CMS Upgrade Program

P5 Workshop on the Future of High Energy Physics

Dec 15, 2013 Brookhaven National Laboratory

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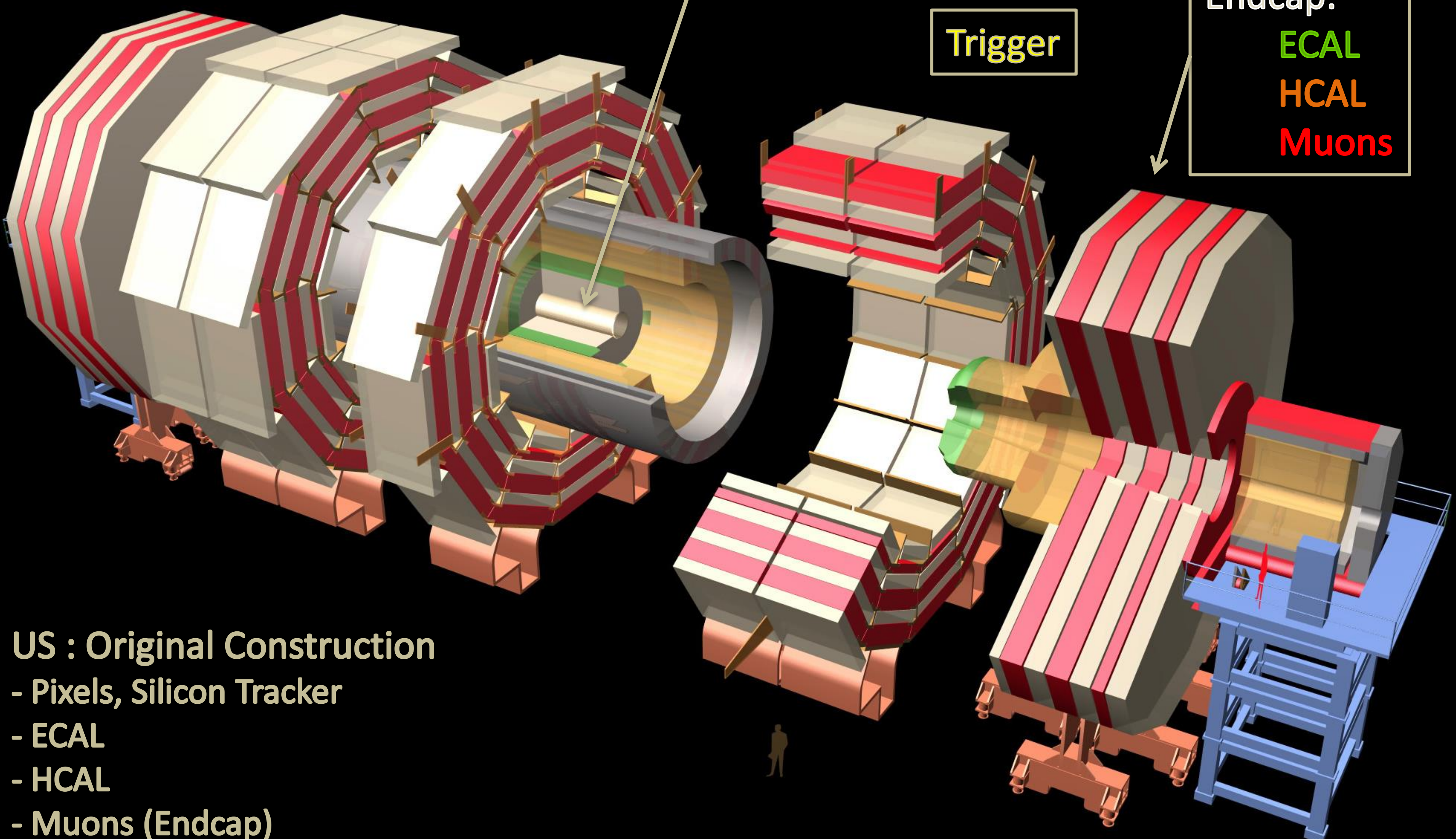
Outline

- Introduction
  - CMS upgrade program
- CMS Phase 1 Upgrade
  - LS1 work, L1-Trigger, Pixel and HCAL upgrades
- CMS Phase 2 Upgrade
  - Driving considerations: Phase 1 detector longevity
  - The Phase 2 scope
  - Cost exercise and manpower estimate
- Concluding remarks

CMS

Phase 2:



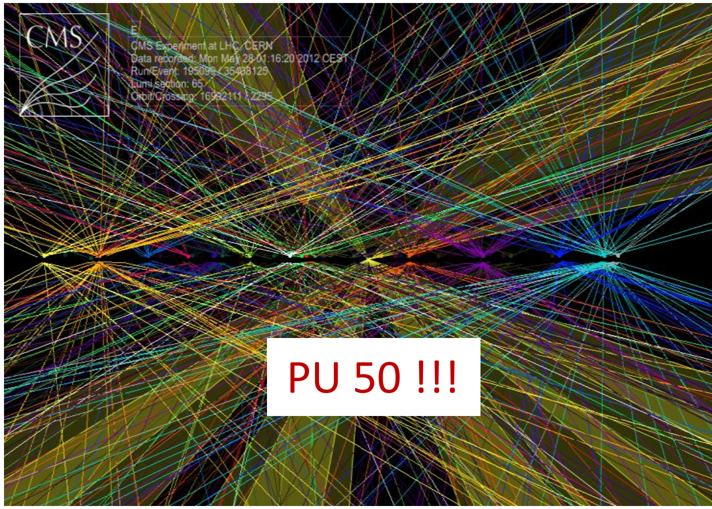
US : Original Construction
- Pixels, Silicon Tracker
- ECAL
- HCAL
- Muons (Endcap)
- L1-Trigger
- Software Framework

LHC to HL-LHC - The Challenge

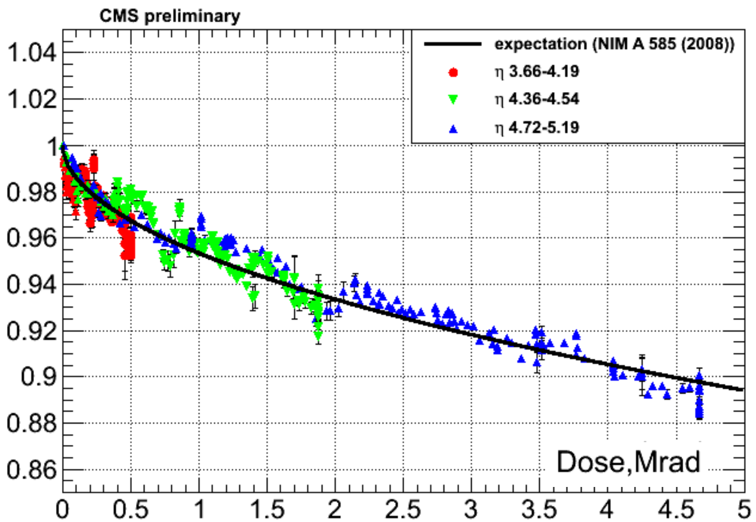
- Maintain sensitivity for discovery and precision measurements at low p_T, under severe conditions

- Driving considerations for the upgrade program
- Pileup
  - <PU> ≈ 50 events per crossing by LS2, >60 by LS3
  - <PU> ≈ 140 at HL-LHC, with lumi-leveling at $5x10^{34}cm^{-2}s^{-1}$
- Radiation damage
  - Light loss (calorimeters), increased leakage current (silicon detectors)
  - Requires a lot of work to maintain calibration
  - And eventually limits the performance-lifetime of the detectors

This event was on the tail of the distribution in 2012, it will be a very typical event by LS2



Observed signal loss in HF quartz fibers, 2011+2012 Laser data vs Radiation dose



CMS Upgrade program

Long Shutdowns

LS1
2013-14

LS2
2019

LS3
2023-25

LS1 : Prep CMS for ~13 TeV, >1 x 10^{34} Hz/cm^2 , <PU> >25, 25ns bunch spacing

- 4^{th} Endcap Muon station, improve readout of CSC ME1/1 & DTs
- Replace HCAL HF and HO photo-detectors
- Tracker operation at -20∘C
- Prepare for further Phase 1 upgrades

Phase 1 upgrades: Prepare for 1.6 x 10^{34} Hz/cm^2 , <PU> ~40, ≤200 fb^{-1} by LS2, and up to 2.5 x 10^{34} Hz/cm^2, <PU> ~ 60, <500 fb^{-1} by LS3

- New L1-trigger system (Calorimeter - Muons - Global) (ready for physics 2016)
- New Pixel detector (installation in technical stop, start of 2017)
- HCAL upgrade: photodetectors and electronics

Phase 2 upgrades: ≳ 5 x 10^{34} Hz/cm^2 luminosity leveled, <PU> ≳ 140 Reach total of 3000 fb^{-1} in ~10 yrs operation

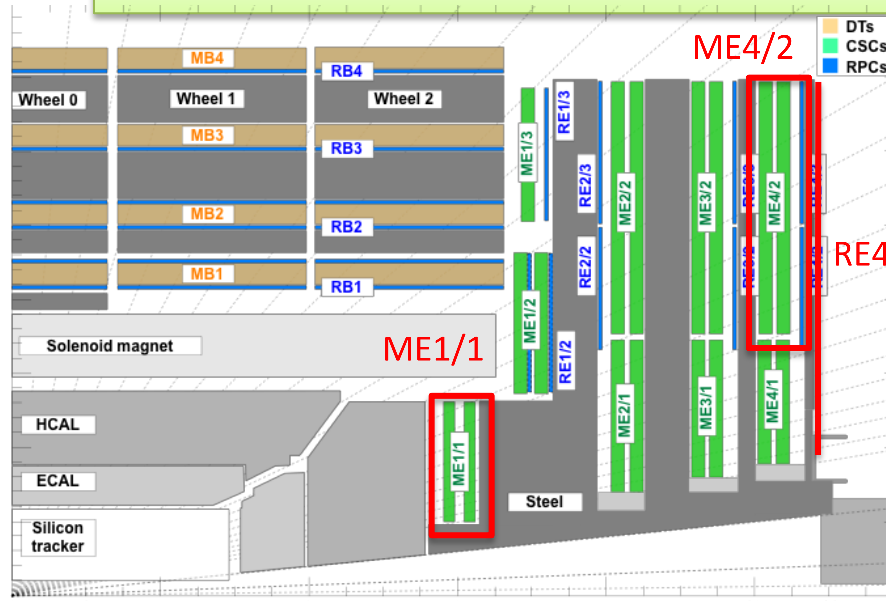
- Replace detector systems whose performance is significantly degrading due to radiation damage
  - Tracker (pixels and strips), Endcap calorimeters
- Maintain physics performance at this very high PU
  - Trigger, electronics, enhanced tracker coverage

LS1 and Phase 1

Long Shutdown LS1 (2013-14)

- Prepare for >$1x10^{34}cm^{-2}s^{-1}$
  - Muon endcap system
    - ME1/1 electronics (unganging)
    - ME4/2 completion of stations & shielding
  - Tracker
    - Prepare for cold operation (-20ºC coolant)
- Address operational issues in Run 1
  - HCAL Forward Calo photo-detectors
    - Reduce beam-related background
  - HCAL Outer Calo photo-detectors
    - operation in return field: replace with Silicon Photo Multipliers (SiPM)
- Preparatory work for later Phase 1 Upgrades
  - New beam pipe (reduced radius) and "pilot blade" installation for the Pixel Upgrade
  - New HF backend electronics - ahead of HCAL frontend upgrade
  - Splitting for L1-Trigger inputs to allow commissioning new trigger in parallel with operating present trigger

Muons: ME1/1 ad ME4/2 during LS1



Slice test: μTCA BE electronics for HF

Long Shutdown LS1 (2013-14)

US leadership and expertise

- Prepare for >1x10 cm s
  - Muon endcap system
    - ME1/1 electronics (unganging) US
    - ME4/2 completion of stations & shielding
  - Tracker
    - Prepare for cold operation (-20°C coolant)
- Address operational issues in Run 1
  - HCAL Forward Calo photo-detectors US
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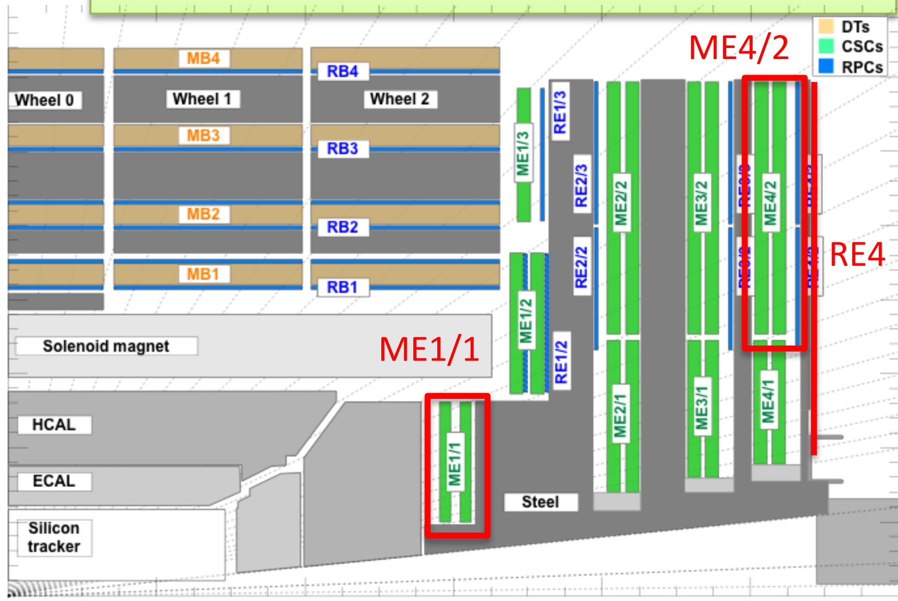


Slide test: μTCA BE electronics for HF

L1 Trigger

TDR: http://cds.cern.ch/record/1556311/files/CMS-TDR-012.pdf

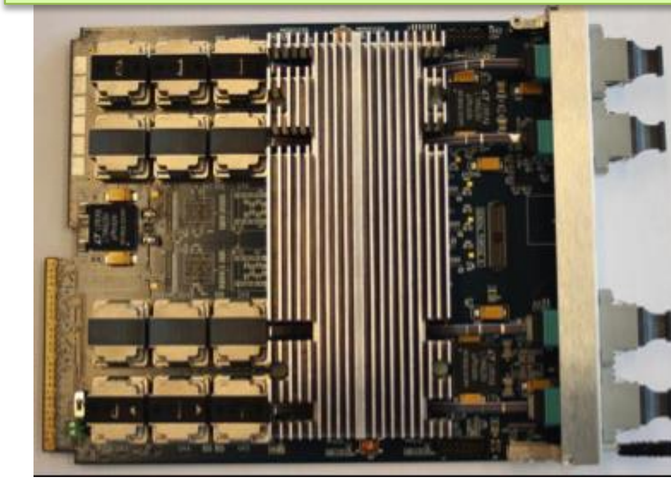
- Architecture based on powerful FPGAs and high bandwidth optical links
- Upgrade entire L1 Trigger: Calorimeter, Muon and Global
- **Based on only 3 types of board – all using Virtex 7 FPGA** 2 of them developed in US
- Trigger inputs split during LS1 to allow full commissioning of new trigger in parallel to operating legacy system
- Staged approach: grow from slice tests to full system commissioning during 2015 → ready for physics in 2016

➢ New trigger allows much improved algorithms for PU mitigation and isolation

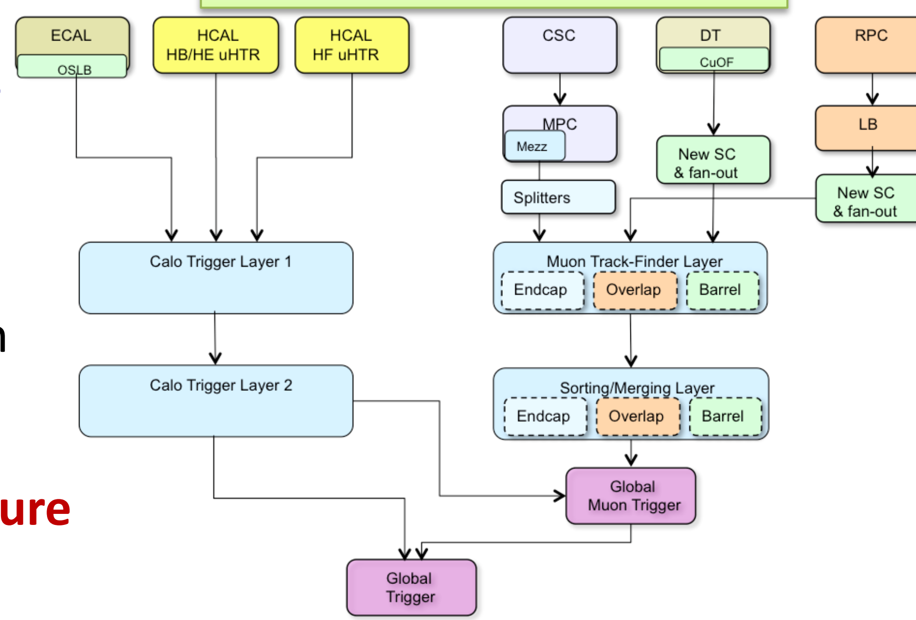
US: algorithms and software

Phase 2 upgrade will build on this architecture

Processor Board
(Virtex 7, 72TX + 72RX links @ 10Gb/s)



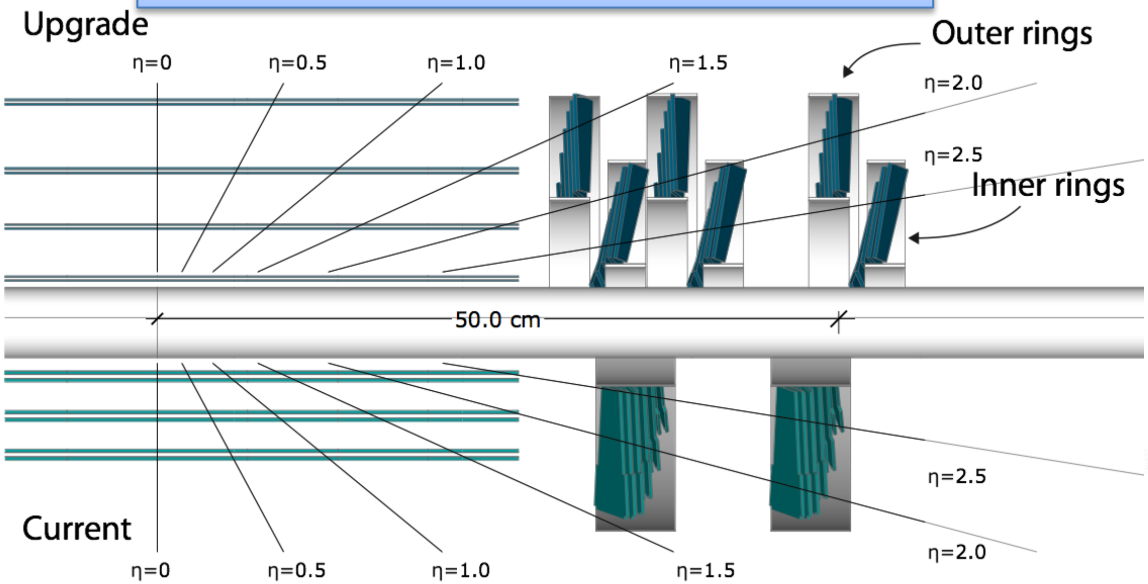
Level 1 Trigger Upgrade

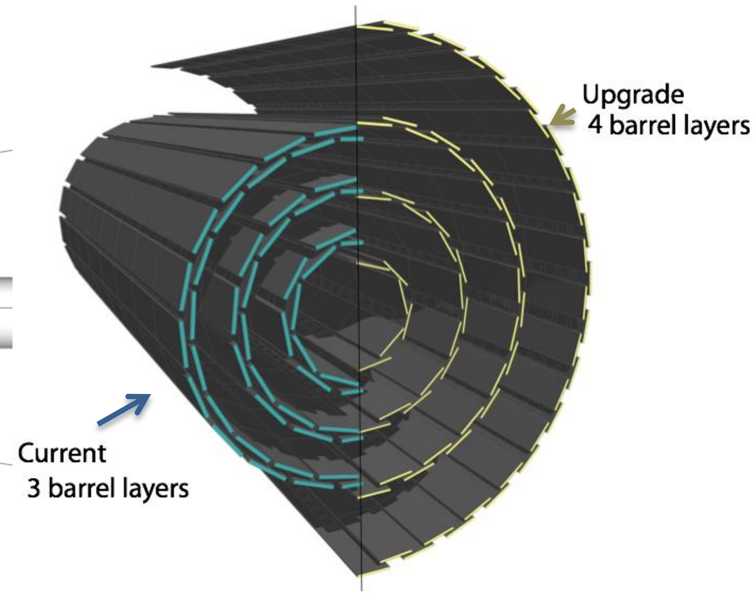


Pixel Detector

TDR http://cds.cern.ch/record/1481838/files/CMS-TDR-011.pdf

US: primary responsibility for the disks





- 4 layers / 3 disks
  - Improved track resolution and efficiency
- New readout chip
  - Recovers inefficiency at high rate and PU
- Less material
  - CO2 cooling, new power scheme (DC-DC)
- Longevity
  - Tolerate 100 PU and survive to 500 fb^{-1}, with exchange of innermost layer

Ready to install at end of 2016

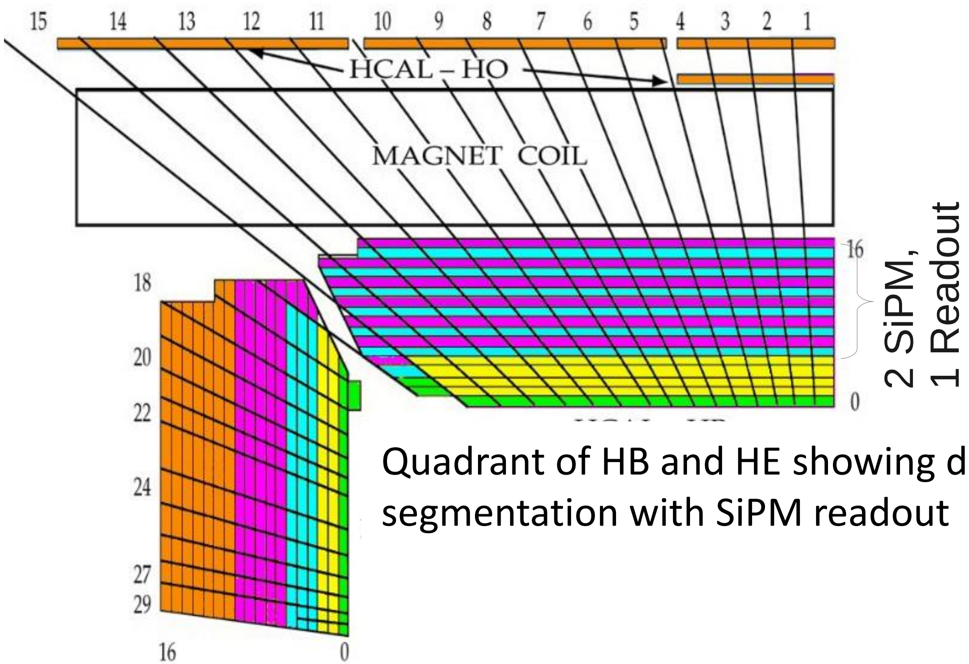
- Higher rate capability – limited performance degradation up to PU ~70
- Improved track reconstruction - and resolution
- Better association of tracks at primary vertex (IP) and improved b-tagging

HCAL

US: extensively involved / lead role

TDR http://cds.cern.ch/record/1481837/files/CMS-TDR-010.pdf

- Replace Hybrid Photodetectors with Silicon Photomultipliers
  - Improved photo detection efficiency and lower noise
  - Allows depth segmentation: improves hadronic clusters, background rejection, re-weighting for rad damage



Quadrant of HB and HE showing depth segmentation with SiPM readout

SiPMs

successful R&D program

- Tested to 3000 fb-1
- Neutron sensitivity low

QIE10 (readout chip)

- Preproduction chip performs extremely well for both charge measurement and time measurement

Electronics

- In production for HF (first)

- Electronics upgrade to μTCA to support higher bandwidth
- New readout chip (QIE10), optimized for SiPM, and including a TDC
  - Timing: improved rejection of beam-related backgrounds

Phase 2

Driving Considerations for the Phase 2 Upgrade

- HL-LHC presents an extensive and rich physics program

- Experiment must maintain sensitivity for discovery and precision measurements at low p_T, under severe conditions
- By LS3: integrated luminosity will exceed 350 fb^{-1} (prepare for 500 fb^{-1})
- Post LS3: ~10 times more data, at 200-250 fb^{-1} per year

- Driving considerations for Phase 2
  - Performance longevity of the Phase 1 detector
  - Physics requirements for the HL-LHC program at HL-LHC beam conditions
  - Development of cost effective technical solutions and designs
  - Logistics and scope of work during LS3

Longevity of the Phase 1 Detector

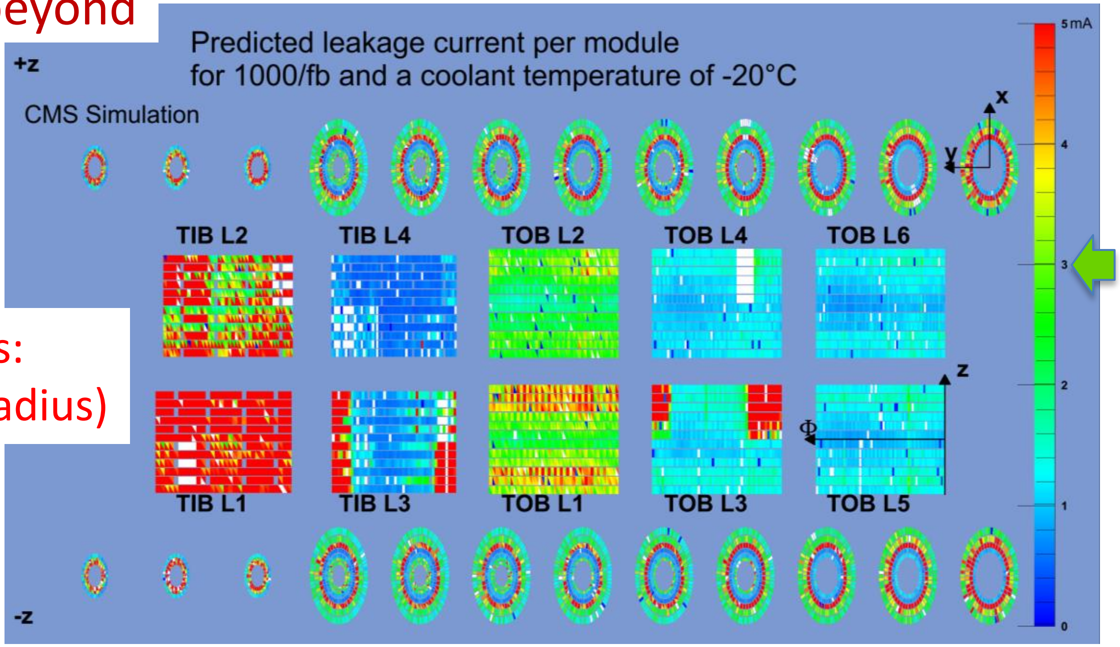
- Extensive studies of radiation damage for the present detector
  - Detailed analysis of aging experienced in 2012 & dedicated radiation exposures
  - Damage models developed and benchmarked to data
  - Incorporated into the full simulation of the detector for physics studies

Tracker

- Limitation is leakage current. Cold operation is essential.
- ➢ Tracker will survive to 500 fb^{-1} if operated at -20∘C, but will lose a significant fraction of modules beyond

Module leakage current map for 1000 fb^{-1} (red is 5mA)

Barrel Layers:
(inner to outer radius)



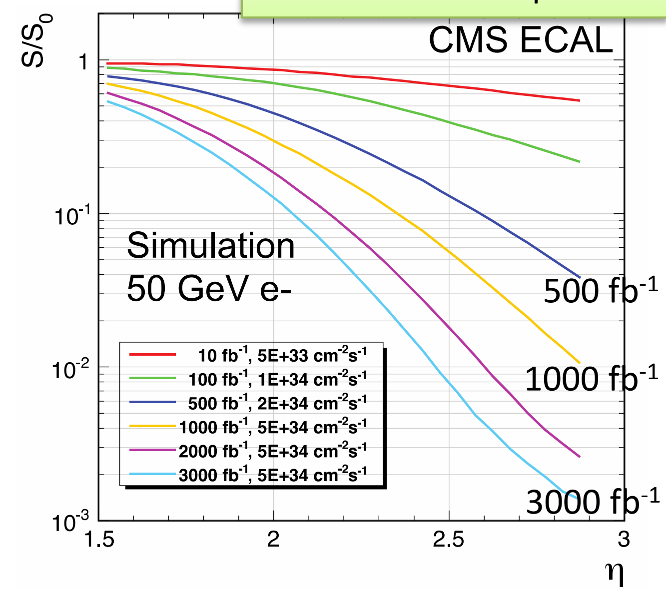
Operational limit ~ 3mA

Risk thermal runaway

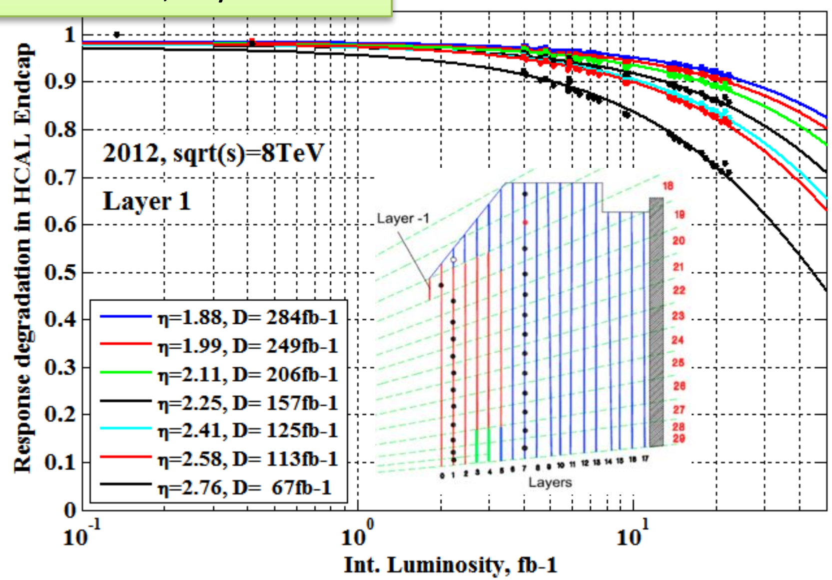
Longevity of the Phase 1 Detector

- **ECAL:** Must replace Endcap calorimeter
  - Barrel survives to 3000 fb^{-1}, but light transmission in the in Endcap drops to few % at high η, resulting in significant loss of resolution
  - Have extensively investigated ideas for enhanced annealing and/or partial replacement. No solution
- **HCAL:** Must replace/rebuild Endcap calorimeter
  - Barrel survives to 3000 fb^{-1} (just). Endcap light yield drops to few % over large part of calorimeter by LS3

Relative light yield in ECAL Endcap

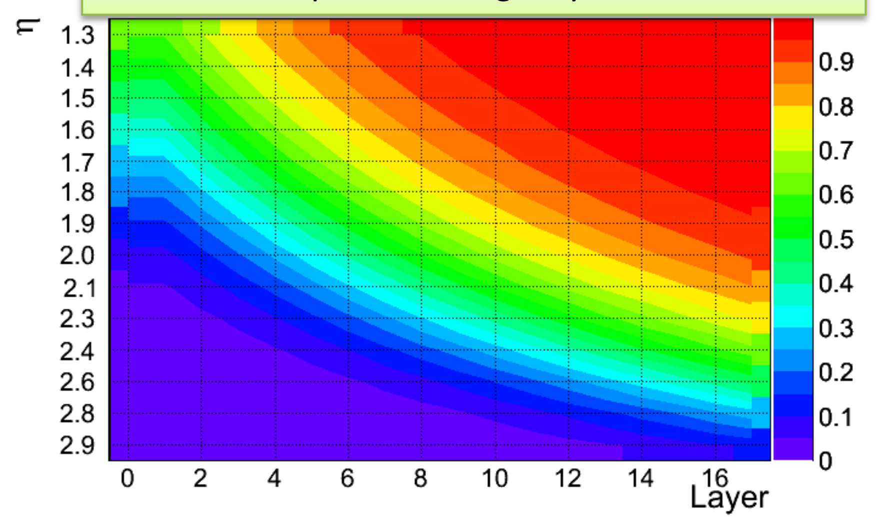


Response degradation in HE, 2012 Laser data, Layer1



(Phase 1: improved S/N and depth segmentation, and can replace worst tiles in LS2 if needed to reach LS3)

HCAL Endcap: relative signal yield for 500 fb^{-1}



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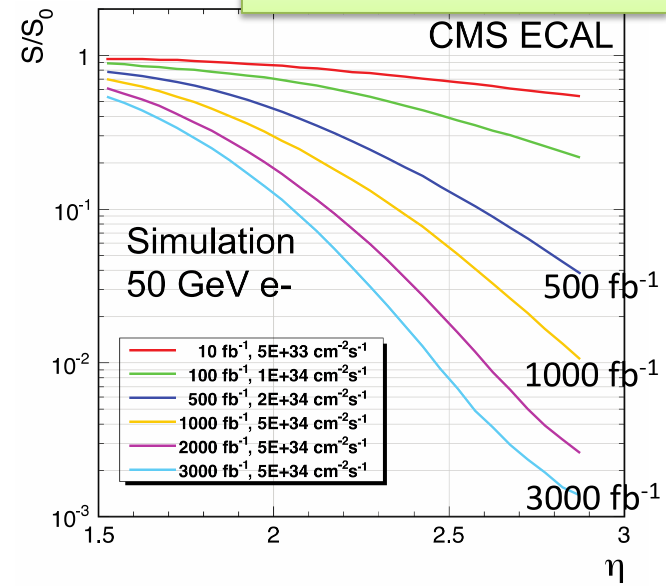

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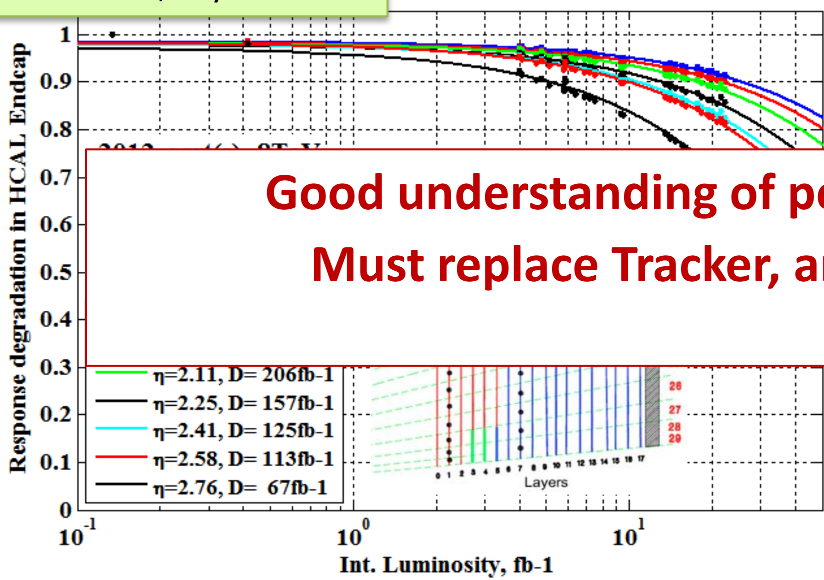

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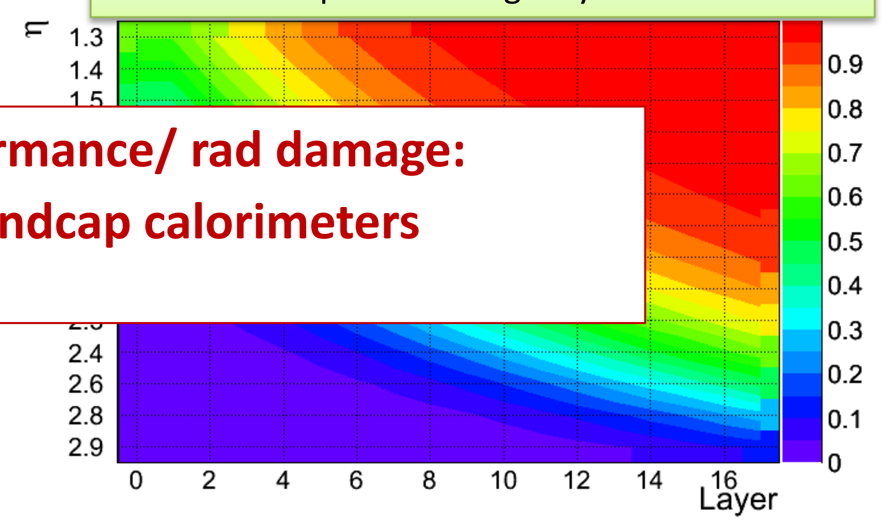


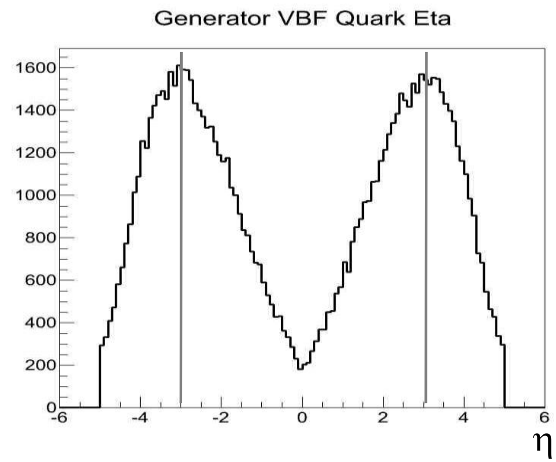
Good understanding of performance/ rad damage:

Must replace Tracker, and Endcap calorimeters

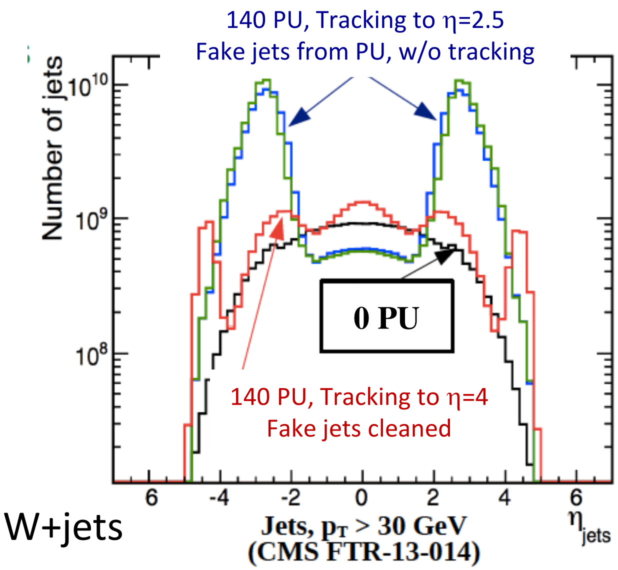
Performance Considerations

- Mitigation of high PU relies on particle flow reconstruction & excellent tracking
  - Propose to extend the tracker coverage to higher η where VBF jets peak, and where PU effects are very significant

VBF jets peak at η~3



W+jets



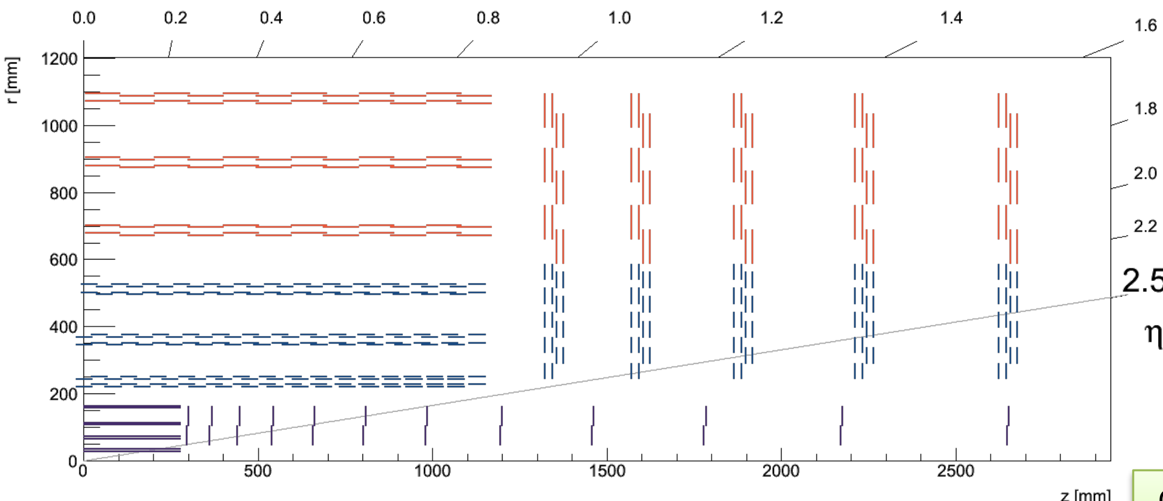
- Trigger rates will be a major issue. Thresholds for Higgs are well understood. Increasing thresholds will lose physics acceptance
  - Increase latency to 10μs to allow integrating tracking into all L1 trigger objects
    - improves lepton id, isolation, & PU mitigation through vertex association
  - Increase bandwidth to further improve acceptance for all objects

Phase 2 Tracker

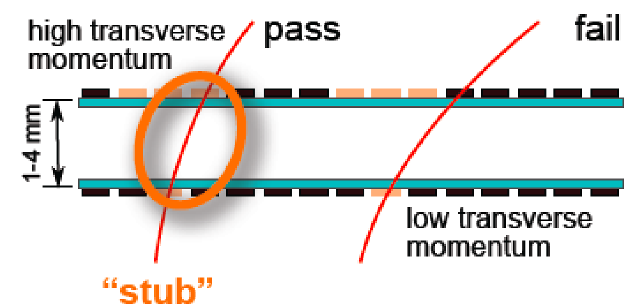
US: extensive engagement and expertise in Tracker and Track Trigger

○ Outer tracker

- High granularity: efficient track reconstruction to beyond 140 PU
- Two sensor "Pt-modules" to provide trigger information at 40 MHz for tracks with Pt≥2GeV
- Improved material budget



Trigger track selection in FE



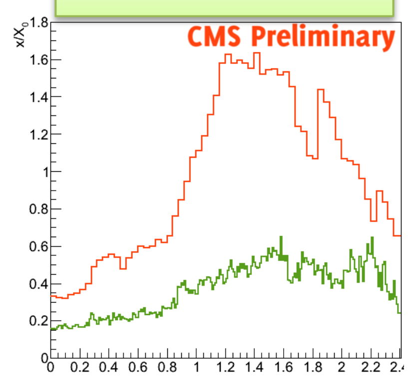
○ Pixel detector

- Similar config as Phase 1, with disks to high η
- Thin sensors 100 µm; smaller pixels 30 x 100 µm

○ R&D activities

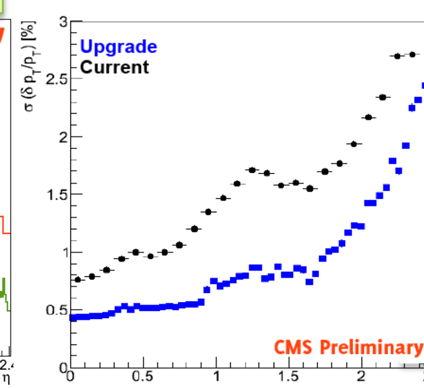
- In progress for all components - prototyping of modules ongoing
- Track-trigger with Associative Memories

Outer tracker material
Phase 1 & Phase 2



P_T resolution

Single µ p_T=10 GeV/c
Transverse momentum resolution

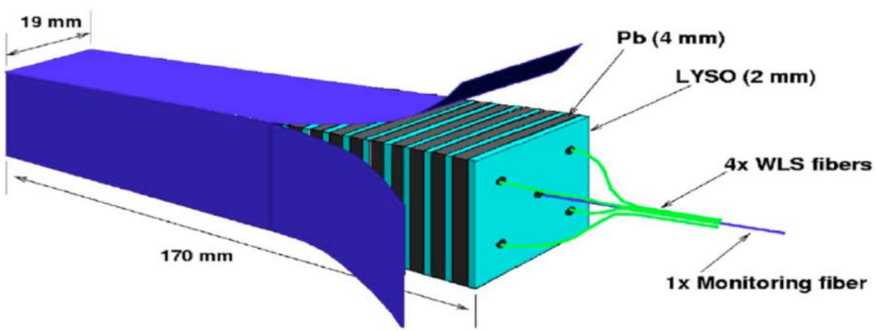


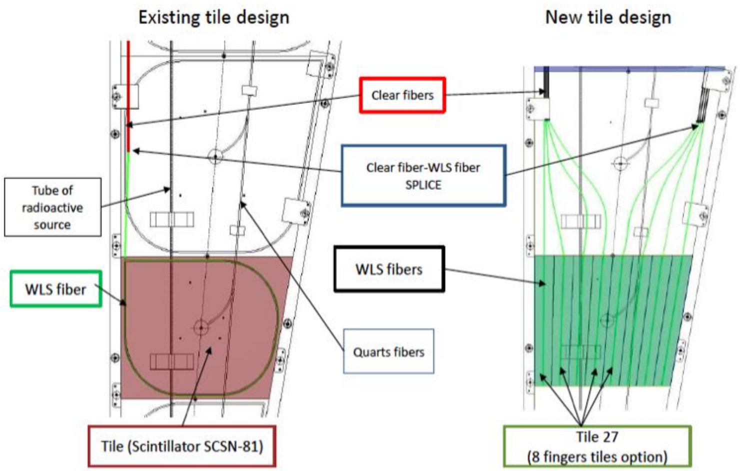
Endcap Calorimeters

US: extensive expertise in EM and HAD calorimeters, and engagement in RD52 and CALICE

Two approaches

1) Maintain standard tower geometry - develop rad tolerant solutions for 3000 fb^{-1}
- Build EM towers in Shashlik design (crystal scintillator: LYSO, CeF_3)
- Rebuild HAD with more fibers, rad-hard scintillators





R&D well underway

2) Alternative geometry/concepts

Potential for improved performance at high pileup
- Dual fiber read-out: scintillation & Cerenkov – following work of DREAM/RD52
- Particle Flow Calorimeter (high granularity) – following work of CALICE

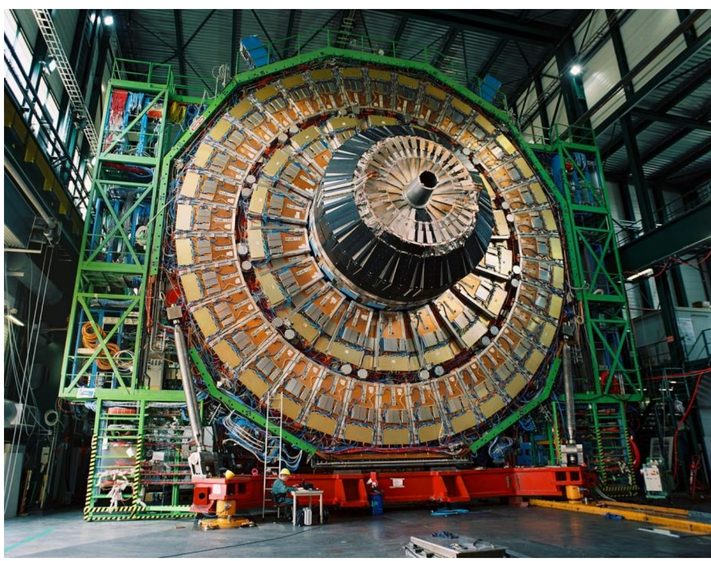
Capitalize on extensive work so far. Simulation & R&D for HL-LHC environment underway

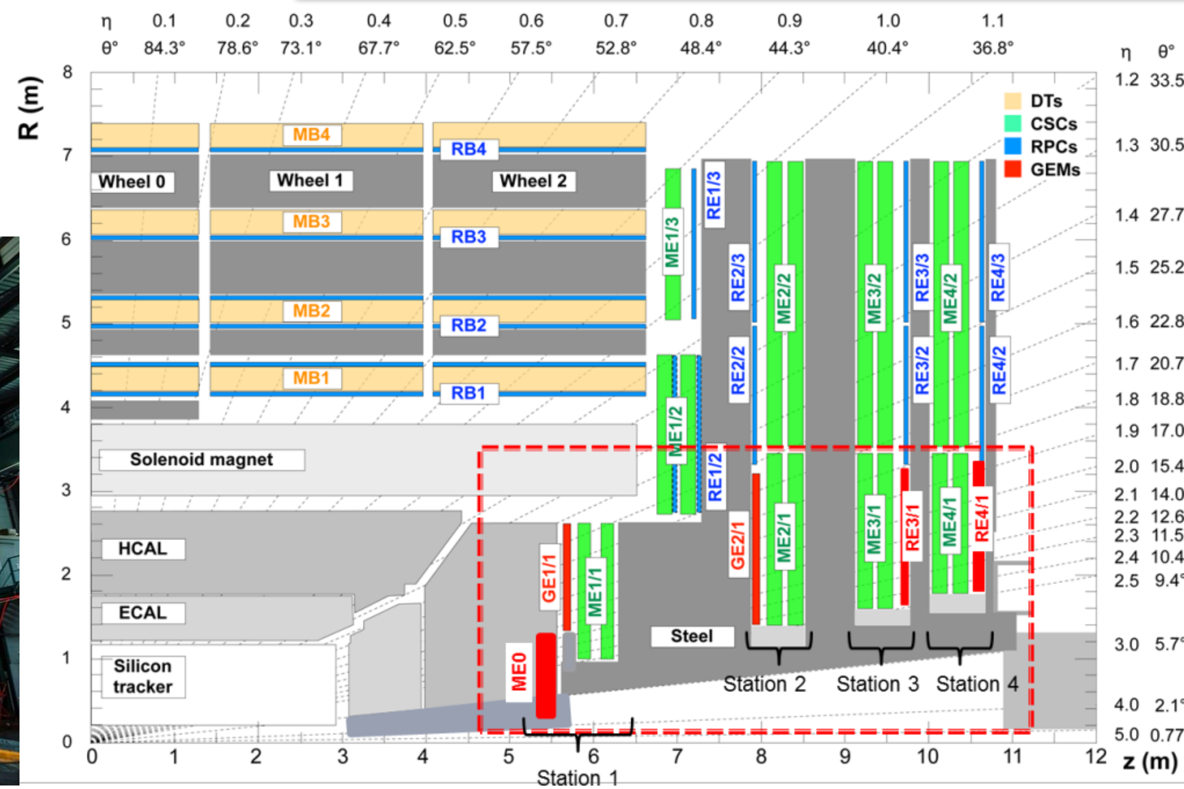
Forward muon system

- Present chambers survive through HL-LHC
- Emphasis on trigger performance and redundancy in the high rate, high PU region
  - Under study: add chambers in the region $1.6 < |\eta| < 2.4$
    - GEM / Glass-RPC
  - Investigating muon tagging beyond $|\eta| = 2.4$

US: responsibility for existing chambers in this region. Simulation and trigger expertise

- R&D activities well underway in CMS for GEM and Glass-RPCs

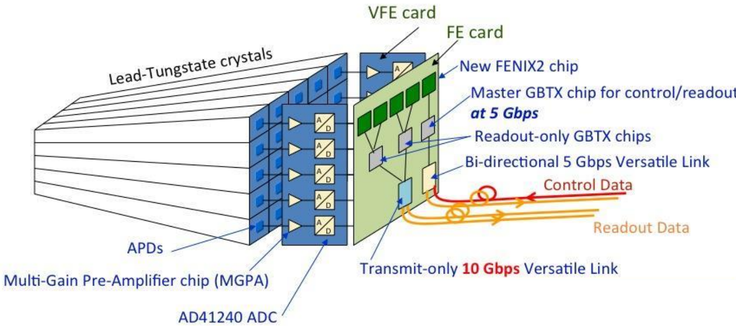




Trigger and DAQ

US: extensive expertise in calorimeter and muon triggers (Phase 1: boards and algo's) and in Track Trigger Processor

- The L1-trigger will build on the Phase 1 architecture, with
  - track information (from outer tracker) integrated into all trigger objects
  - increased granularity
  - ability to operate up to 1 MHz
    - Match leptons with high resolution tracks
    - Improved isolation of e, γ, μ, τ candidates
    - Vertex association to reduce effect of pileup in multiple object triggers
- Replacement ECAL Barrel Electronics
  - Allows crystal granularity at L1, and 10 μs latency
  - Provides improved APD noise rejection at L1



- High Level Trigger farm and DAQ
  - Prepare for up to 1 MHz into HLT and 10 kHz out
  - Technology improvements on the timescale of LS3 should enable this at reasonable cost

Phase 2 Project

- Breakdown of costs
  - Replacement of radiation damaged detectors (Tracker, Endcap Calo) ~70%
  - Retaining performance at very high pileup (Trigger, Electronics, Muons) ~15%
  - Extending coverage (Extended Pixels, Muons) <8%
  - Common fund (common infrastructure and installation) ~7%

- As we did for Phase 1, CMS is preparing a Technical Proposal motivating and describing the full Phase 2 upgrade program (2014)
- This will be followed by TDRs for each upgrade project (2016-17)

- R&D for Phase 2 is ongoing, with design and technology decisions by 2016-17
  - Tracking: design development
    - rad-tolerance sensors, ASICs, packaging, trigger processing
  - Calorimetry: R&D on calorimeter materials/technology
    - active materials, WLS fibers, photo-detectors
  - Simulation studies
- US spending approval needed by 2017 (see cost profile later)

Phase 2 Cost Exercise

Phase 2 Cost Exercise

CMS presented a document on the Phase 2 scope and cost exercise to the CERN Resource Review Board in October (document ref. CERN-RRB-2013-124)

The document reports CORE costs (M&S cost in fixed-year CHF)
[CORE is an acronym for "Cost Review" Committee established for original construction projects]

- CORE costs include materials and services for final qualification, production, assembly and installation
- CORE costs do not include labor provided by CMS institutions, and contingency

To this the national projects then include inflation, labor costs and contingency according to their own costing system

R&D is funded in the US by the Operations Program

Phase 2 Cost Exercise for the RRB

- Costs are estimated at the component level, typically relying on similar work for Phase 1 to provide the cost basis augmented by preliminary vendor quotes
- Where designs are less advanced (notably calorimeters), representative assumptions are made for the design, number of channels etc

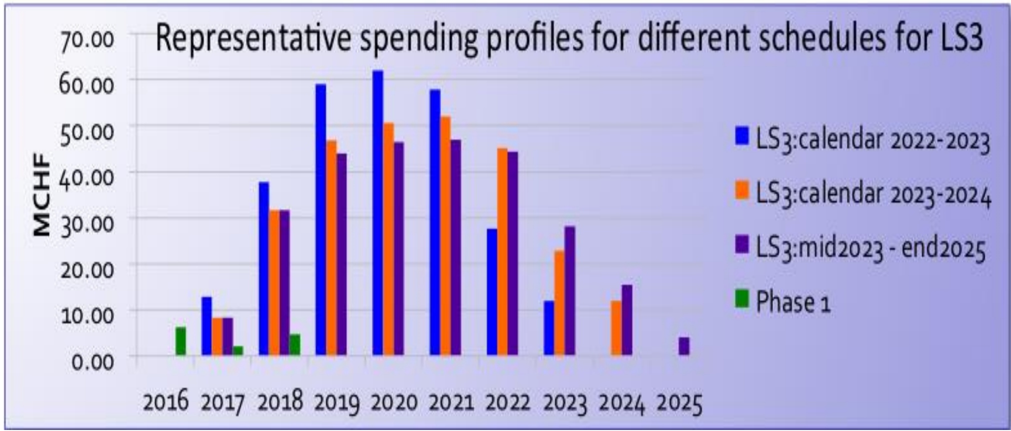
○ Total CORE cost for CMS Phase 2 is approximately 270 MCHF (2013)

- No contingency is included

○ The spending profile was presented to the RRB for three schedule scenarios

- The schedule update from CERN on Dec 2 corresponds closely to the third (purple) scenario. We use this in what follows

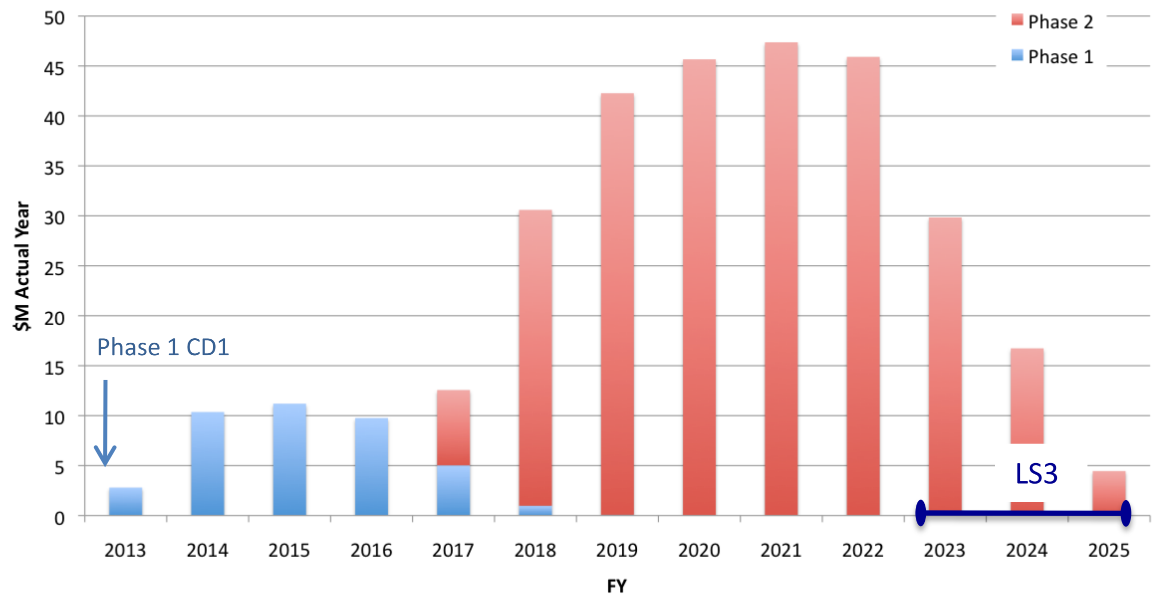
Item	Sub-item	Estimated CORE Cost (MCHF 2013)
	Silicon Tracker	94
	Pixel Detector	34
Tracker		**127**
	Endcap Calorimeter Upgrade: EM & HAD	67
	HF upgrade to 4-channels per PMT	2
Calorimeters		**69**
	DT Electronics	7
	Endcap Muon System Upgrade	12
	High Eta Muon Tagging Station	6
Muon System		**25**
	L1-Trigger	7
	EB Frontend Electronics	11
Trigger System and Front-end Electronics		**18**
	DAQ system: Clock, Readout, Network	5
	HLT	6
DAQ and HLT		**11**
	Shielding Changes for HL-LHC	6
	Tooling, rail systems, cranes for LS3 work	5
	Common Systems and Installation	9
Infrastructure and Common Systems		**19**
Total		**269**



US CMS Phase 2 Cost Exercise

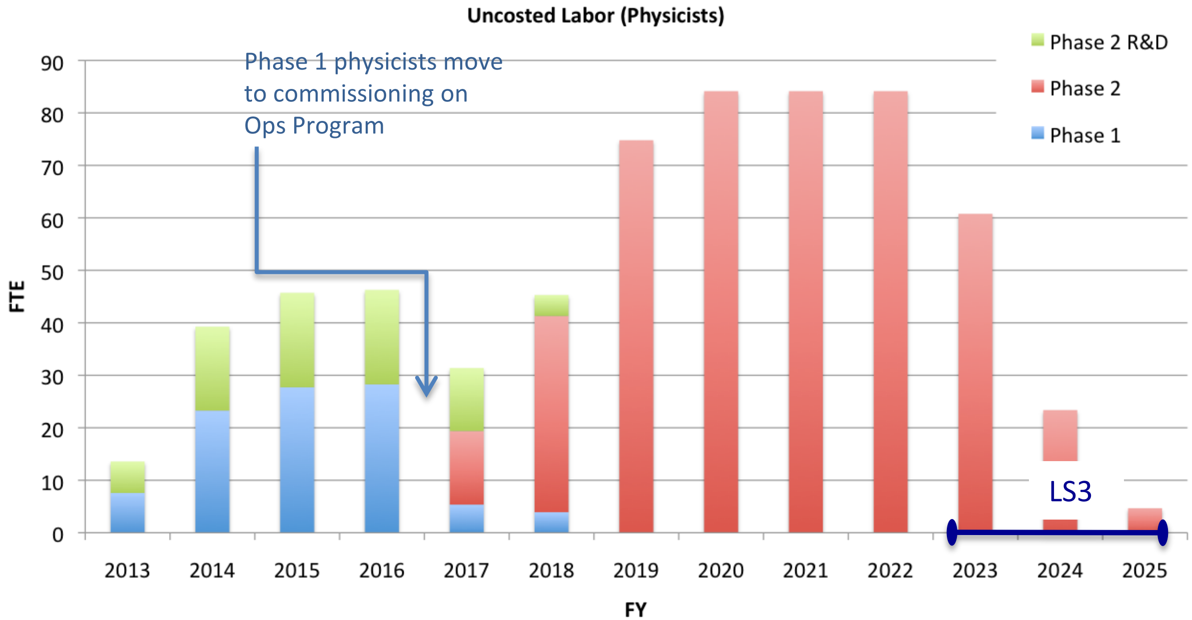
- We are developing the US scope of work for Phase 2 - will be finalized along with the Technical Proposal next year
- Given US expertise, leadership and interest (demonstrated in the LOIs for R&D support) we expect major contributions to parts of the Tracker, Endcap Calorimeters and Trigger, with a contribution to Endcap Muons probably focused on the trigger
- In the interim we use the full resource-loading for the Phase 1 project (Trigger, Pixels & Had Calo) to estimate the resource loading for Phase 2. We consider this to be a good representation for the complexity of work for Phase 2
- In CMS the guidance is for each country to contribute to Phase 1 and Phase 2 according to their fraction of authorship. Currently 28% for US HEP (DOE and NSF). This is consistent with our initial considerations
- We include 50% contingency on M&S and labor costs

Total US cost
(incl. labor, contingency)
$270M (Actual Year)
with the profile shown



Projection for US Physicist Effort

- Physics effort is included in the Phase 1 resource-loading (as no-cost labor). Adding the ongoing effort on Phase 2 R&D, this amounts to about 45 FTE
- We scale the Phase 1 construction effort to Phase 2, resulting in a peak need of 84 FTE



Note that a continuing healthy Ops program is assumed, to complete installation and commissioning

- CMS requires a minimum of 25% FTE "service to the experiment" per author (on operations and upgrades)
- US CMS snapshot 2013: 678 physicists (247 graduate students & ~150 post-docs)
- 84 FTE corresponds to 50% of US service work, and 20% of total student + post-doc effort

The present size of the US collaboration is well matched to the estimated physicist need for Phase 2, operations and physics analysis

Summary on Cost and Resources

- The US CMS cost for Phase 2 is estimated to be ~$270M (Actual Year)
- The size and capability of the US collaboration is well matched to the scale of project we anticipate for Phase 2

Concluding Remarks

- US HEP is 28% of CMS. We have expertise and leadership in major aspects of the experiment. (Building on the experience of the Tevatron program)
- We have expertise in several key areas for the upgrades and a tradition of leadership for building major detector elements
- This is good for US HEP – to maintain strong, technically capable US groups and facilities – and good for US physicists, providing training in detectors along with excellent analysis opportunities
- This US engagement in Phase 2 is critical for the success of CMS