detector

Off detector: DAQ & Trigger

Phase-1 Upgrade Schedule



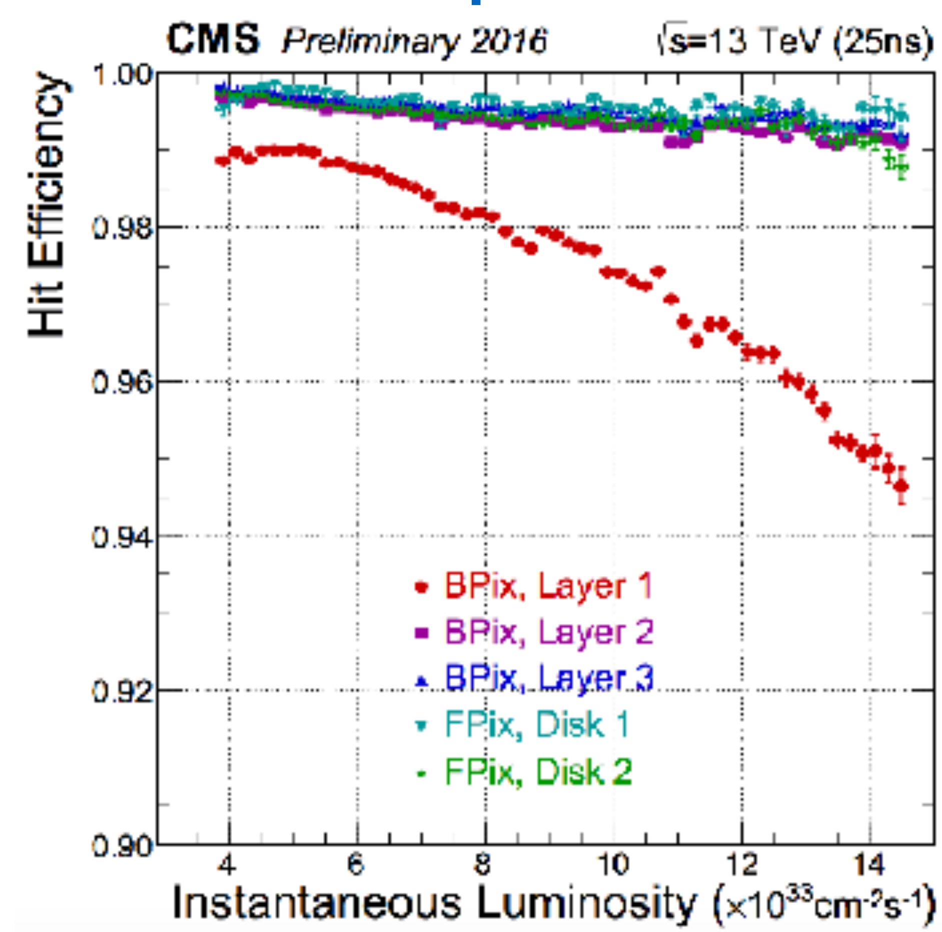
Completed

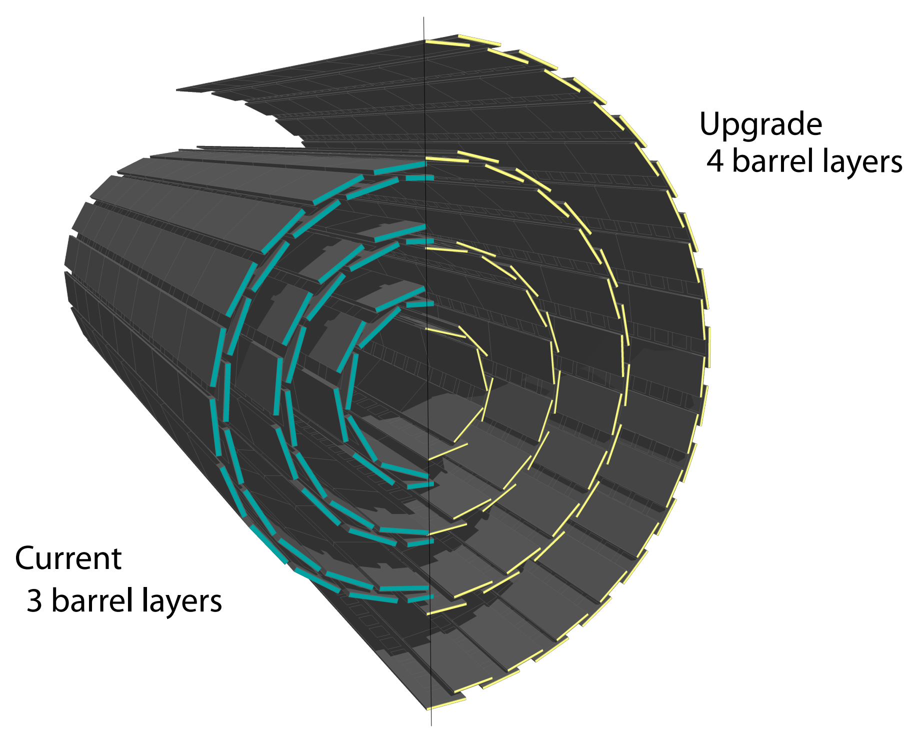
Still to come

Pixel Phase-1

- Original (Phase 0) pixel detector designed to operate up with 25 pileup at instantaneous luminosity of 1×10^{34} $cm^{-2}s^{-1}$
  - Already surpassed by LHC
  - Degradation of hit efficiency observed
- To cope with LHC running environment, a new pixel detector was installed winter 2016/17

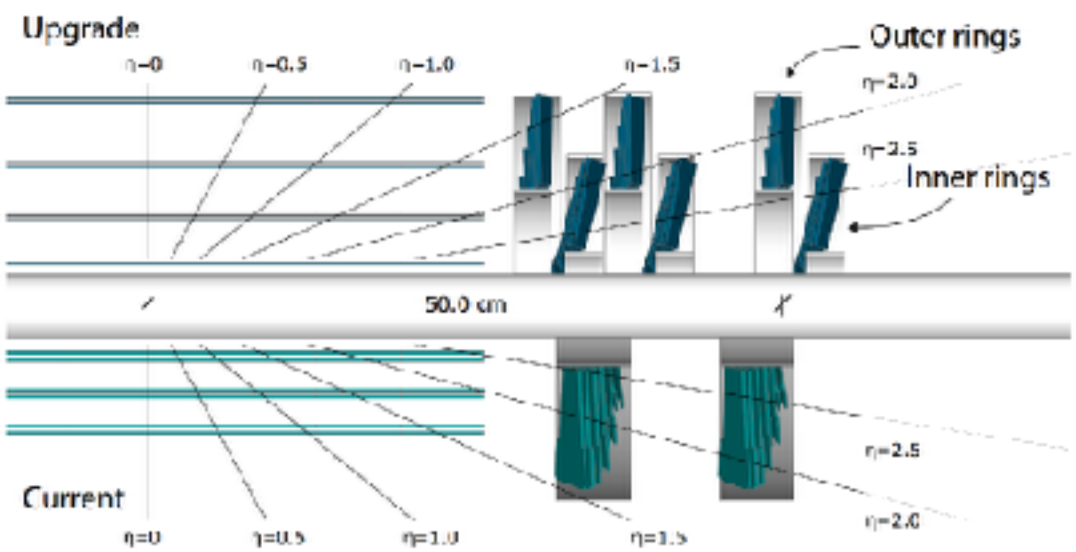
Phase-0 performance



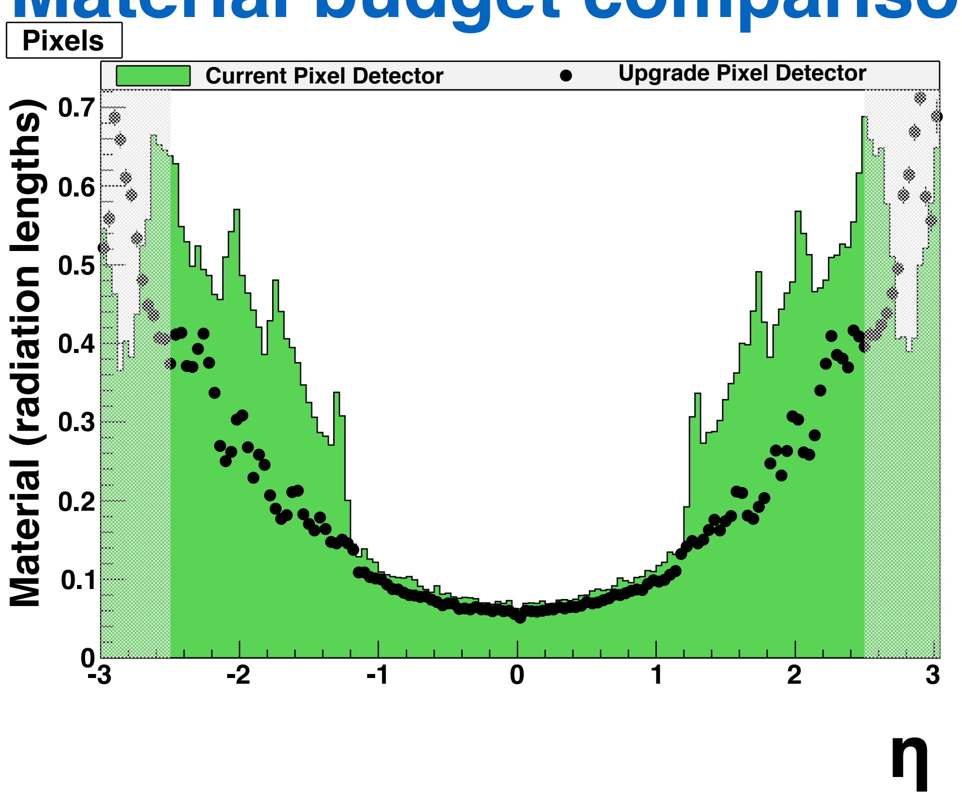


Pixel Phase-1 Design

- Improved pixel readout chip
  - Larger buffer to maintain hit efficiency at higher instantaneous luminosity
- Additional layers:
  - 4 barrel layers, 3 forward disks
  - More channels :
    - 48M → 79M (barrel),
    - 18M → 45M (forward)
- Reduced material budget
  - Two-phase CO_2 cooling
  - Move more material outside acceptance
- Detector designed to be installed mid-run (during year end technical stop)

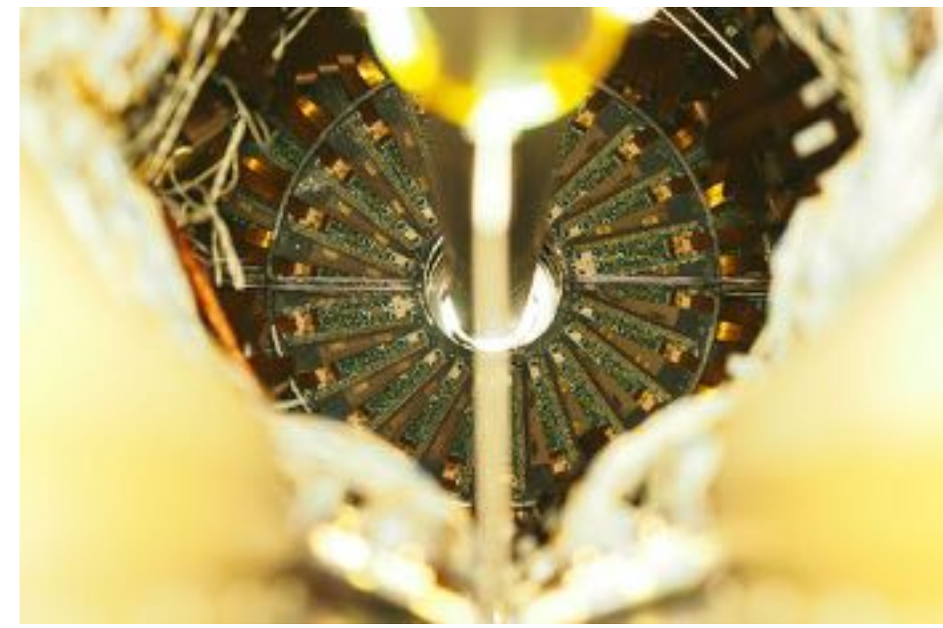


Material budget comparison

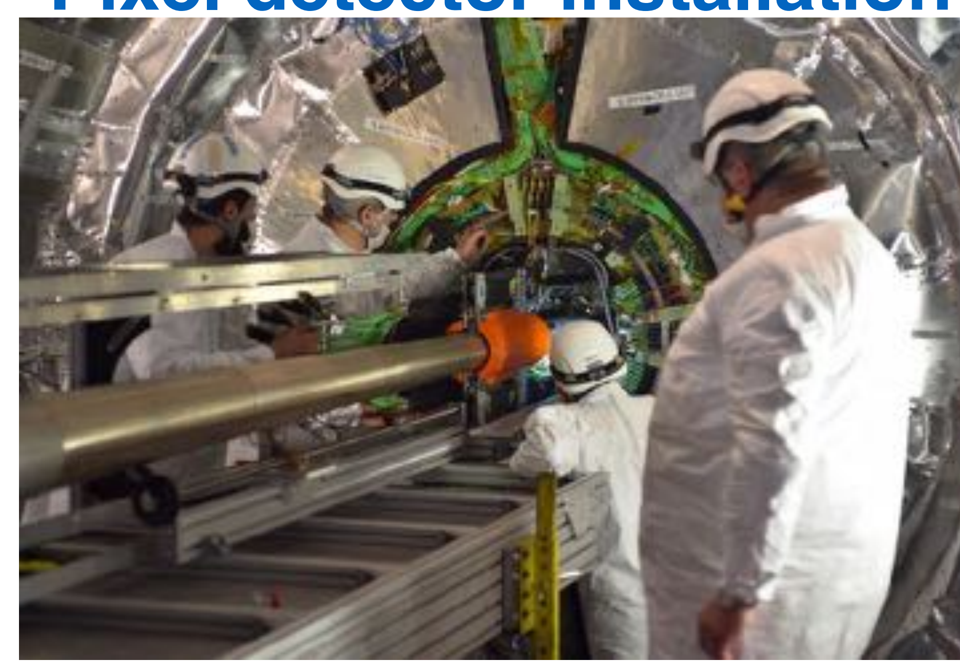


Pixel Phase-1

- Forward pixels designed, produced, and integrated in the US
  - Module assembly and testing at university sites, final assembly at SiDet @ FNAL
- Installed during 2016/17 winter shutdown
- Issues with DC/DC converter ASIC discovered during operations in 2017
  - Radiation effects found to cause failures upon power cycling
  - All DC/DC converters replaced during 2017/18 shutdown
  - New version of ASIC chip being developed, will be installed during long shutdown 2 (2019)



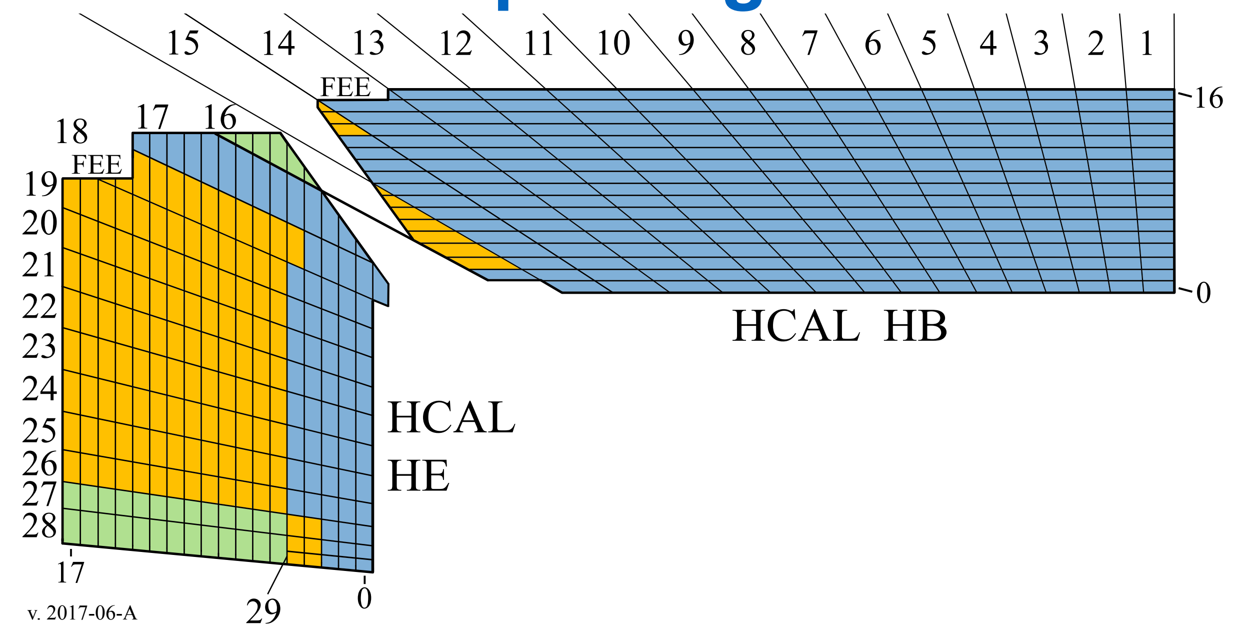
Pixel detector installation



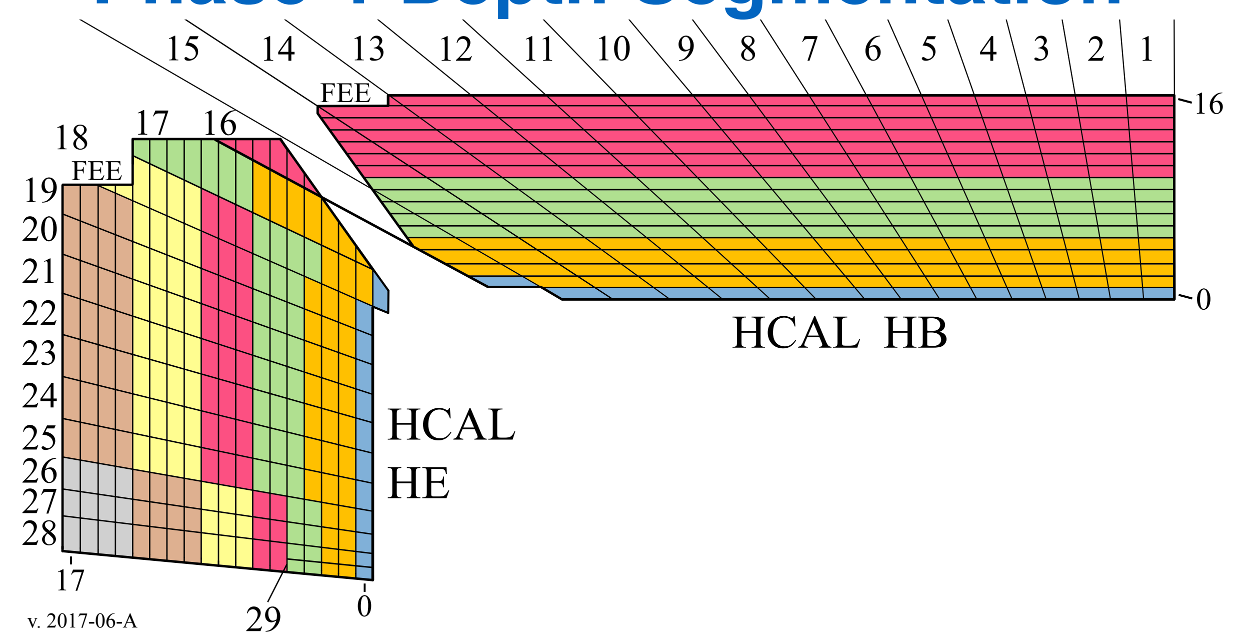
HCAL Phase-1

- **Upgrade Motivation**: Noise and radiation damage cause degradation of the detector
- **Forward (HF)** : Cherenkov calorimeter, steel absorber with quartz fibers feeding light into PMT
  - Replacement of PMT's,
  - New front end electronics with timing information
- **Endcap (HE) / Barrel (HB)** : Sampling calorimeter brass / plastic scintillator layers
  - Replacement of photodetectors
  - New front end electronics with more channels; better depth segmentation
  - More precise calibration of depth-dependent radiation damage
- **New front-end electronics** feature QIE10 and QIE11 ASICs,
  - Designed by Fermilab, tested and calibrated with university partners

Phase-0 Depth Segmentation

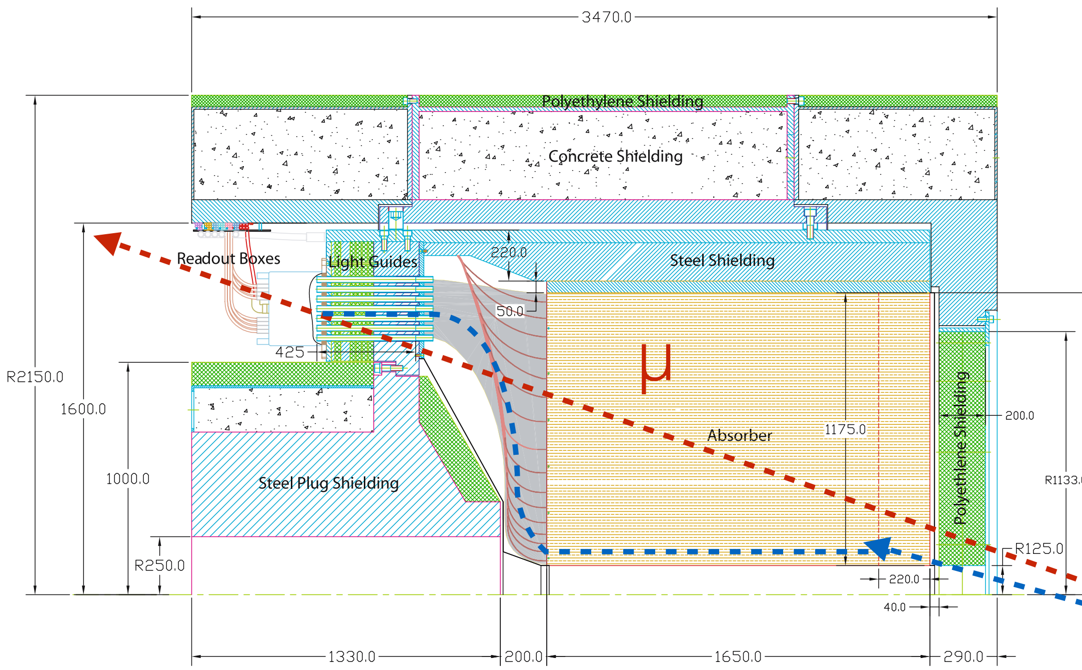


Phase-1 Depth Segmentation

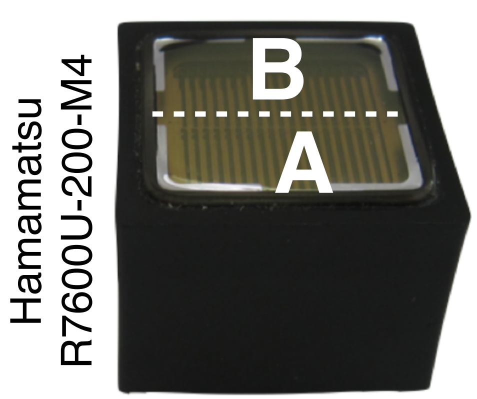


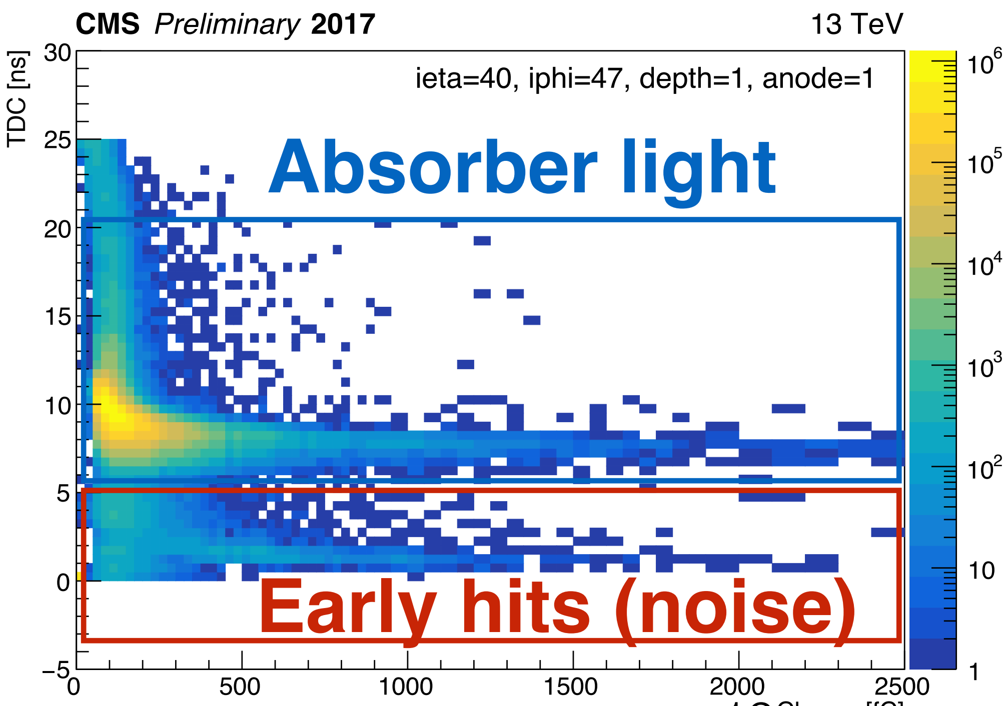
HCAL - Forward

- Significant background noise from anomalous hits in the PMT's themselves
- Upgrade to the electronics and replacement of PMT's
  - PMT's readout in dual anode mode, thinner window
  - New electronics provide timing information critical for noise rejection
- Installed during winter 2016/17



Dual Anode PMT

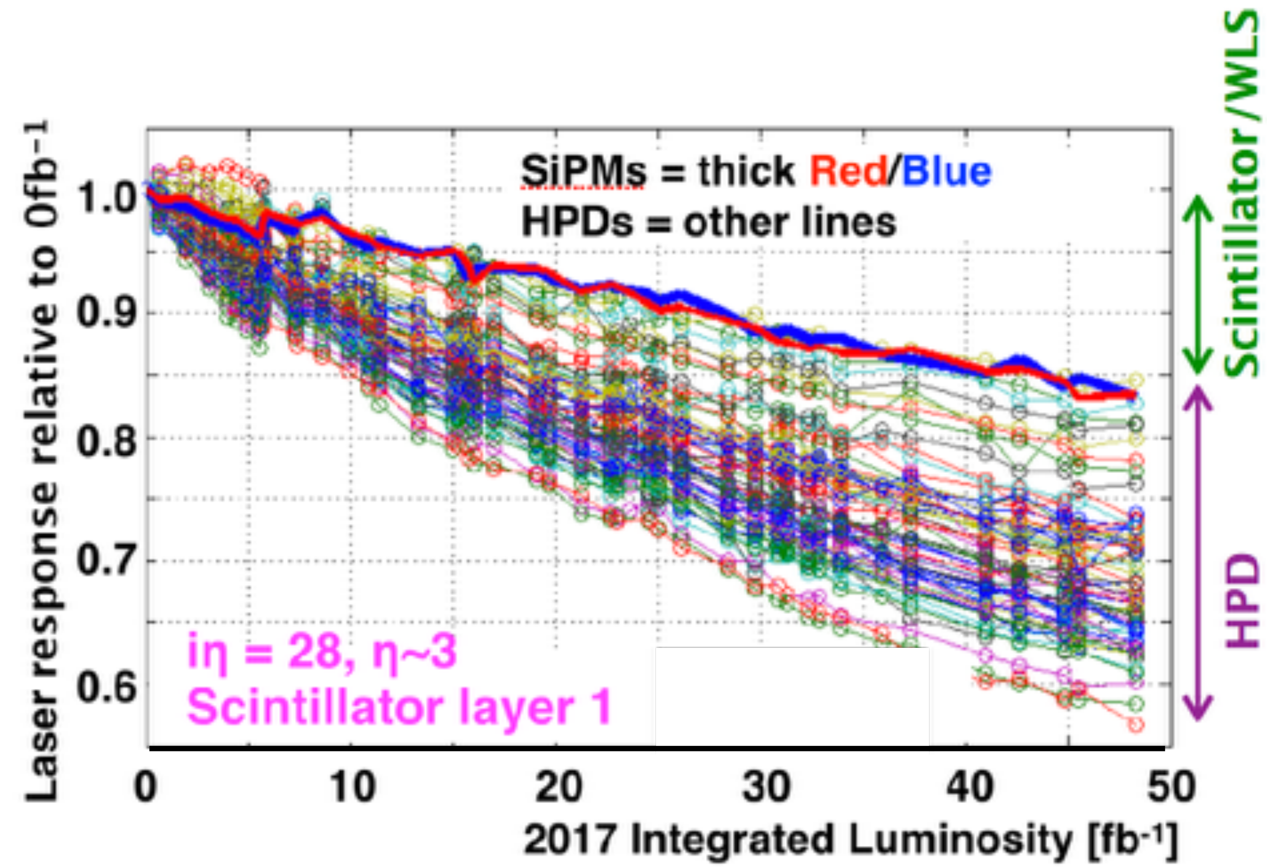




Installation of HF electronics

HCAL - Endcap

- Degradation in performance due to radiation and aging observed
  - Damage to both photodetectors and scintillators
- Phase-1 Upgrade:
  - Replacement of hybrid photo diodes (HPD's) with silicon photomultipliers(SiPM's)
  - New front end electronics
- Significant improvement to performance
  - SiPM's eliminate HPD damage
  - SiPM's have 3x higher photo detection efficiency, mitigate scintillator damage
- Full installation during winter 2017/18
  - Performing exactly as expected in 2018



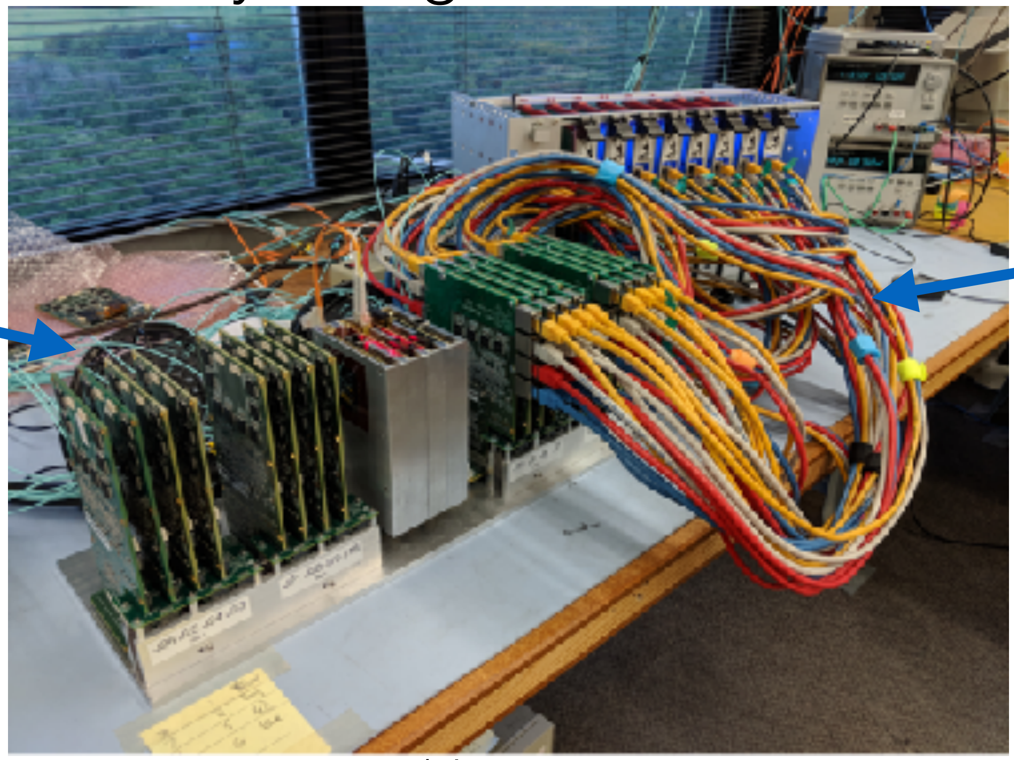
HE Installation

HCAL - Barrel

- Will be upgraded with SiPM's and QIE11 front end in long shutdown 2 (2019)
- Testing of all readout electronics taking place right at FNAL this summer
    - Quality control and calibration of ~900 QIE cards
        - Testing performance of QIE
        - Calibrating response to input charge
    - Happening in 14th floor HCAL lab right now
    - First 20 QIE cards already being tested

HB QIE Card

HB QIE Cards

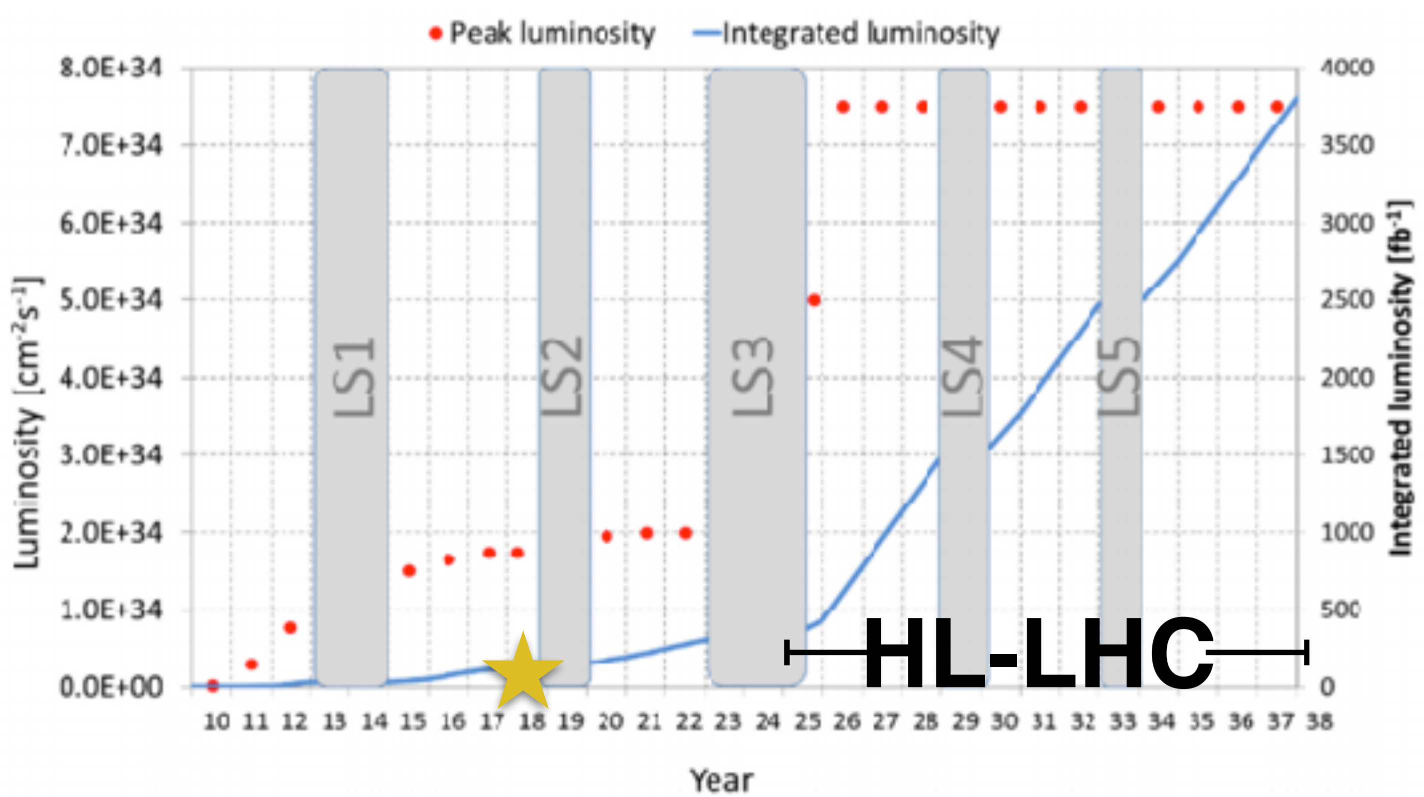


QIE Calibration setup

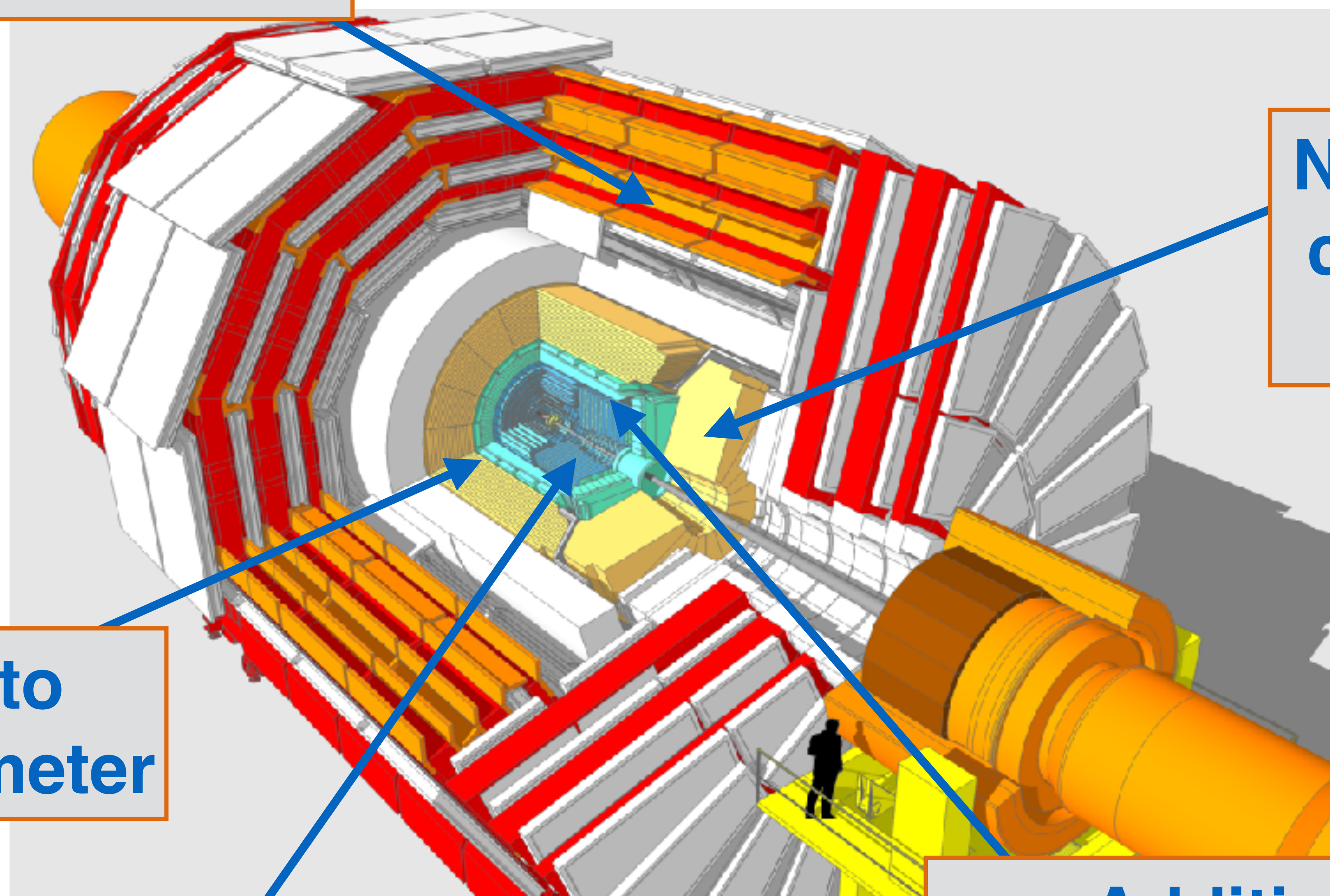
Phase-2 Upgrades

Phase-2 Upgrades

- HL-LHC upgrades present entirely new challenges for CMS
  - Instantaneous luminosity increase by a factor of 5-7.5 over design value (between 5 and 7.5x10^{34} $cm^{-2}s^{-1}$)
  - Up to 200 pileup interactions per bunch crossing
- Upgrades to nearly all of the subsystems of CMS required to operate in HL-LHC conditions
  - 90% of all CMS data will be taken in HL-LHC

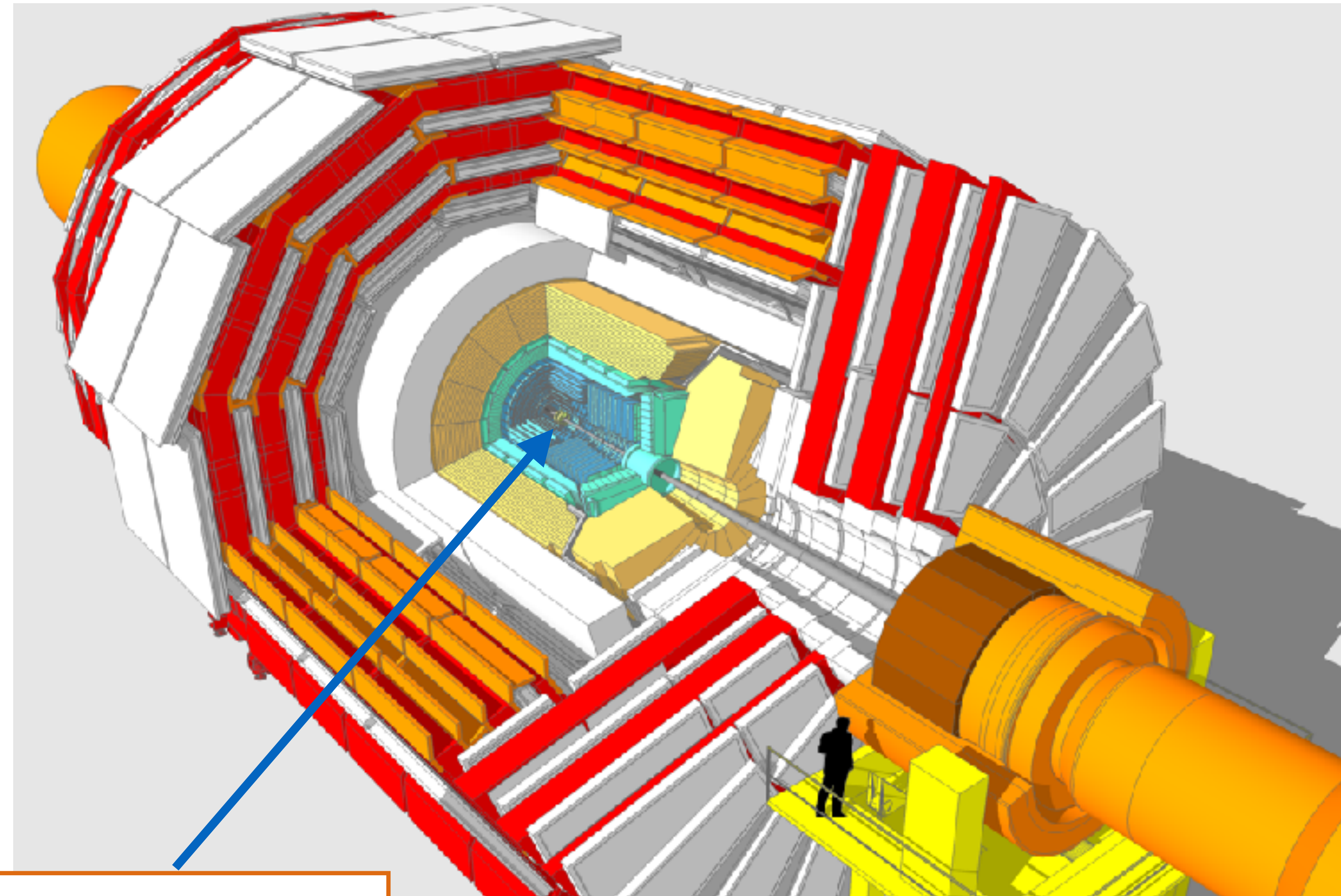


Phase-2 Upgrades



Phase-2 Tracker

CMS-TDR-014

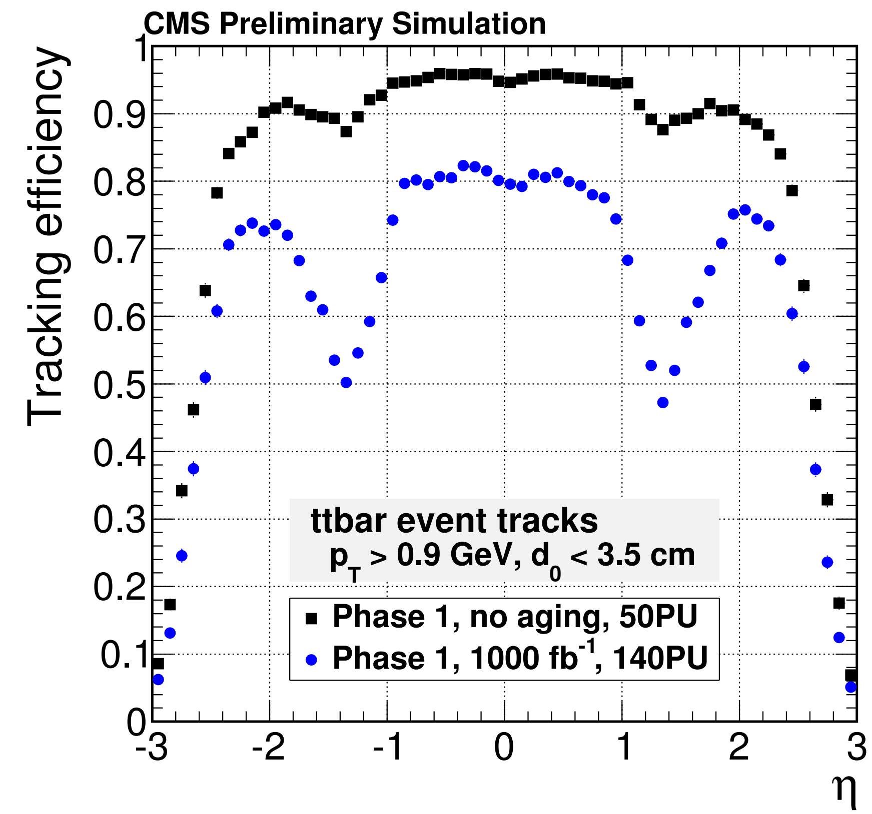


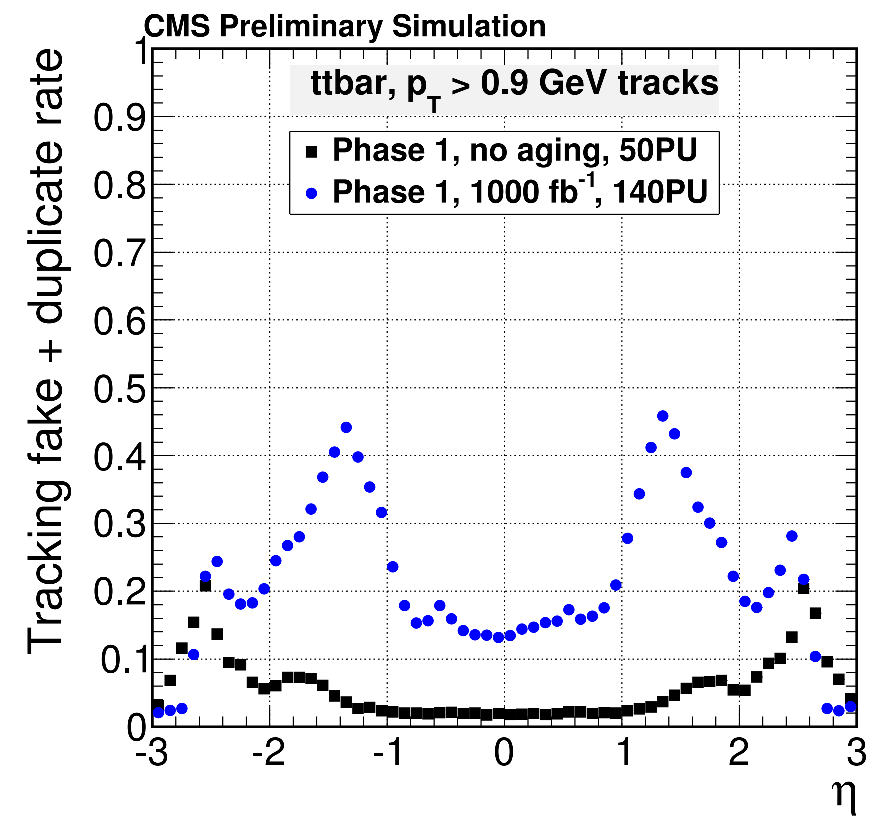
New Tracker

- Extended coverage in η
- Improved radiation hardness
- 40 MHz readout for trigger (outer tracker)

Tracker Upgrade Motivation

- Current tracker will not survive through HL-LHC
  - Radiation damage will lead to increased leakage currents
  - After 1000 fb^{-1} (1/3rd of HL-LHC), 40% of the phase-1 tracker will be non-functional
  - Substantial reduction in tracking efficiency
- Improvements to the sensor design and cooling will improve radiation hardness

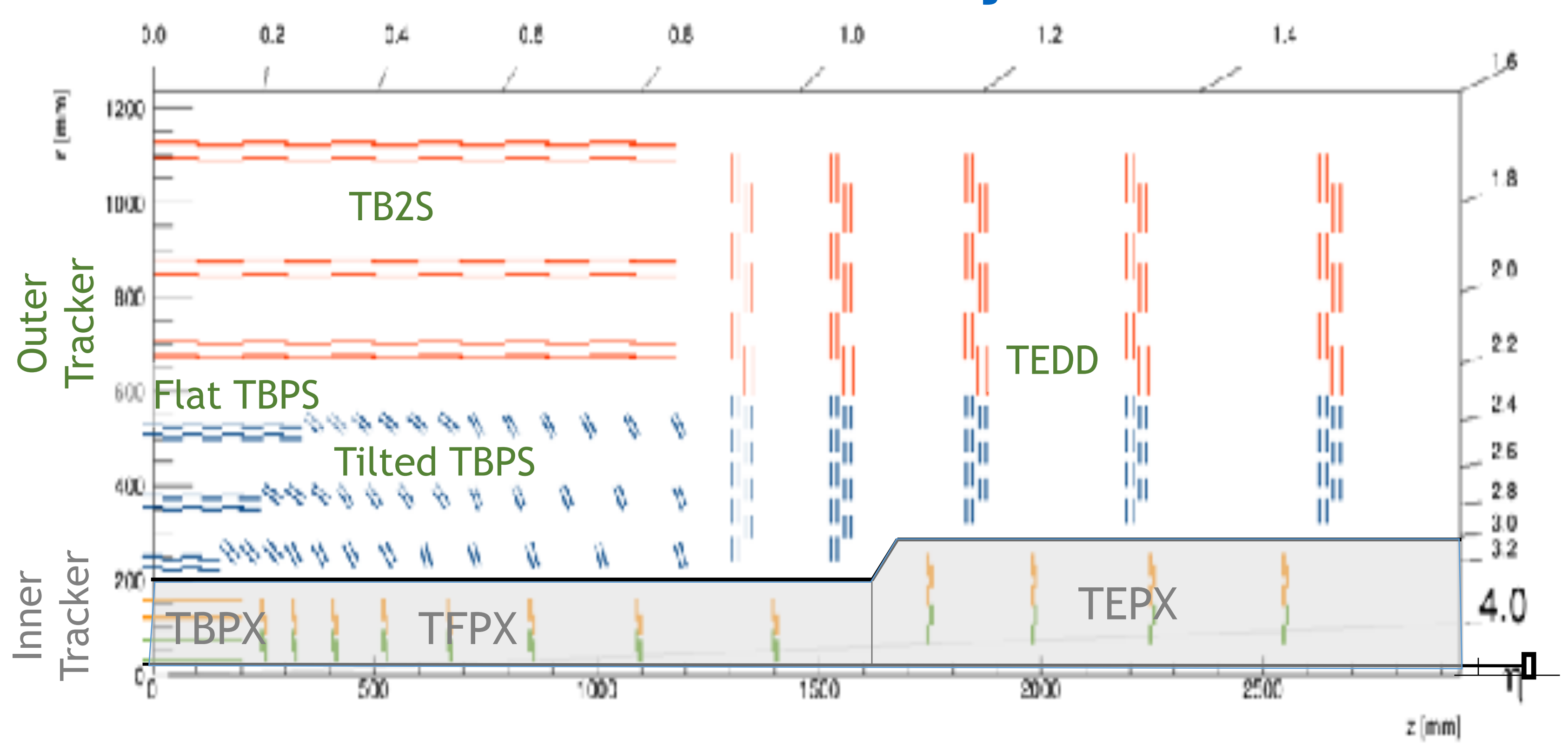




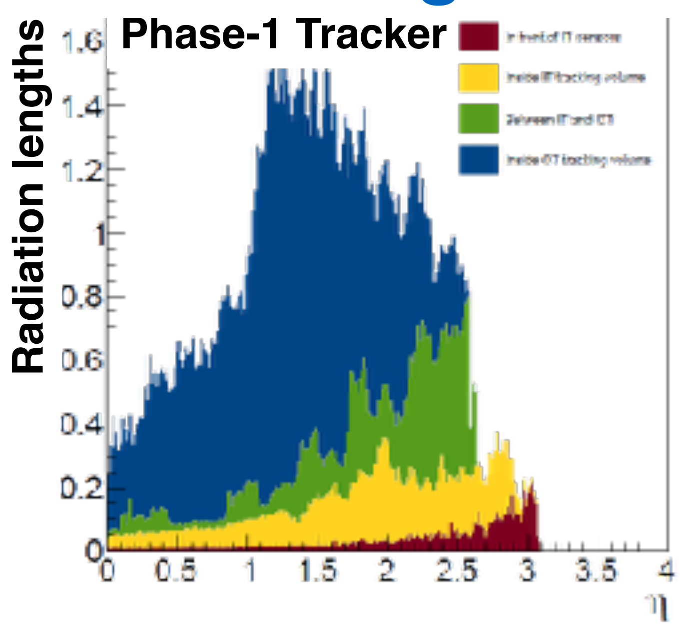
Phase-2 Tracker

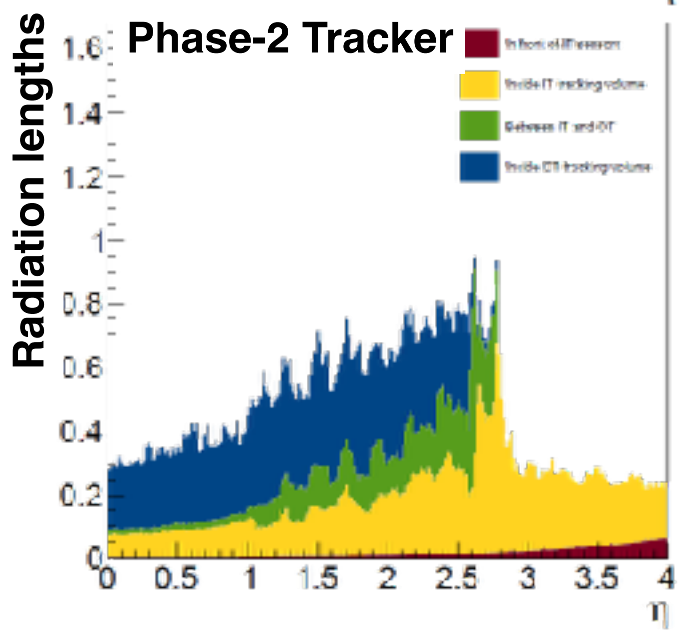
- All-silicon tracker, split into two subsystems
- **Inner tracker**
  - Extend coverage to $\eta < 4$
- **Outer tracker**
  - Provides input into trigger system
- Reduced material budget w.r.t. Phase-1 Tracker

Phase-2 Tracker Layout



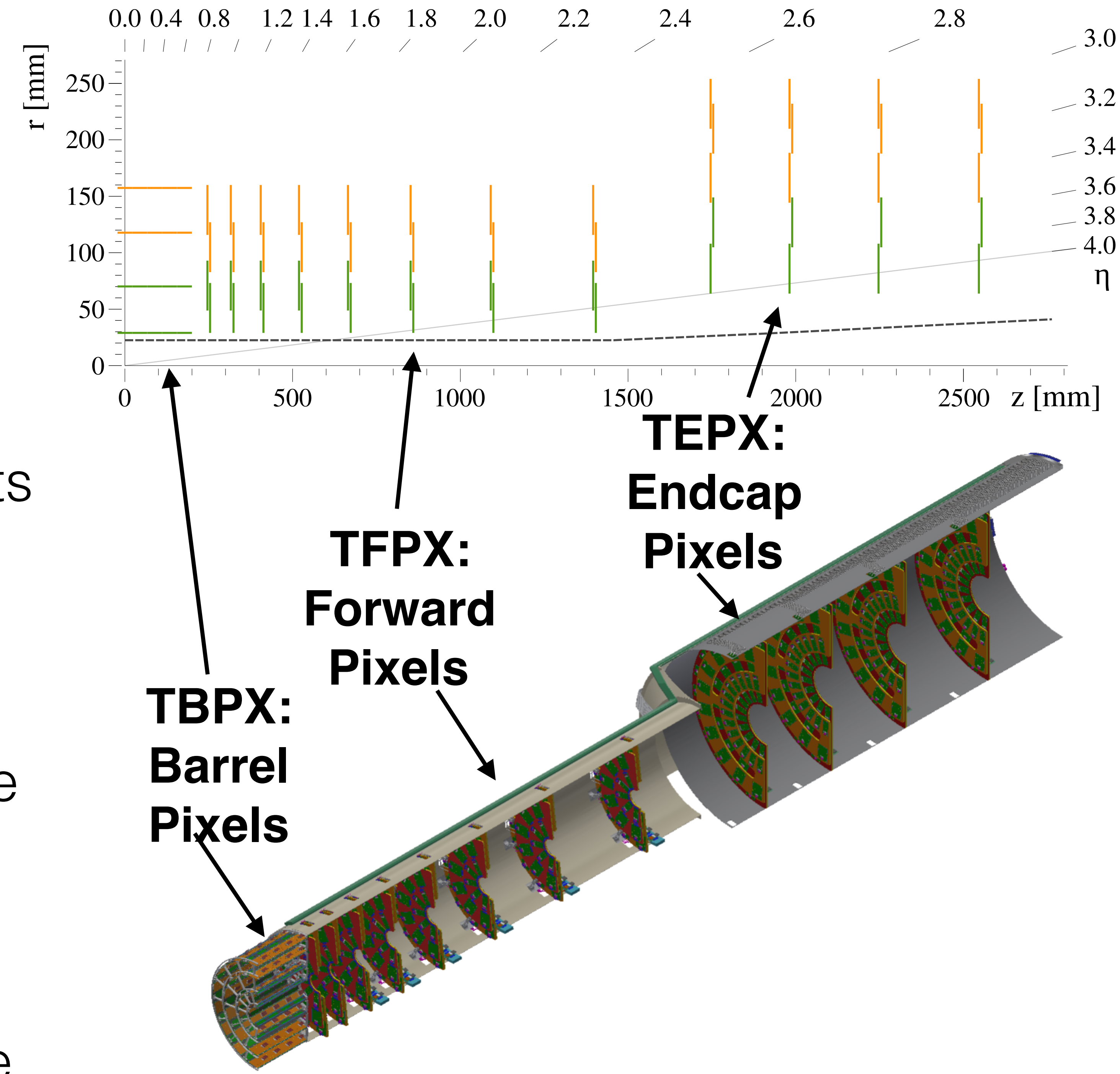
Tracker Material Budget





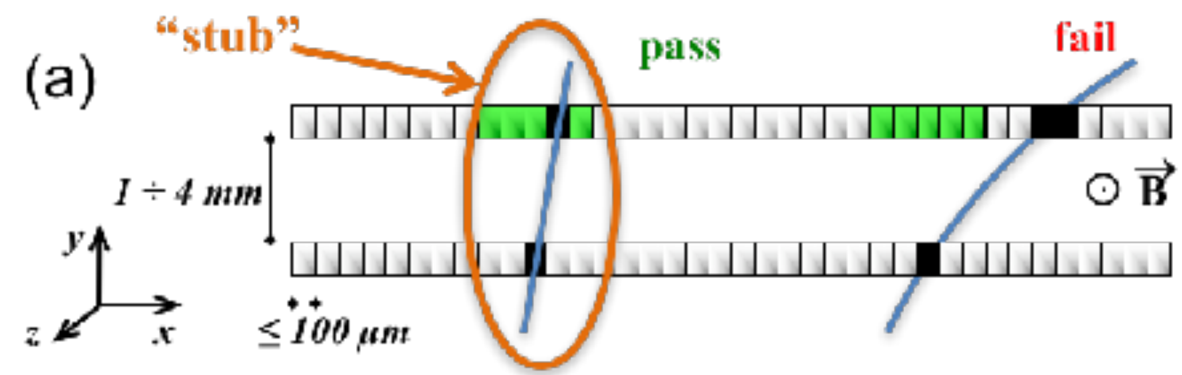
Inner Tracker

- Extended coverage to η < 4
- Smaller pixel size (2500 μm²)
  - Nearly 2 billion channels
  - Improves track resolution
  - Reduces pixel occupancy to per-mille level
  - Improves track separation in jets
- New pixel readout chip being developed within RD53, joint ATLAS-CMS collaboration
- Designed to survive radiation dose expected for 3000 fb^{-1}
  - Still allows possibility to extract and replace components if deemed necessary in the future

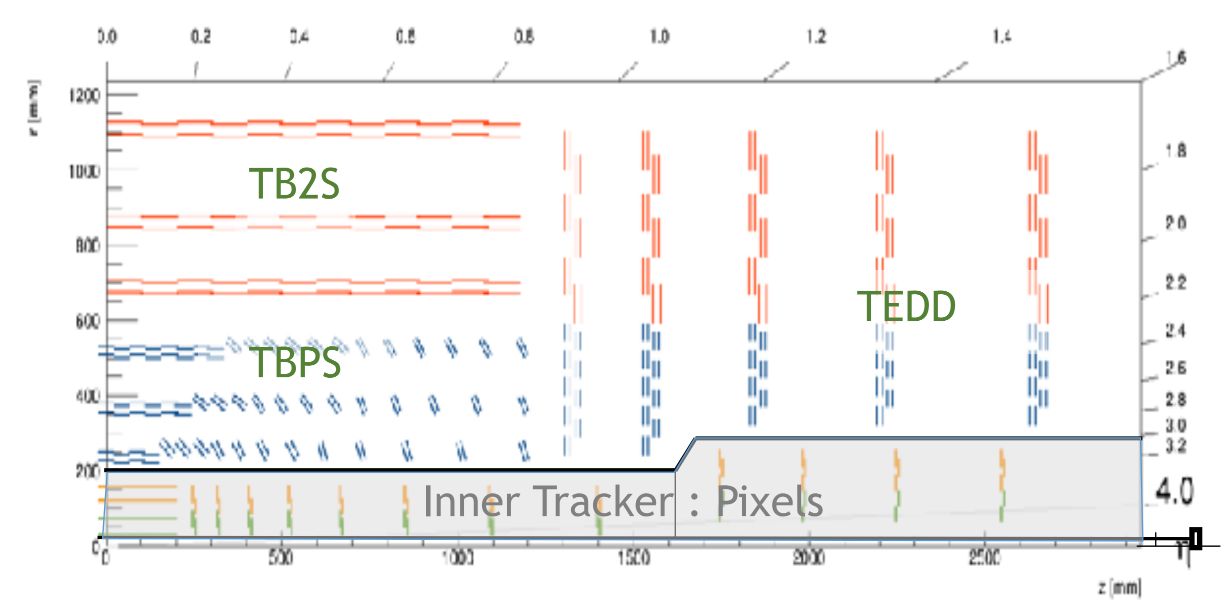


Outer Tracker

- Inclusion of track information into trigger
- Sensors made up of “p_T-modules” :
  - Pairs of closely spaced, parallel strip sensors
  - On-detector correlation measurements allows discrimination between high/low momentum hits
  - Restrict 40 MHz trigger system readout to stubs above tunable threshold
- Two types of p_T-modules:
  - Pixel-strip (**PS**) : pairs of macro-pixel and strip sensors, 100 μm pitch, 2.4 cm in length (0.15 cm pixels)
  - Strip-strip (**2S**) : pairs of parallel strip modules, 90 μm pitch, 5 cm in length

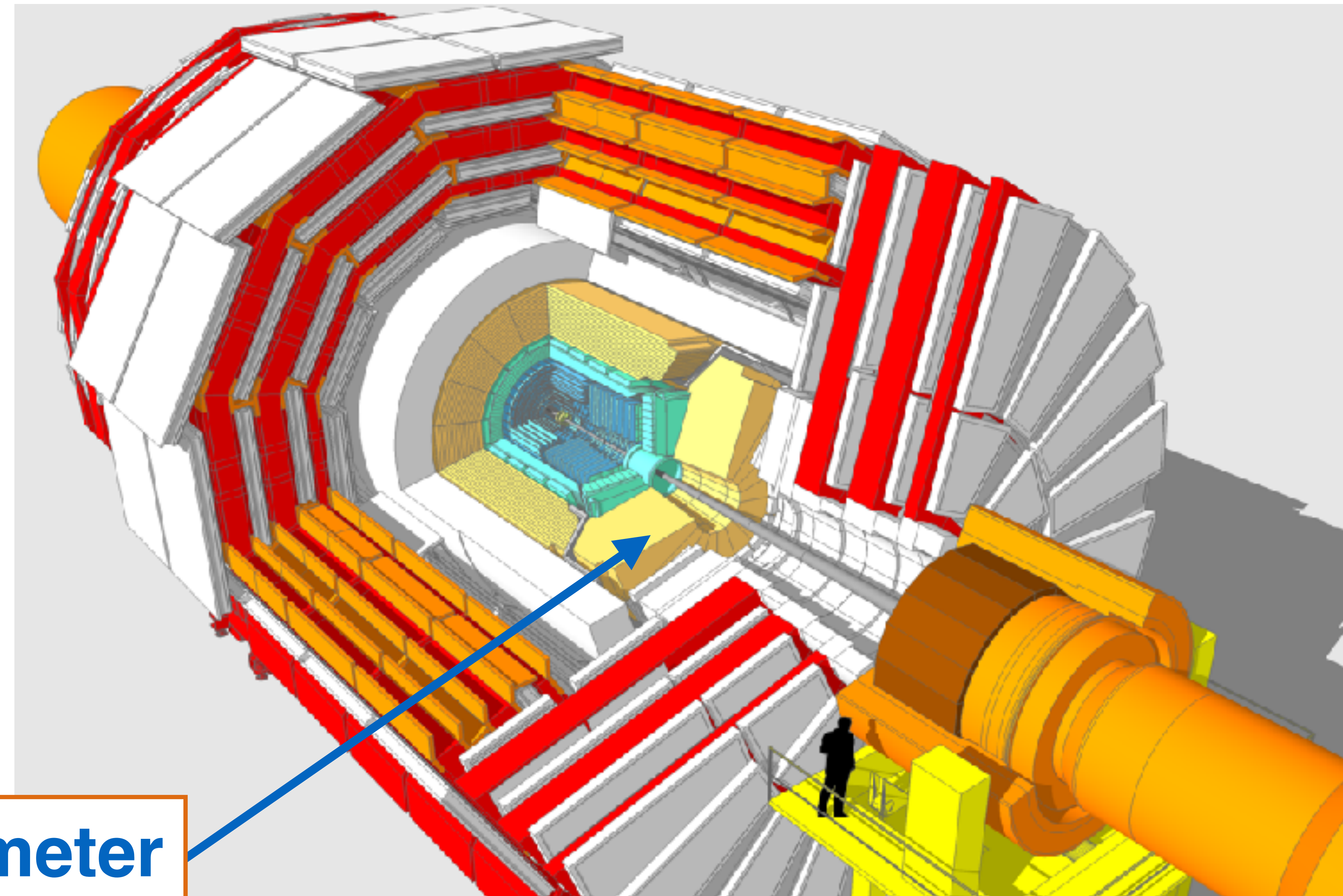


Bend in track from magnetic field can distinguish high/low momentum “track stubs”



Phase-2 Calorimeter

CMS-TDR-019

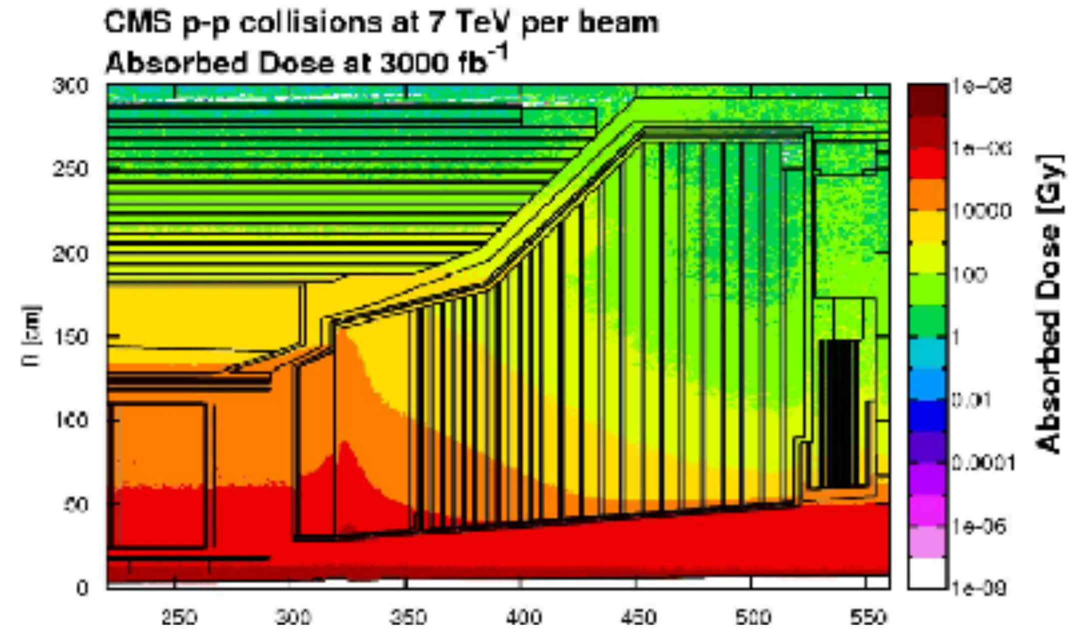


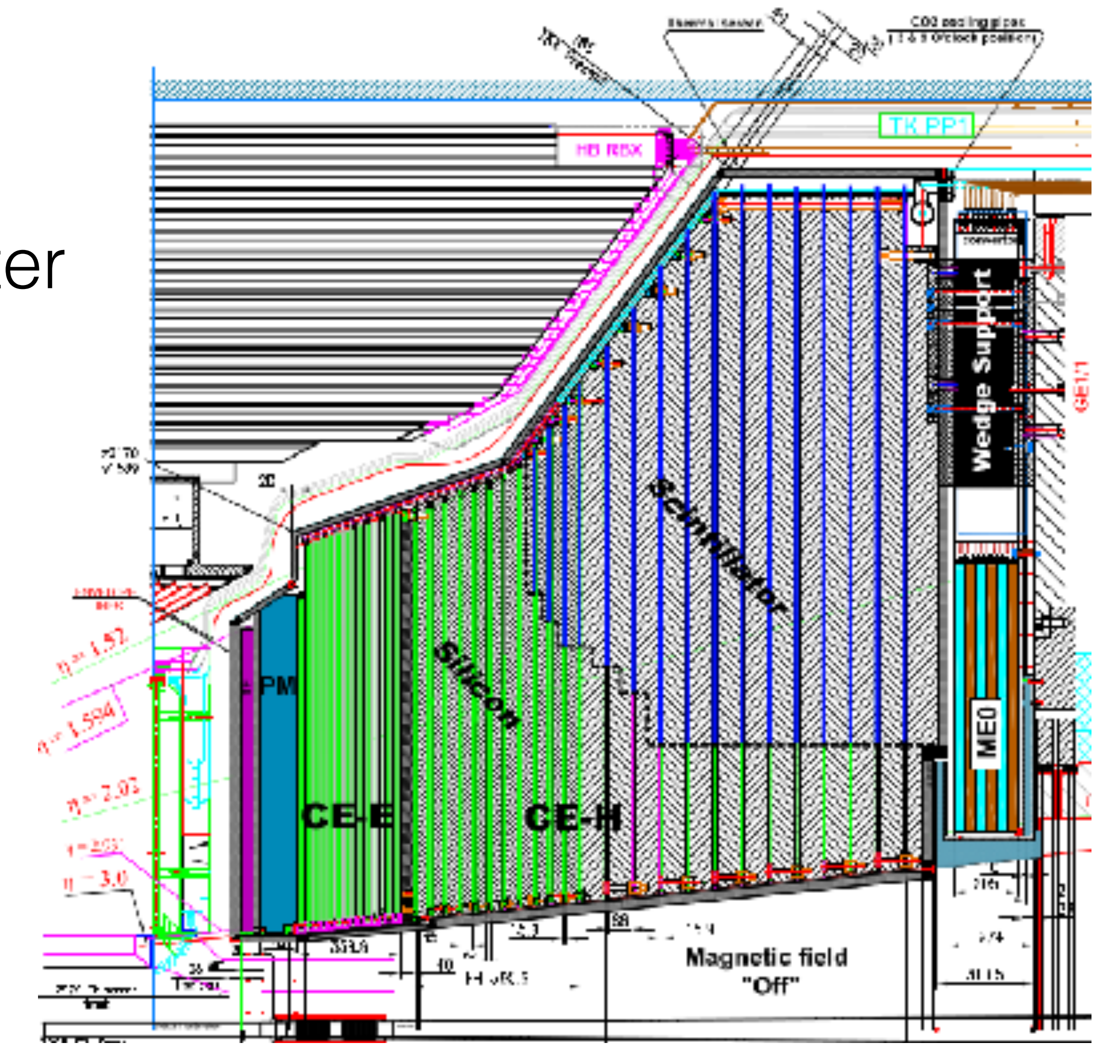
New Endcap Calorimeter

- High Granularity Calorimeter
- Mix of Silicon and Scintillators
- Improved radiation tolerance

Phase-II Endcap Calorimeter

- Current crystal & scintillator based calorimeter will not survive radiation in HL-LHC
- **High Granularity Calorimeter (HGCAL)**
  - Replacement of the current endcap calorimeter
  - Silicon sensors in high radiation environment
  - Scintillator sensors in lower radiation sections
- First use of high granularity imaging calorimeter at a hadron collider
  - Over 6 million channels
  - Provides fine longitudinal and transverse segmentation
  - Provides timing information of shower development

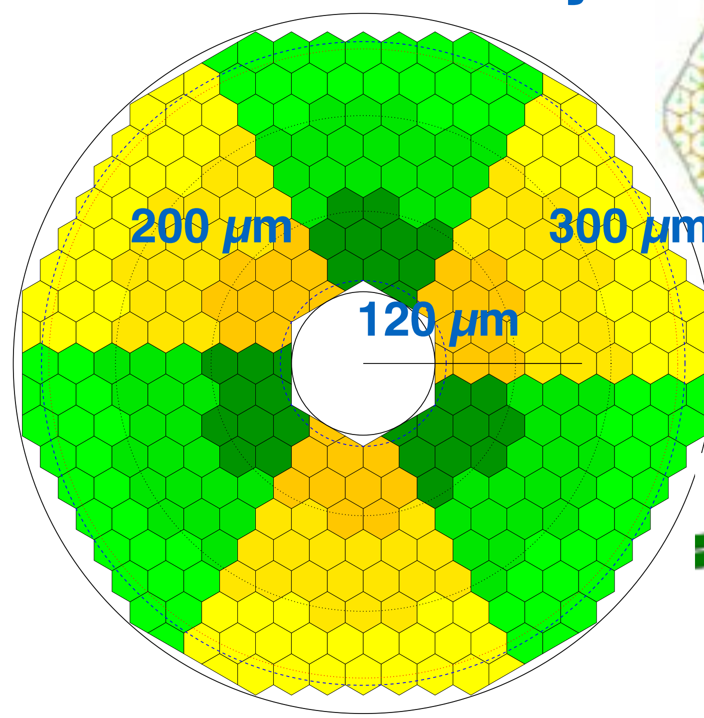


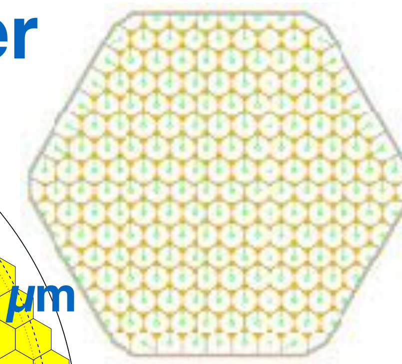


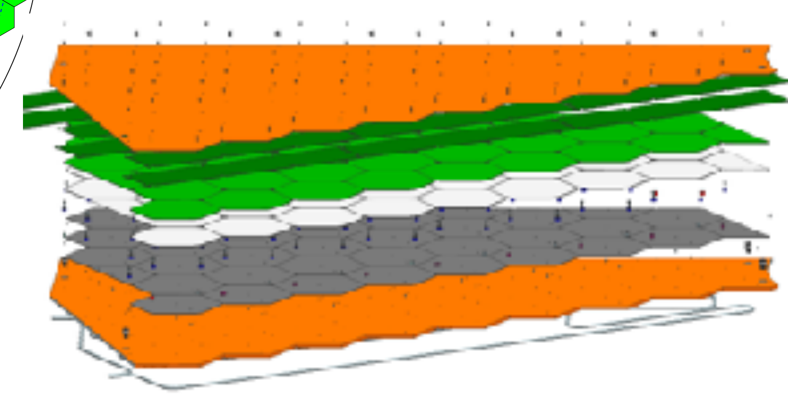
HGCAL

- Silicon sensors:
  - 8-inch module, varying from 120 to 300 μm silicon thickness
- Scintillators modules:
  - Plastic scintillator tiles with SiPM readout
- US leadership role in design and production of sensors

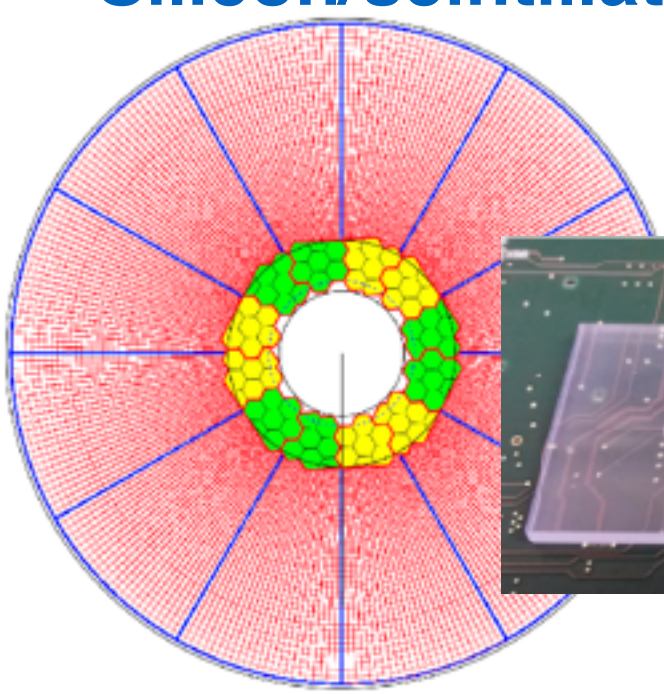
All-silicon layer

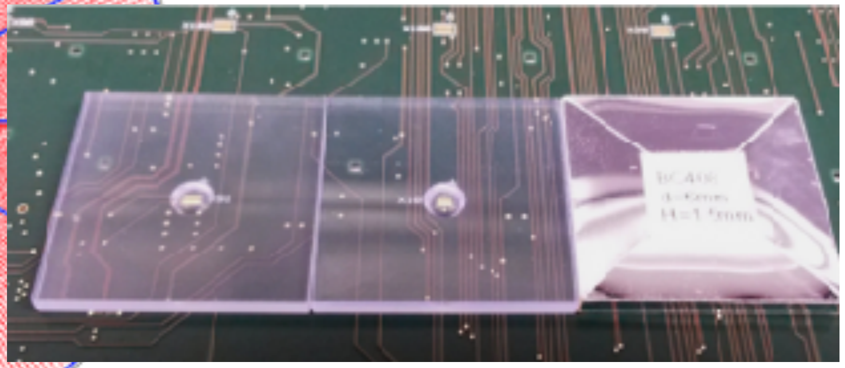






Silicon/scintillator layer

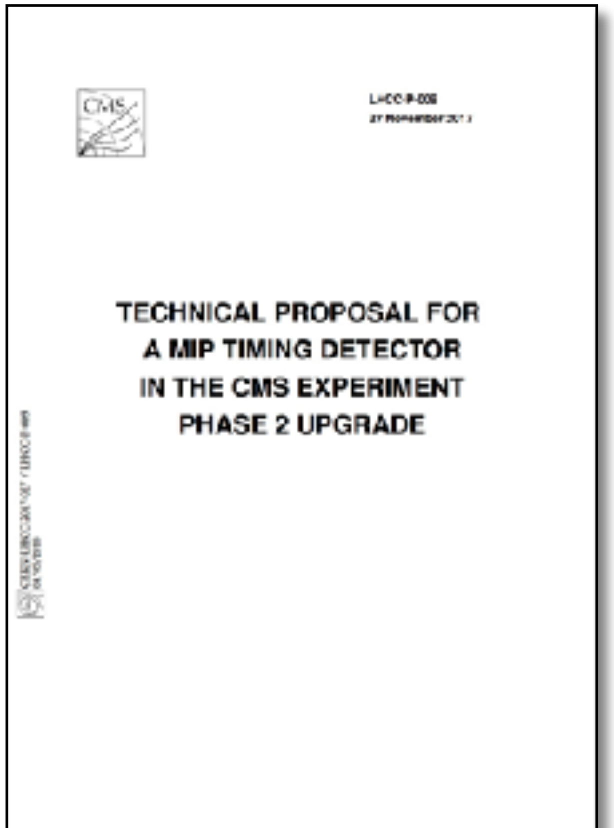


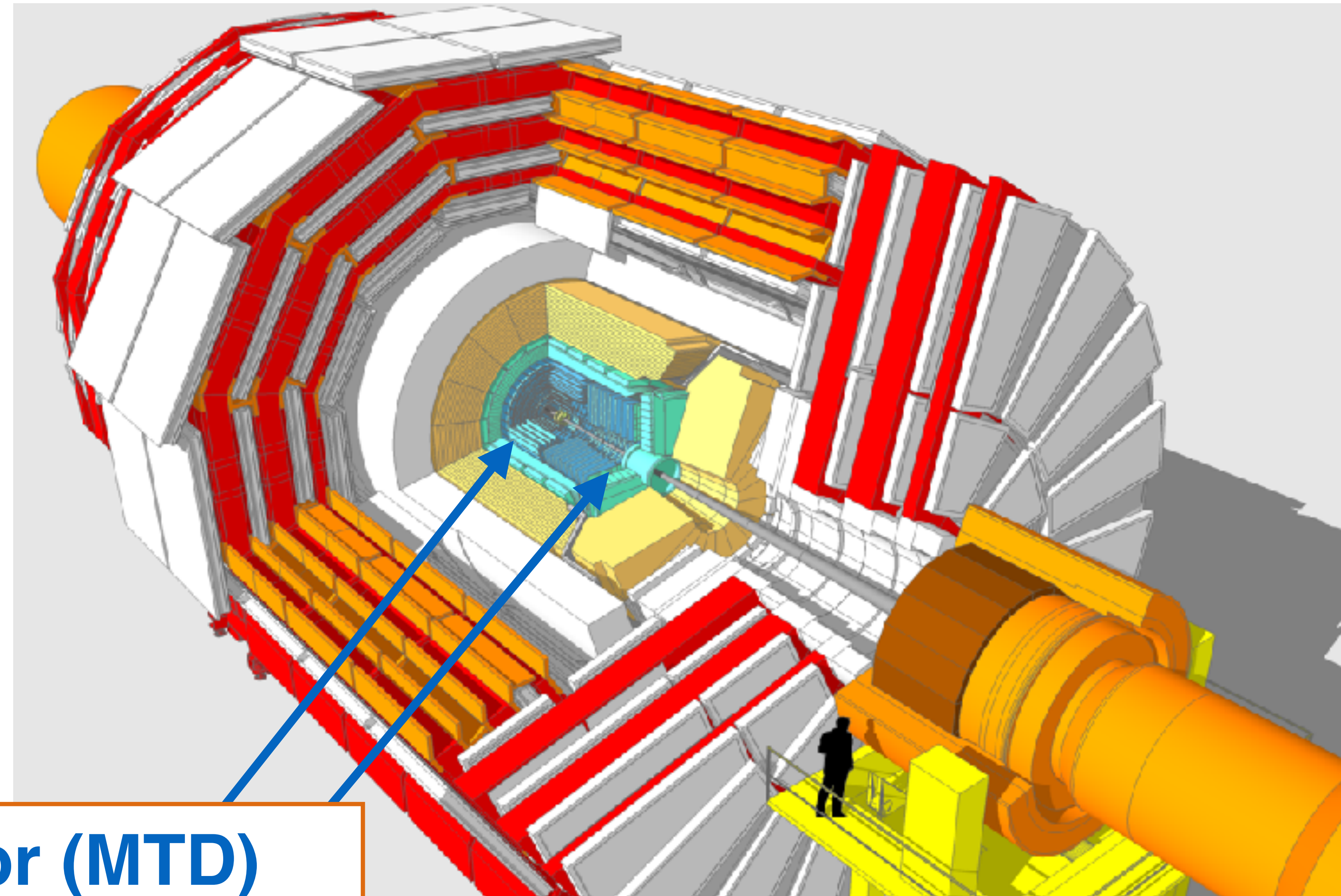


- Endcap Concentrator ASIC being developed by Fermilab and US universities
  - Critical for trigger and data acquisition readout
  - On detector clustering of trigger data to reduce output bandwidth

Phase-II MIP Timing Detector

LHCC-P-009

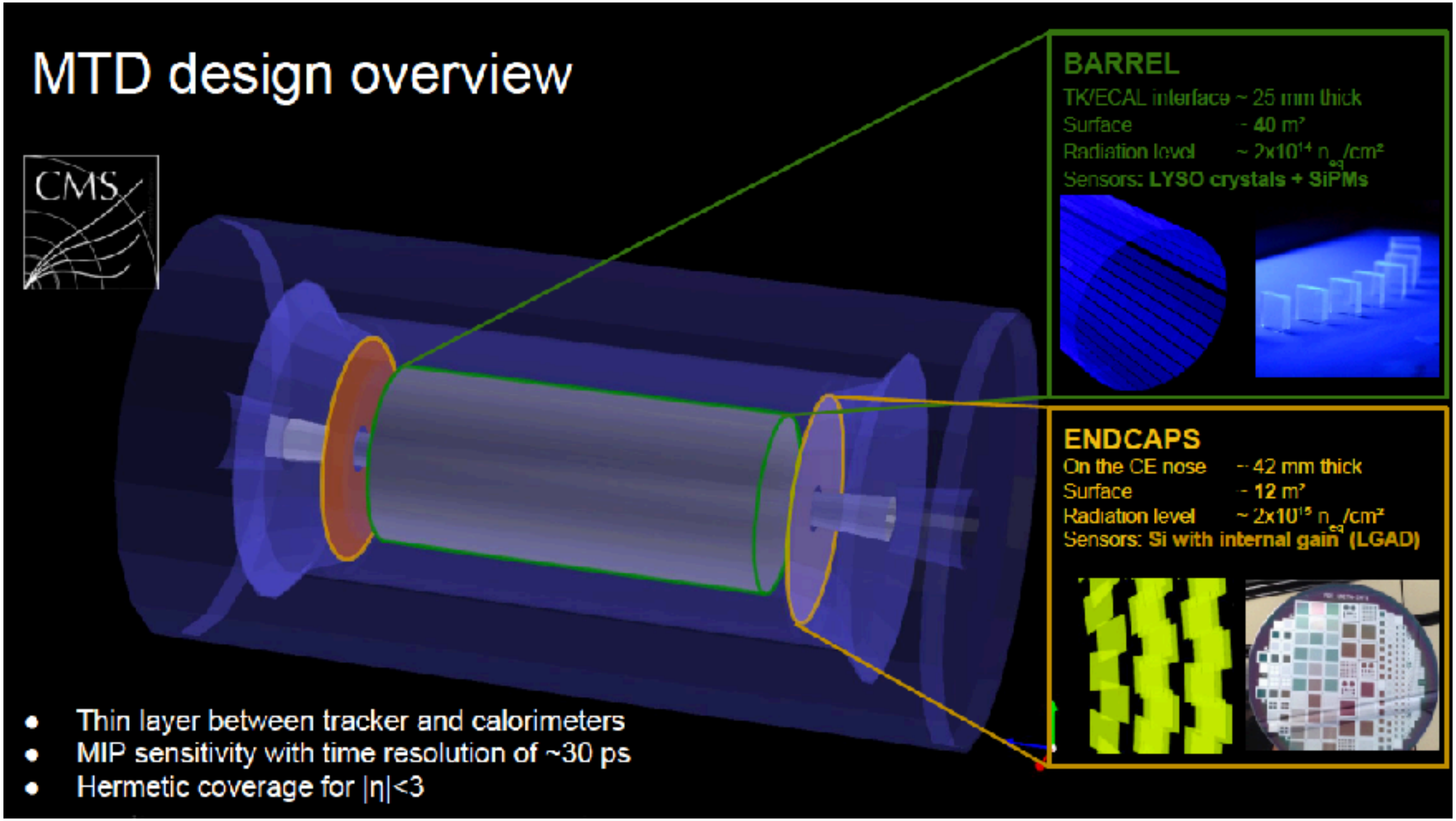

TECHNICAL PROPOSAL FOR
A MIP TIMING DETECTOR
IN THE CMS EXPERIMENT
PHASE 2 UPGRADE



MIP Timing Detector (MTD)

- New subsystem
- Provides precision timing information in both barrel and endcap
- Mitigate the effect of pileup in track and vertex reconstruction

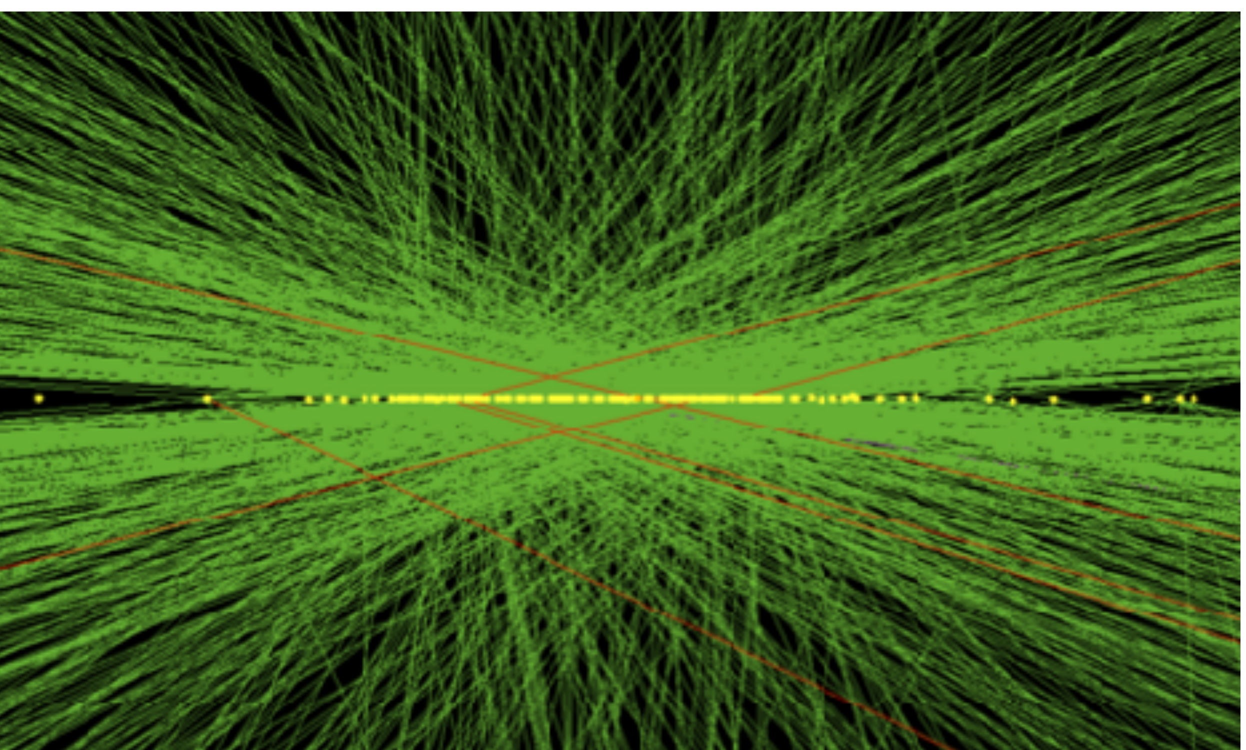
MIP Timing Detector

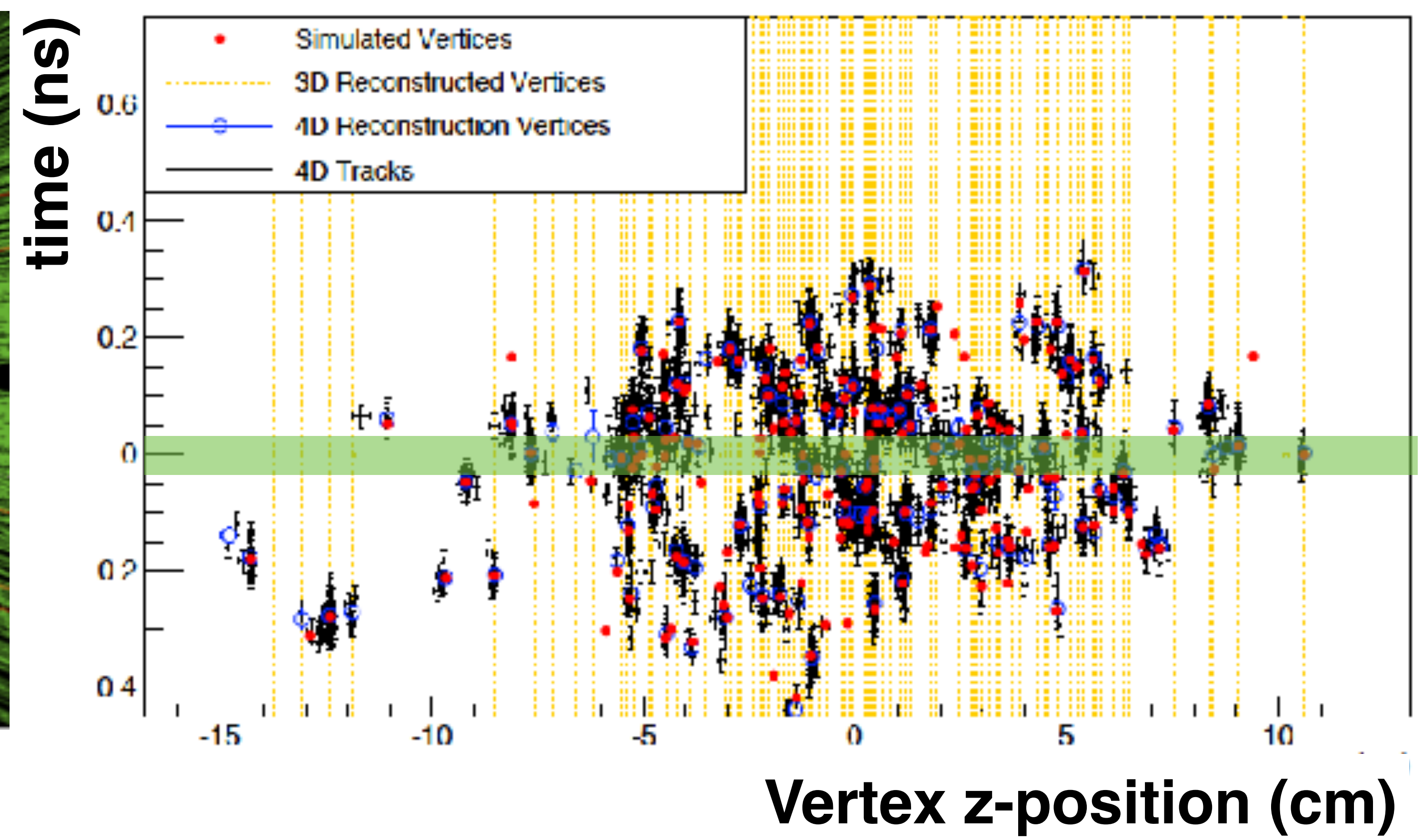


- Fermilab and US universities have leadership role

MIP Timing Detector

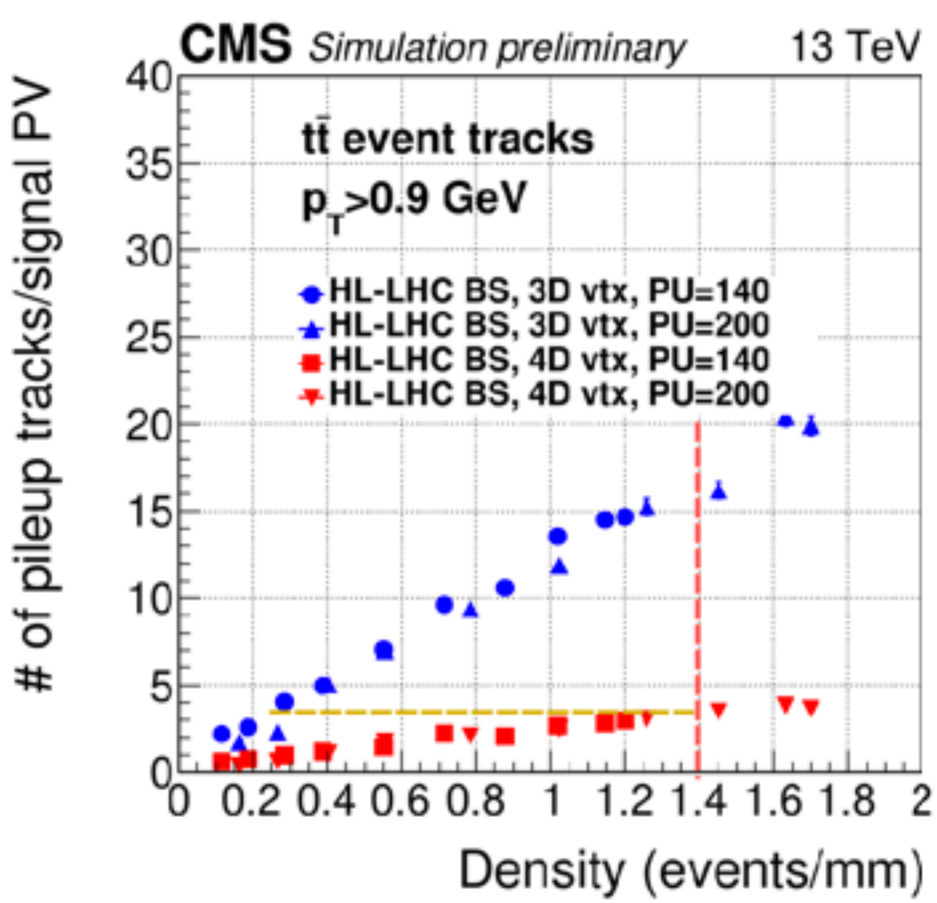
- High pileup conditions will significantly degrade vertex reconstruction
  - Precision timing information provides another dimension to separate vertices (4D reconstruction)
  - With track timing at a 30 ps precision, most overlapping vertices can be distinguished

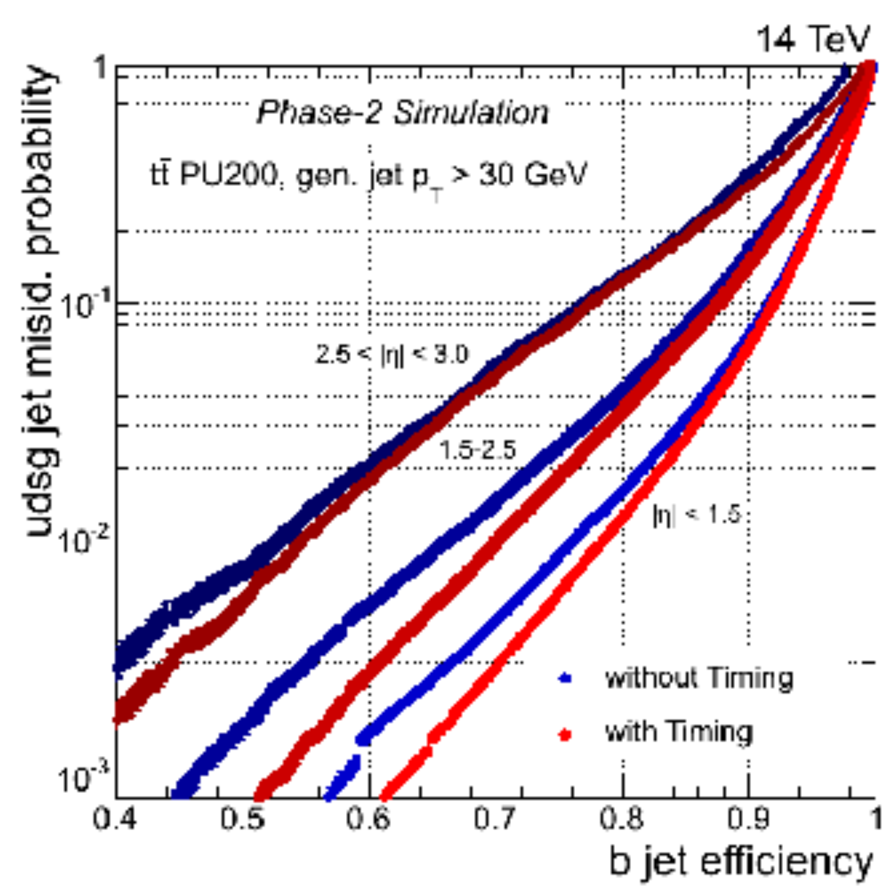




MIP Timing Detector

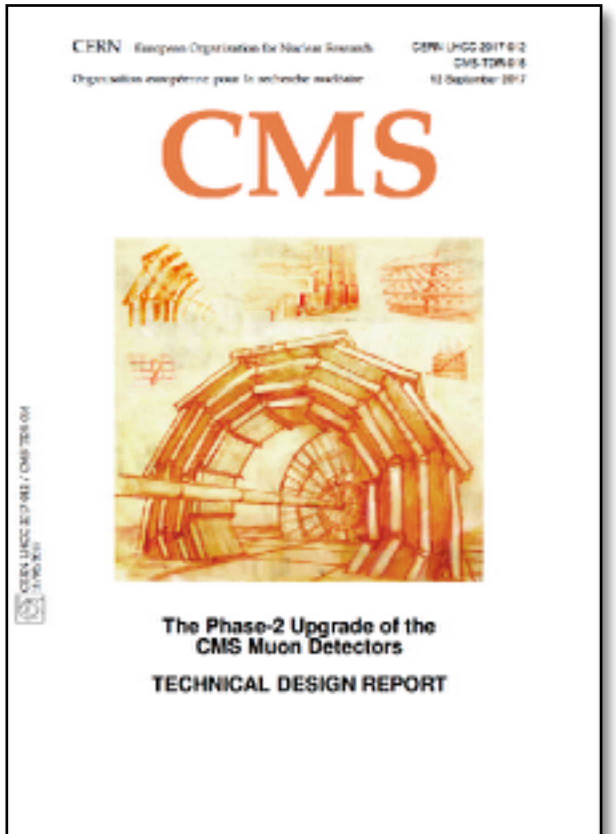
- Timing information allows for better association of tracks to the correct vertex
  - Reduces contribution of pileup tracks to signal vertex by a factor of 5
- Results in significant improvement to b-tagging performance at 200 PU compared to reconstruction without timing information

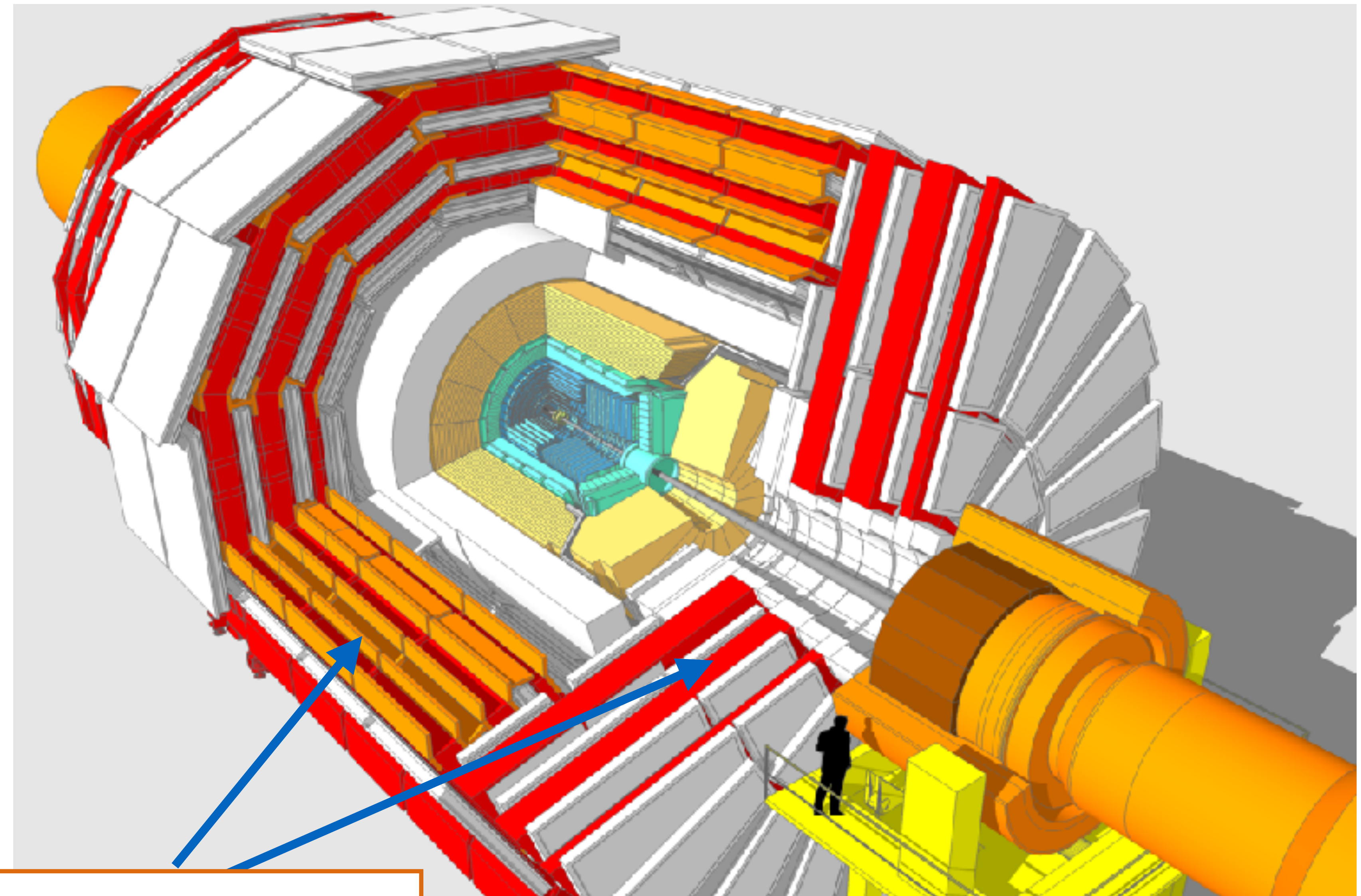




Phase-II Muons

CMS-TDR-016



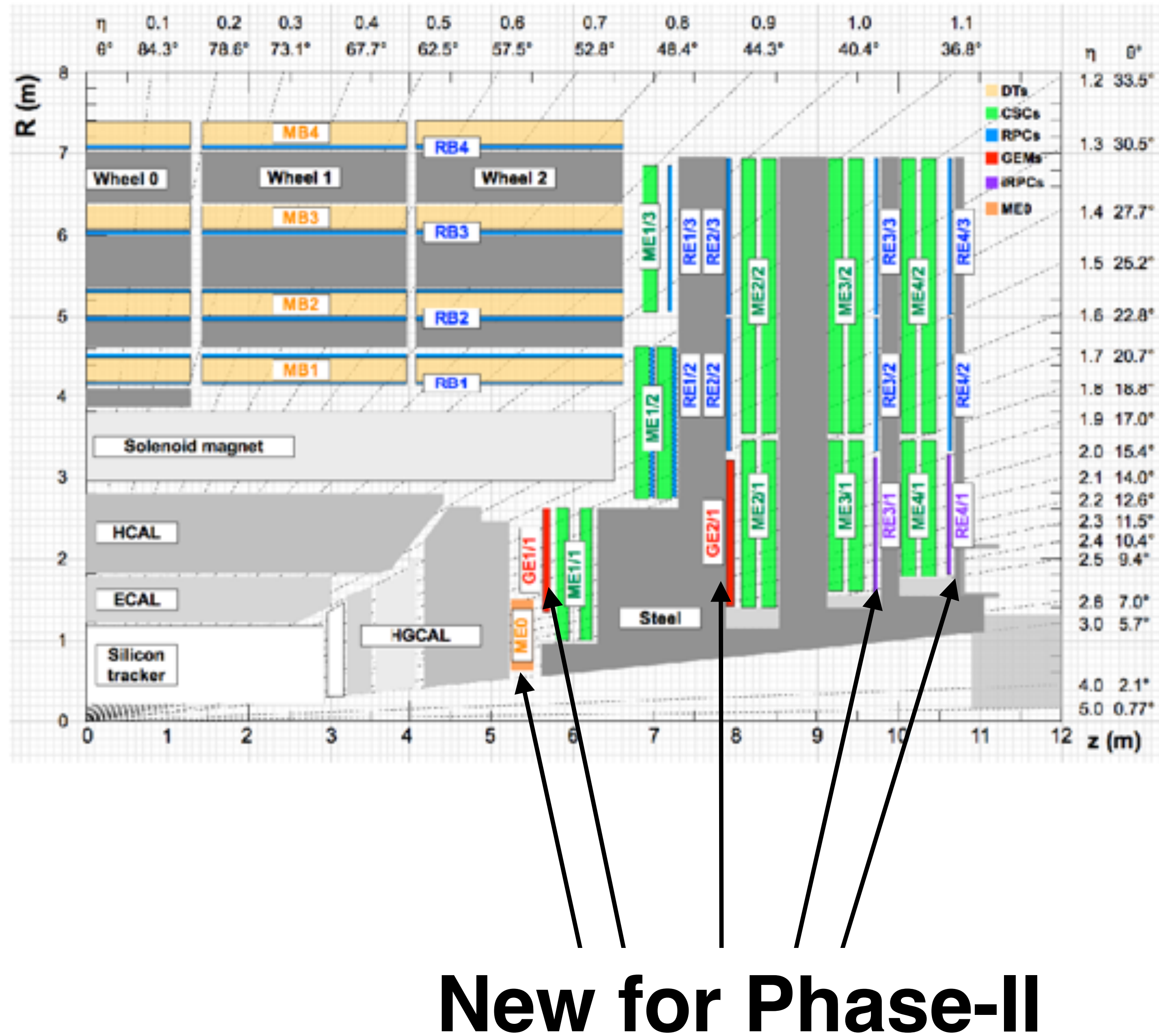


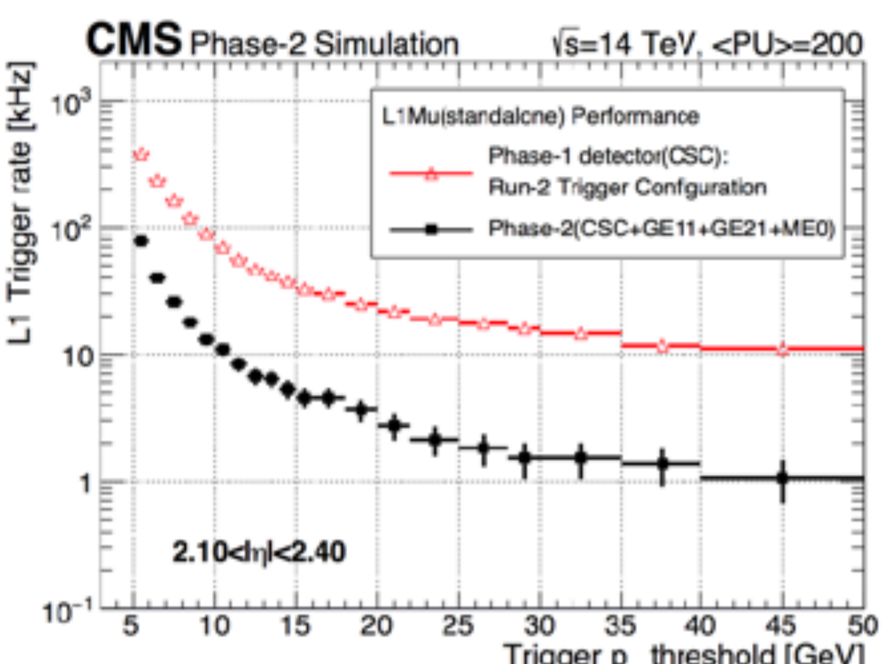
Muon Upgrade

- New GEM detectors
- Additional layers at high-eta
- New FE/BE electronics for current detectors

Muon Detector

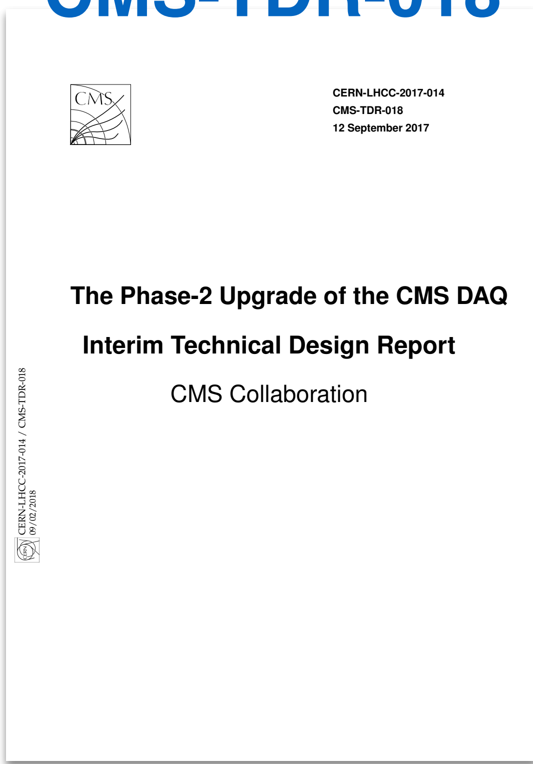
- New sub-system (GEM) and layers to improve coverage at high pseudorapidity
- For existing detector: upgrades to frontend and backend electronics to handle data rates of HL-LHC





Trigger / DAQ Upgrade

CMS-TDR-018



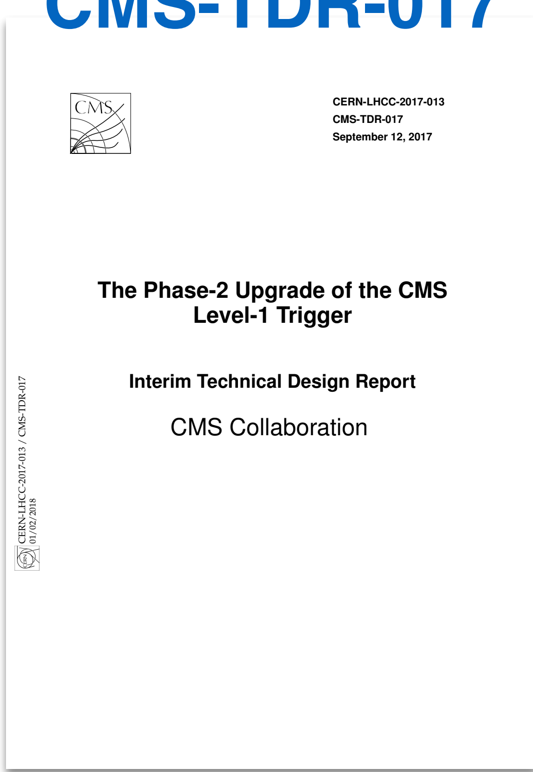
CERN-LHCC-2017-014
CMS-TDR-018
12 September 2017

The Phase-2 Upgrade of the CMS DAQ

Interim Technical Design Report

CMS Collaboration

CMS-TDR-017



CERN-LHCC-2017-013
CMS-TDR-017
September 12, 2017

The Phase-2 Upgrade of the CMS Level-1 Trigger

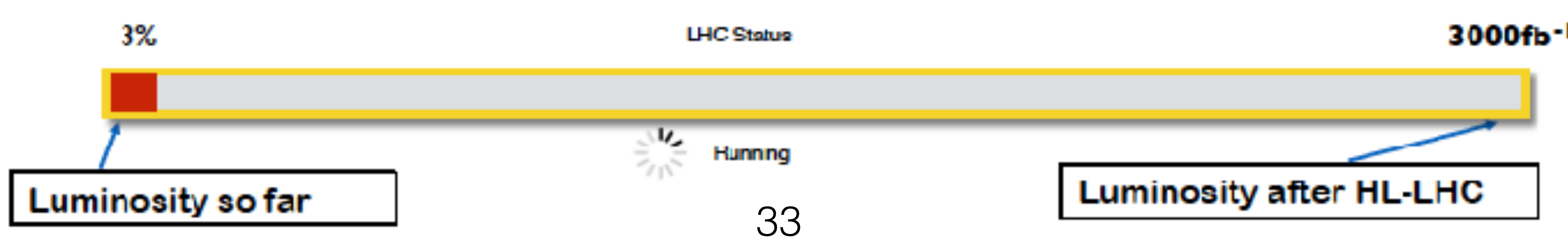
Interim Technical Design Report

CMS Collaboration

- Improvements in the readout electronics and data acquisition system will allow for increases in trigger readout rates
  - Level-1 trigger (hardware-based) can increase from 100 kHz to 750 kHz
  - High-level trigger (software-based) rate can increase from 1 kHz to 7.5 kHz
- Improvements to hardware allow more advance triggering algorithms
  - Tracker information included in level-1 trigger for first time
  - New correlation trigger, combining information from multiple subsystems at level-1
  - Particle flow algorithms can be implemented as part of level-1 trigger

Summary

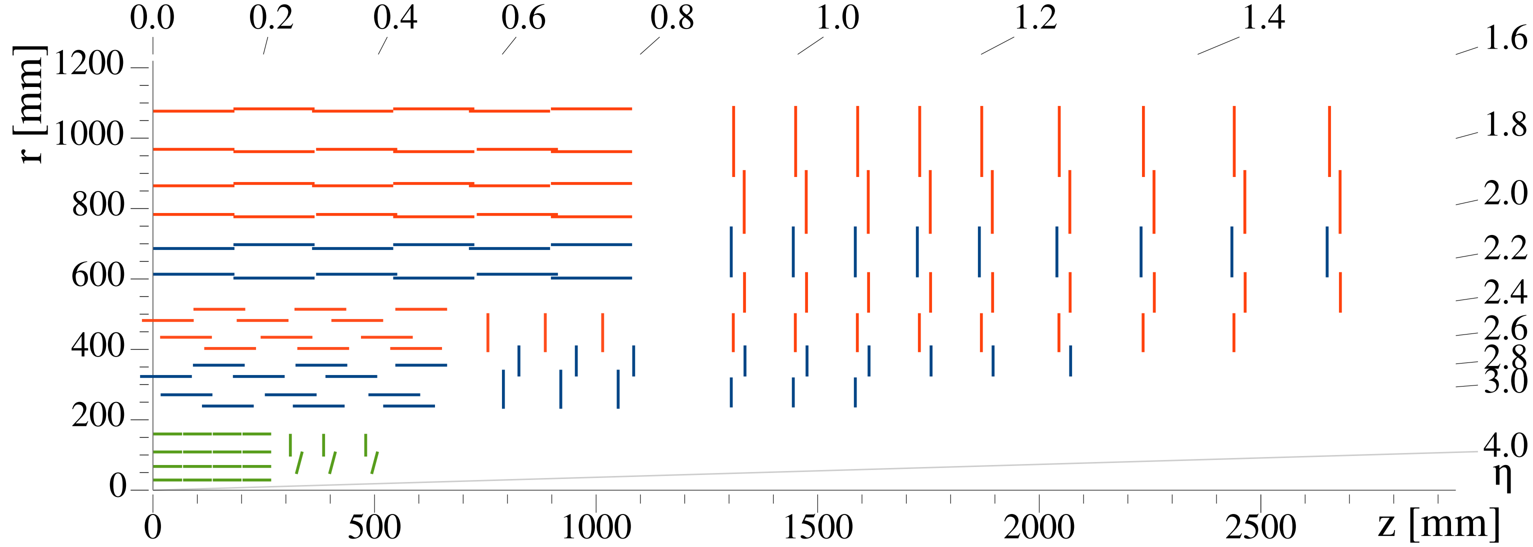
- Phase-1 upgrades represent a significant improvement to the original detector
  - New pixel detector improves tracking efficiency at current pileup conditions
  - Upgrades to HCAL FE/BE electronics mitigate radiation damage
- HL-LHC will provide substantial improvement in LHC performance
  - Increase in instantaneous luminosity by a factor of 5 to 5-7.5x10^{34} $cm^{-2}s^{-1}$
  - Phase-1 detector would not be able to cope with the increased radiation and instantaneous luminosity
- Upgrades of the CMS detector will improve overall performance of CMS
  - Phase-2 upgrades will allow CMS to fully exploit the improvements to the LHC



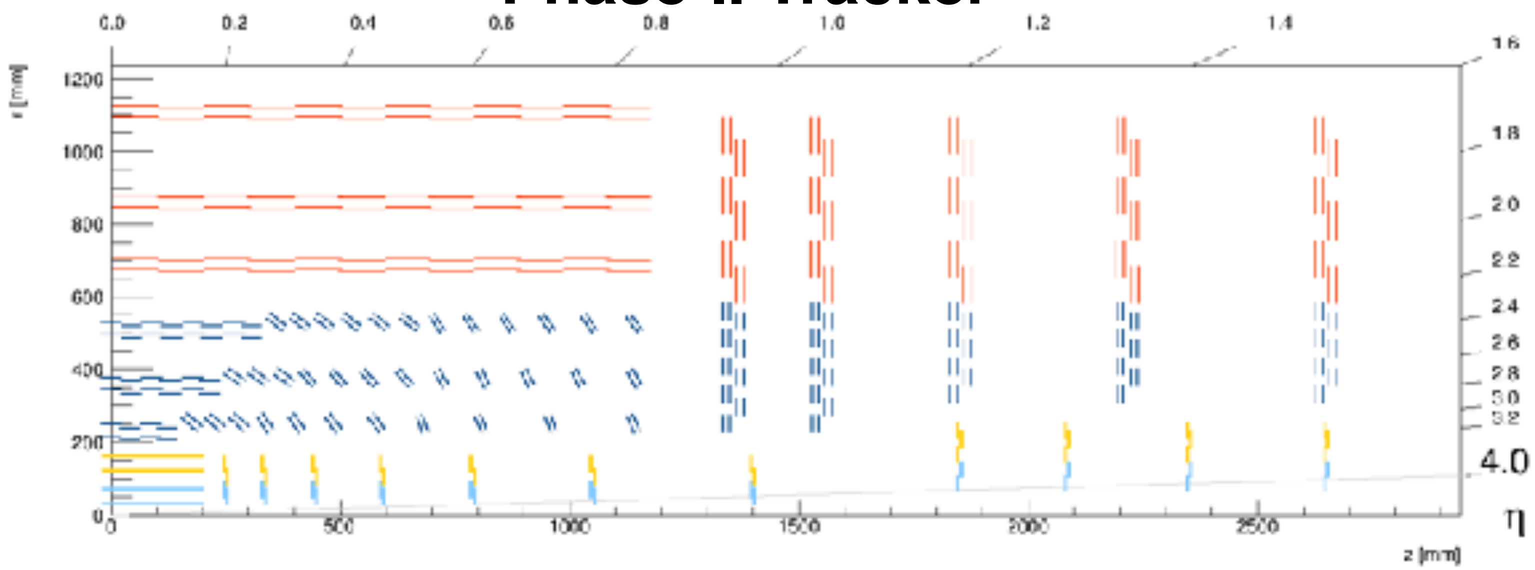
Bonus Slides

Tracker Phase-II

Phase-I Tracker



Phase-II Tracker



Pixel ROC

Table 4.4: Pixel readout chip specifications.

Technology	65 nm CMOS
Chip size	22 mm × (16.4 mm + 2 mm)
Pixel size	$50 \times 50\,\mu m^2$, $25 \times 100\,\mu m^2$
Number of pixels	144 320
Detector capacitance	< 100 fF (200 fF for edge pixels)
Detector leakage current	< 10 nA (20 nA for edge pixels)
Detection threshold	< 600 e-
In-time threshold	< 1200 e-
Hit rate	$< 3\,GHz/cm^2$
Noise hit occupancy	$< 10^{-6}$
Charge resolution	4 bit ToT (Time over Threshold)
Pixel region organization	2 × 2 pixels (alternatively 4 × 1 or 4 × 4)
Hit buffer depth (2 × 2 region)	≥ 8 (for 12.5 μs latency)
Hit loss (dead-time + buffer loss)	$< 1\%$ at $3\,GHz/cm^2$
Trigger rate	≤ 1 MHz
Readout data rate	1–4 links at 1.28 Gb/s = max. 5.12 Gb/s
Radiation tolerance	500 Mrad, $1 \times 10^{16}\ n_{eq}/cm^2$ at −15 °C
SEU affecting whole chip	< 0.05/hr/chip at $1.5\,GHz/cm^2$ particle flux
Power consumption at max. hit/trigger rate	$< 1\,W/cm^2$ including SLDO losses
Temperature range	−40 °C to +40 °C

HGCAL

- Silicon/tungsten+lead electromagnetic calorimeter (CE-E), 28 layers
  - Total $26X_0$ thickness
- Stainless-steel absorber for hadron calorimeter (CE-H), 24 layers
  - 8 layers with silicon-only readout and $\Delta\lambda$=0.25 longitudinal segmentation
  - 4 layers with mixed silicon and scintillator readout and $\Delta\lambda$=0.25
  - 12 layers with mixed silicon/ scintillator and $\Delta\lambda$=0.45
- CO2 cooling to -30° C