Overview of U.S. CMS HL-LHC Upgrades

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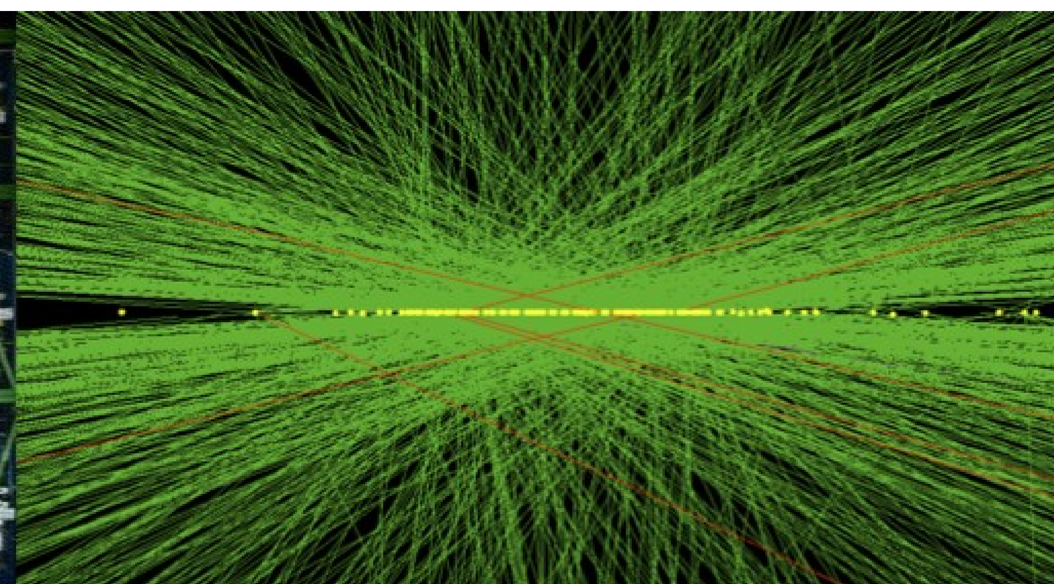
On behalf of U.S. CMS

HEPAP Meeting, Newport Beach CA, Dec. 9-11, 2015



P5 Science Drivers

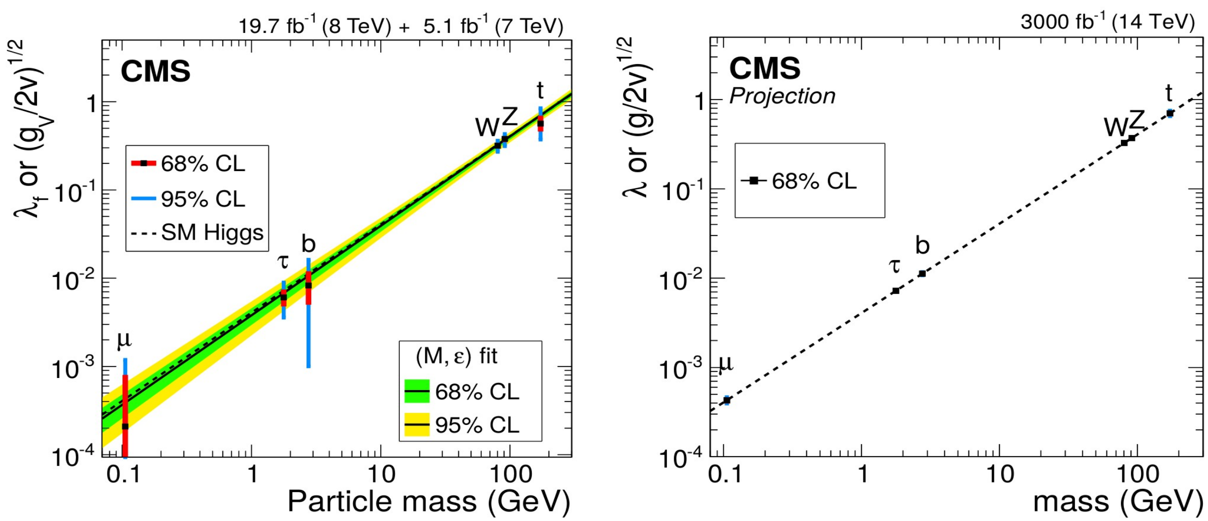
- In May 2014 the P5 Report "Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context" laid out a vision based on five intertwined science drivers and the techniques used to access that science. As taken from the report,

Science Driver	Technique (Frontier) – Large Projects
Use the Higgs boson as a new tool for discovery	**Energy frontier**
Pursue the physics associated with neutrino mass	Intensity and Cosmic frontier
Identify the new physics of dark matter	**Energy frontier**
Understand cosmic acceleration; dark energy and inflation	*
Explore the unknown: new particles, interactions, and physical principles	Intensity, Cosmic and **Energy frontier**

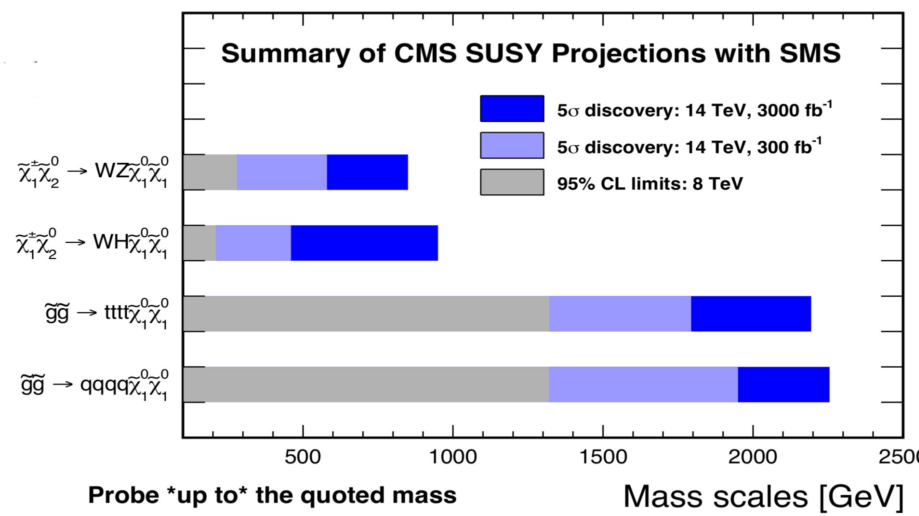
* This appears under medium scale projects

Physics Goals for HL-LHC Operation

- Detailed exploration of the Higgs discovered during Run 1 is one of the main motivations, e.g. precise coupling strengths:



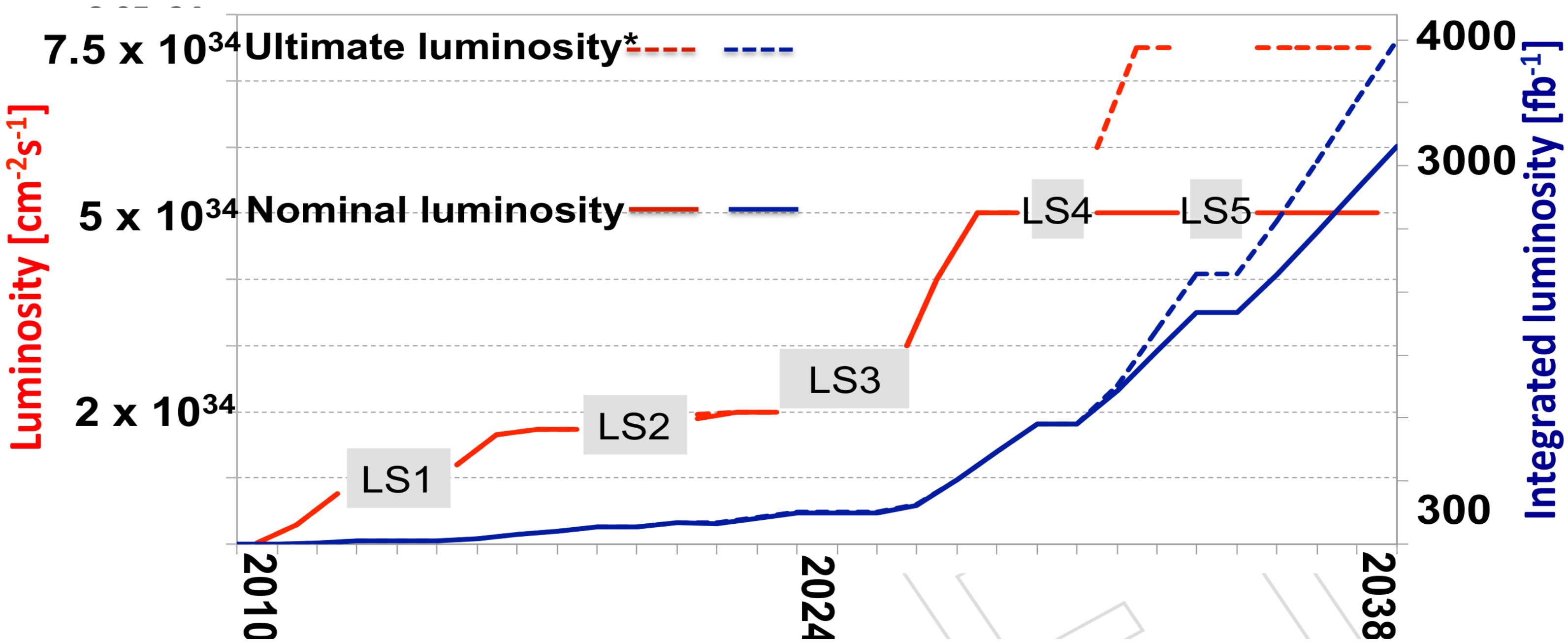
- Search for di-Higgs production
- Tagging of forward jets (VBF)
- Searches for new physics, e.g. SUSY



HL-LHC Luminosity Goals

HL-LHC will operate with 'lumi leveling':

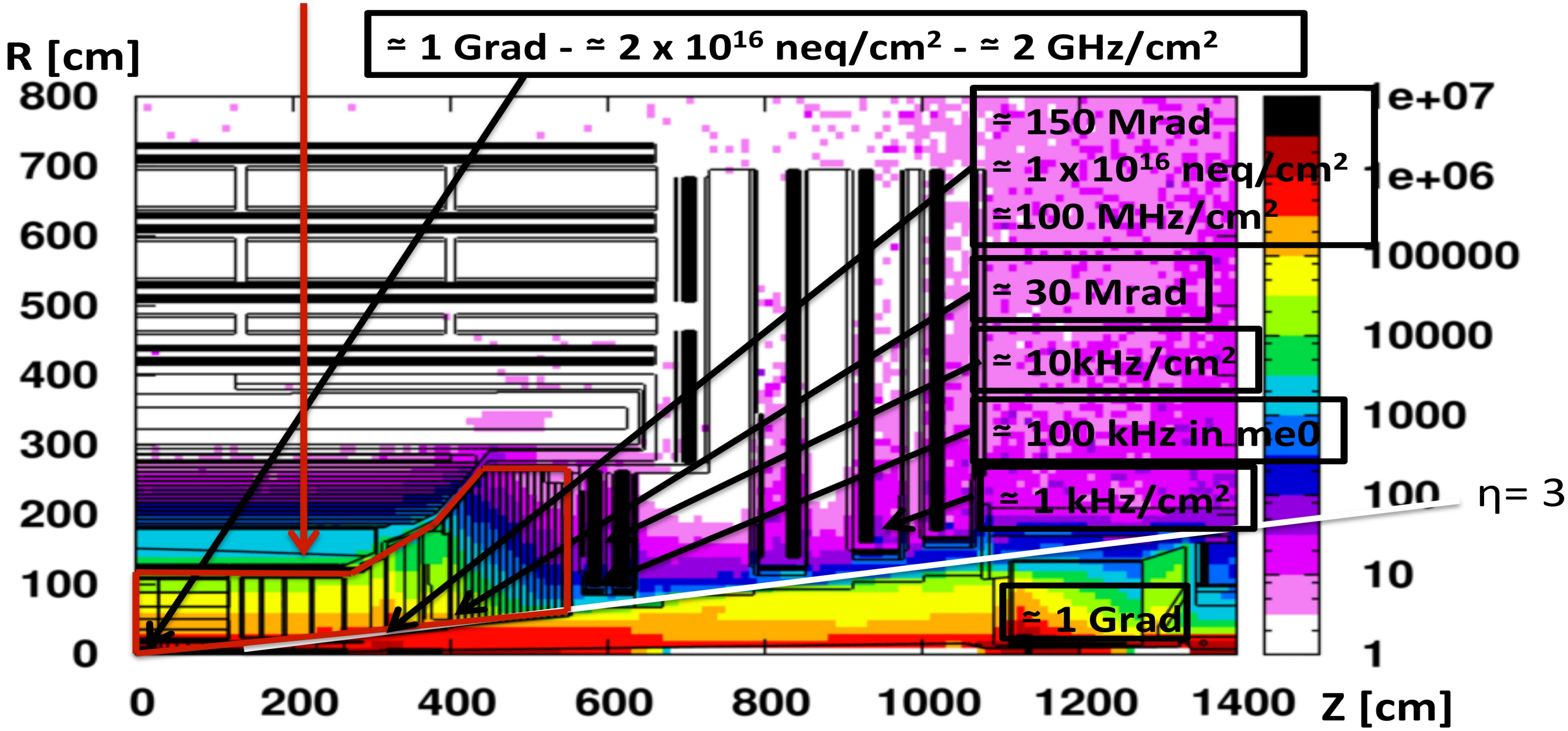
- 'Nominal' HL-LHC luminosity 5×10^{34} Hz/cm^2 - <PU>=140
- 'Ultimate' HL-LHC luminosity 7.5×10^{34} Hz/cm^2 - <PU>=200



- CMS HL-LHC performance targets
  - At <PU>=140 same performance as <PU>=50 for phase-1
  - At <PU>=200 allow moderate degradation

Radiation Dose and Particle Rates

- The large integrated luminosity and the instantaneous rates provides a challenging environment



- Aging studies have shown that the tracker and endcap calorimeters need replacement

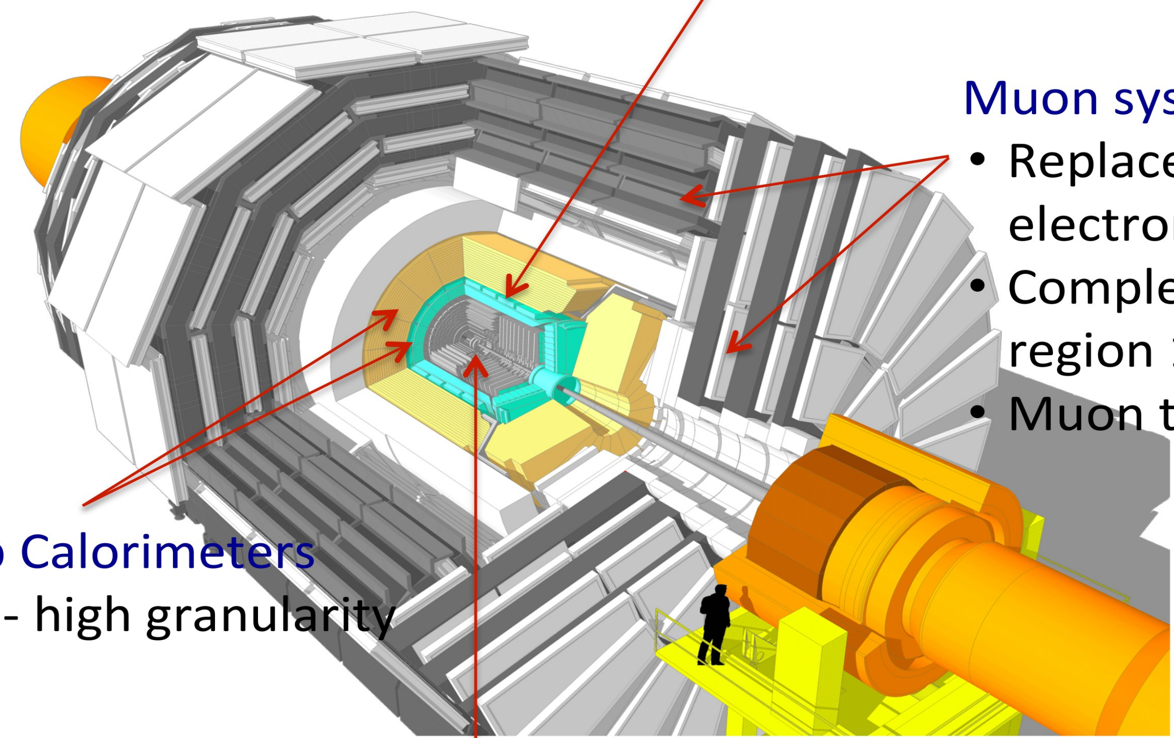
CMS HL-LHC Upgrade Requirements

- Before the start of the HL-LHC operation CMS will have recorded ~300 fb^{-1} of data
  - Beyond this exposure performance of detector components such as the central tracker will significantly degrades
- Occupancies at the HL-LHC requires increased granularity
  - The segmentation in the tracker needs to be improved to control fake rates
  - Endcap calorimeter with fine segmentation
- Pileup mitigation
  - Extended forward tracking coverage for jet tagging
  - Improved calorimeter; timing and high granularity
- Trigger
  - Need to maintain low thresholds, e.g. for Higgs studies
  - Incorporate tracking at first level trigger
  - Increase bandwidth (100→750 kHz) and latency (3→12.5 μs)
    - Requires updates to readout electronics for Calorimeter and Muons

Summary of CMS HL-LHC Upgrades

Trigger/HLT/DAQ DOE or NSF
- Track information at L1-Trigger
- L1-Trigger: 12.5 μs latency - output 750 kHz
- HLT output ≃7.5 kHz

Barrel EM calorimeter
- Replace FE/BE electronics NSF
- Lower operating temperature (8◦)



Muon systems
- Replace DT & CSC FE/BE electronics NSF
- Complete RPC coverage in region 1.5 < η < 2.4
- Muon tagging 2.4 < η < 3 NSF

DOE

Replace Endcap Calorimeters
- Rad. tolerant - high granularity
- 3D capability

Replace Tracker
- Rad. tolerant - high granularity - significantly less material DOE
- 40 MHz selective readout (Pt≥2 GeV) in Outer Tracker for L1-Trigger
- Extend coverage to η = ~4 NSF

CMS Upgrade Costs and Scope

"CORE" costs of the HL-LHC CMS upgrade reference scenario

CORE cost estimate	MCHF (2014)
Pixel Detector	23
Outer Tracker	89
Tracking System	**112**
EB electronics	10
HB scintillators	1
Endcap HGC+BHE	64
Calorimeters	**75**
DT and CSC electronics	10
Muon stations:GE11,GE21, RP31 and RP41	10
Muon extension ME0	5
Muon Systems	**25**
Beam Monitors and Luminosity	**4**
L1 Trigger	7
HLT	11
DAQ	6
Trigger and DAQ	**24**
Infrastructure, Systems and Support, Installation	**25**
Total	**265**

Note that CORE is ***only*** M&S and ***only for construction***

(i.e. no labor, R&D, preproduction, contingency, escalation, management)

In general, countries try to contribute to CORE costs commensurate with their number of CMS authors

US-HEP(DOE+NSF) is ~27% of CMS as of 2015

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From Technical Proposal (https://cds.cern.ch/record/2020886)

Scoping Scenarios

Scoping Scenario 1: Total CORE cost 241.6 MCHF

Upgrade configuration of ≃ 242 MCHF cost			
De-scoped item	**Operation and performance impact**	**Cost reduction (MCHF)**	**Recoverability**
Tilted modules in the outer tracker	Track-trigger resolution	3.9	No
No Muon endcap stations 3 and 4	Redundancy, efficiency and resolution	2.0	Yes
No replacement of CSC stations 3 and 4 readout	Efficiency at trigger rate ≥ 500 kHz	2.5	Yes
HLT/DAQ power	Trigger rate ≲ 300 kHz	8.0	Yes
HGC 24-11 layers	Energy resolution, pileup mitigation, shower pointing, timing	7.0	No
TOTAL cost reduction		**23.4**	

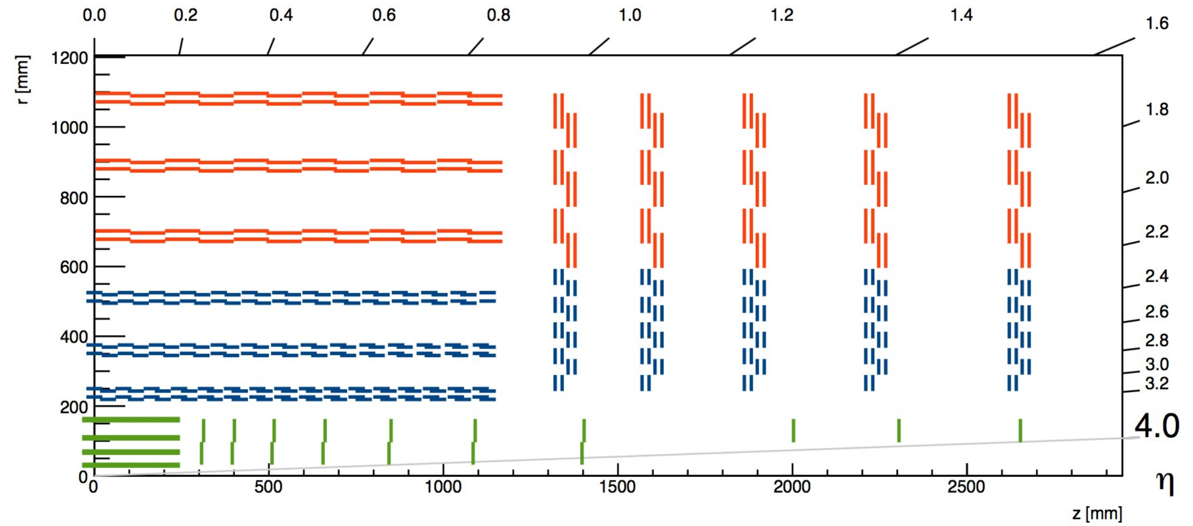
From CMS Scoping Document (https://cds.cern.ch/record/2055167)

- This scenario reduces outer tracker size using a “tilted barrel” design
  - Some impact to level 1 track trigger resolution
- Limits readout bandwidth to ~ 300 kHz
  - Mainly by reducing size of the Data Acquisition System and the Higher Level Trigger (online data filter) farm
- Reduces number of layers in the endcap calorimeter

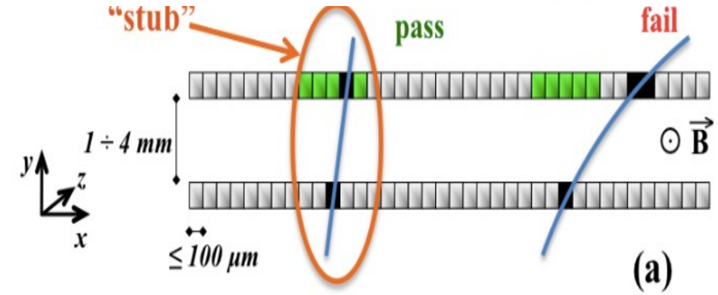
This scenario has no major impact on the U.S. scope

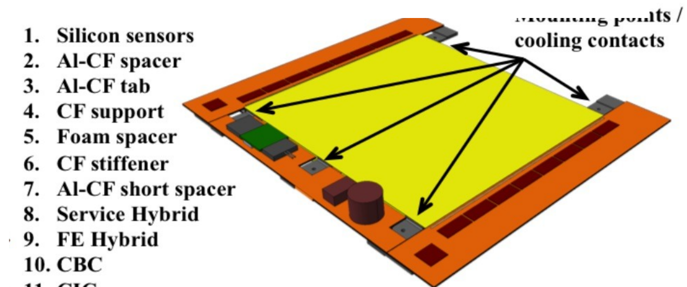
Tracker Upgrade: Outer Tracker

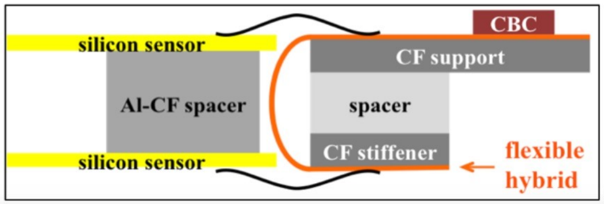
- Tracker will be upgraded with a new high performance tracker that meets HL-LHC physics needs



- New outer tracker composed of layers of modules with two closely spaced (~1 mm) silicon sensors
  - Using CMS's 3.8 T B-field and ~100 µm spatial resolution of silicon sensors, observed curvature can select track "stubs" with with $p_T > 2$ GeV
  - Provide stub information at 40 MHz for track finding at L1
    - Necessary for efficient triggering at HL-LHC



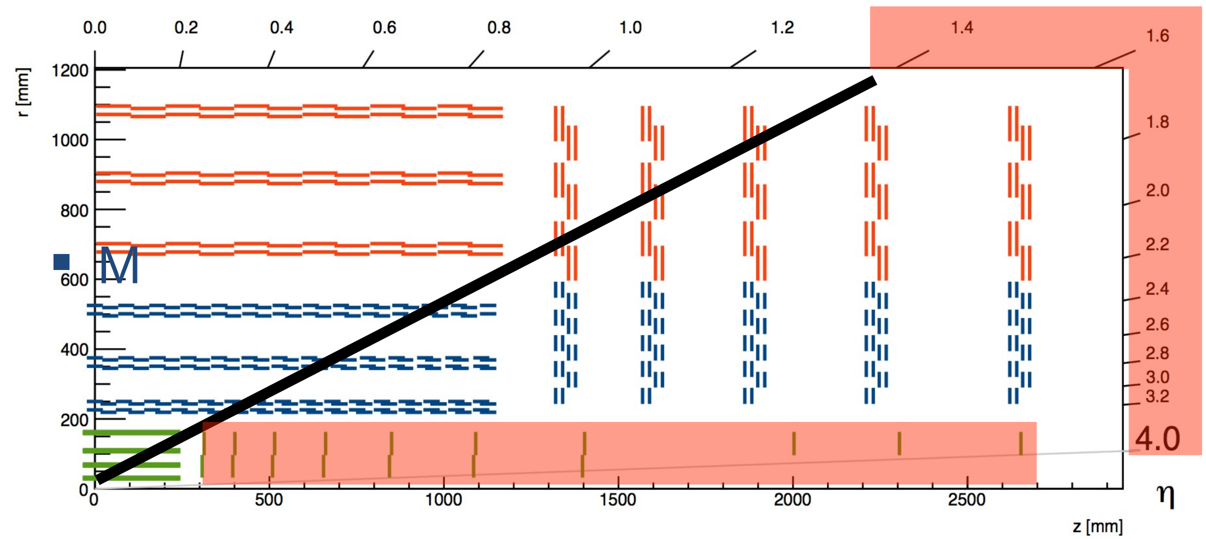




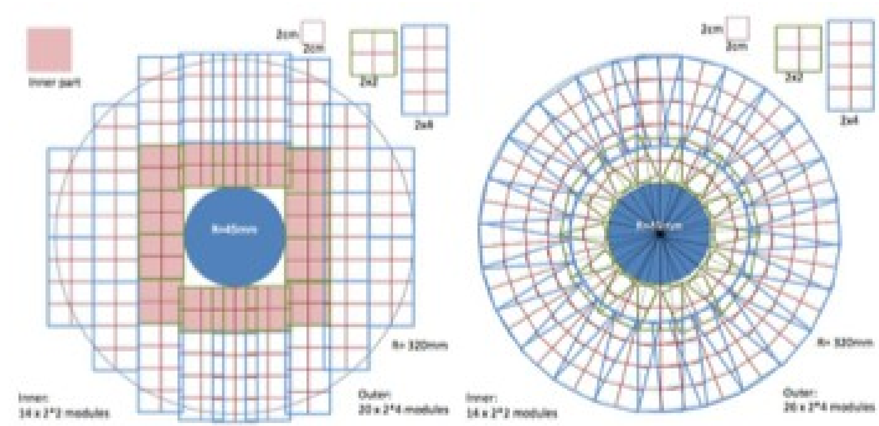
U.S. will build ~6,000 (from total of ~15,000) modules and central barrel mechanics

Tracker Upgrade: Forward Pixels

- As for Phase 1, U.S. will build the entire forward pixel detector for the HL-LHC upgrades
  - Represents ~ 50% of pixel
  - Main CMS part of NSF MREFC
- Up to 10 disks RED SHADING
  - z coverage, ±2.5 m
  - |η| coverage, 1.4–3.8
  - ~2 m^2 Si

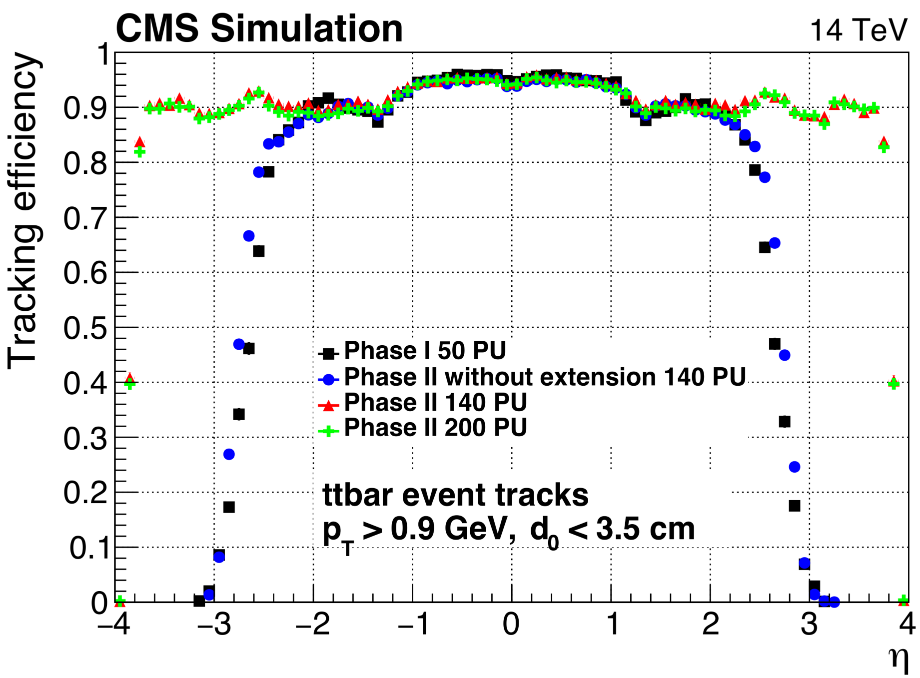


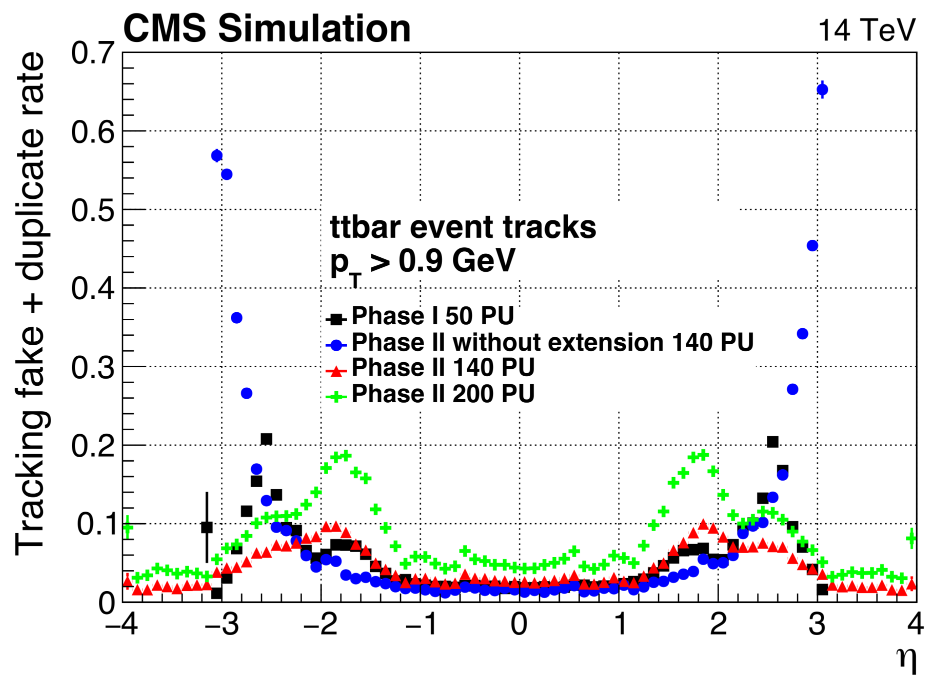
- Radiation hardness drives design
  - Lower bias voltage, less leakage current
    - Shorter drift distance, smaller clusters, better 2-track separation
  - Fluence up to 1×10^{16} cm^{-2}
  - Rad hard readout chip (ROC) bump-bonded to pixel sensors
  - Baseline is thin (150 µm) planar silicon sensors with small pixels (25 x 100 µm or 50 x 50 µm)
- U.S. R&D focused on ROC, mechanical and electrical conceptual designs and performance simulations



Tracking Performance

- Tracking performance with <PU>=140 and 200 similar to the phase-1 detector at <PU>=50.
  - Tracker provides a powerful handle to mitigate the PU
- Momentum resolution improved over the phase-1 detector due to reduction of material (CO_2 cooling and other optimizations)



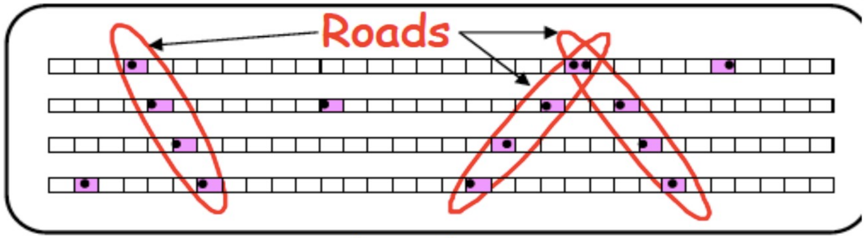


Excellent tracking performance is key to physics performance since tracking is used in reconstructing all objects

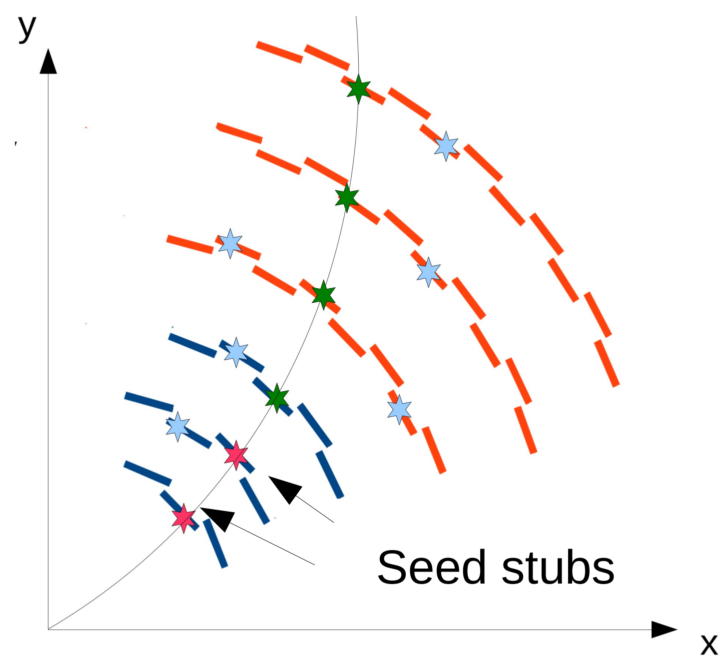
L1 Track Finder

- Major new capability in L1 trigger
  - Tracking in |η|<2.5 region
  - Reconstruct tracks with p_T>2 GeV
  - With latency less than 5 μs
- Technically challenging
  - About 10,000 stubs for each LHC bunch crossing (at 40 MHz)
  - Total input data volume of about 100 Tbits/s
- Major are of R&D to demonstrate that this is feasible for the tracker TDR. Three main efforts
  - U.S. led associative memory (AM), FPGA+ASIC approach
  - U.S. road search based “Tracklet” FPGA only approach
  - U.K. led time multiplexed FPGA only approach

Associative Memory Pattern Matching



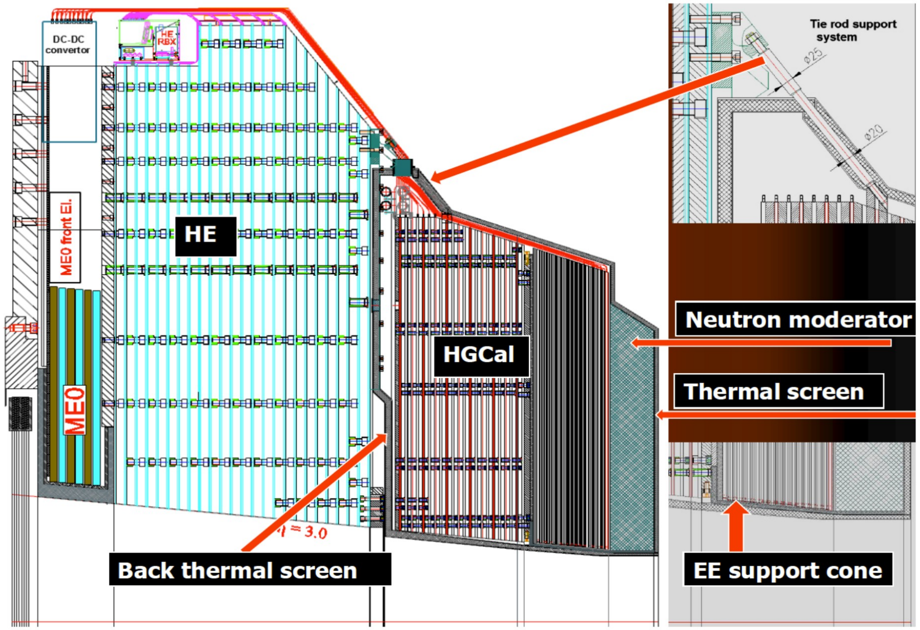
Tracklet Road Search



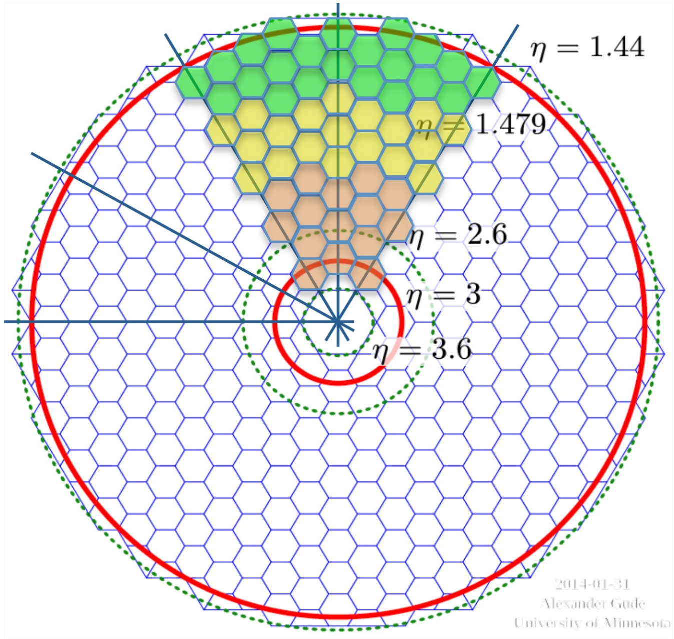
U.S. will contribute to core technologies, architecture, boards, algorithms 50% of the L1 track finder in either of the technologies under study

Endcap High Granularity Calorimeter

- 3D shower measurements in HGC
  - Electromagnetic EE (26 x_0, 1.5λ): 28 layers of Si-W/Cu absorber
  - •Front Hadronic (3.5λ): 12 layers of Si-Brass absorber
  - •Back Hadronic (5λ): 12 layers of Scintilators/Brass



EE: 380 m^2 - 4.3 Mch - 13.9k modules - 16t
FG: 209 m^2 - 1.8 Mch - 7.6k modules - 36.5t
BH: 428 m^2 - 5184 SiPMs



3 sensor active thicknesses 100-200-300 µm
0.5(1) cm^2 pads for 100(200/300) µm

Endcap Calorimeter: U.S. Construction Scope Outline

- Module Construction
  - U.S. develops detector-wide standard procedures for module construction, purchases ~27% of silicon, constructs 8500 standard modules and 3500 odd-size/edge modules
- Cassette Assembly and Services
  - U.S. develops cassette assembly procedure, designs services for low-voltage and readout, constructs 280 cassettes
- Backing calorimeter
  - U.S. constructs active material (scintillator+WLS) in joint facility with HB, constructs on-detector readout electronics
- Off-detector electronics
  - U.S. constructs readout electronics (joint effort with EB/HB), contributes to international firmware effort for trigger primitive preparation

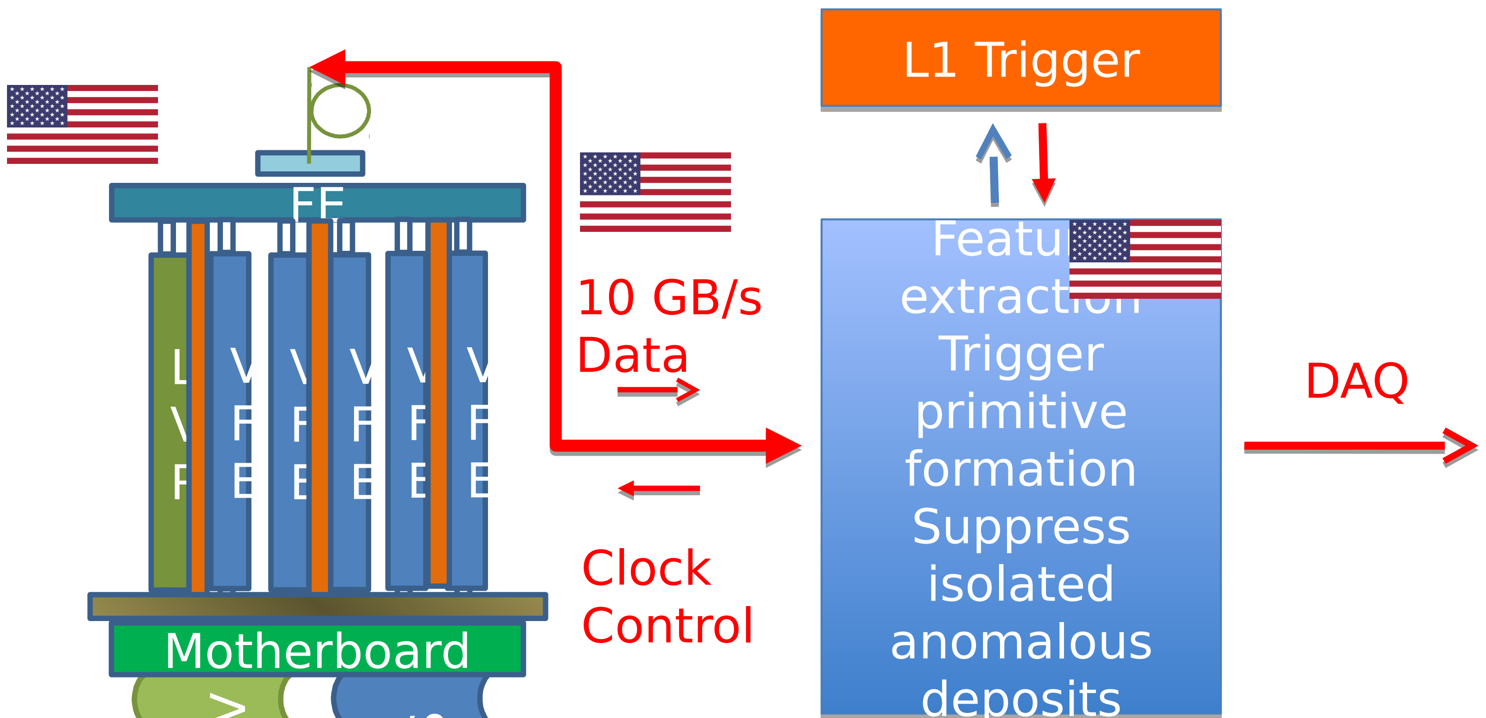
US isn't doing:

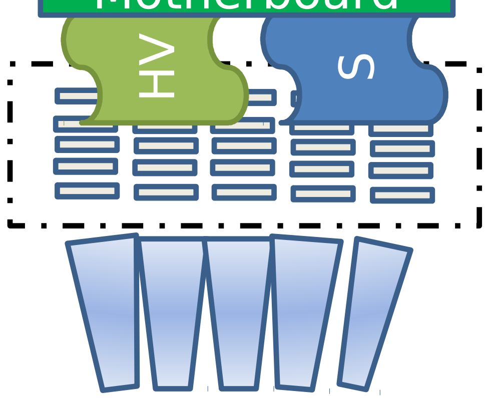
- Absorber/mechanics
- Cooling system
- High voltage system
- Trigger primitive electronics
- Primary development of readout ASIC

Barrel ECAL (EB) Electronics Upgrade

Upgrade readout electronics:

- Trigger readout (40MHz) of full crystal level granularity
- Handle higher trigger rate (750 MHz) and latency (12.5 μs)



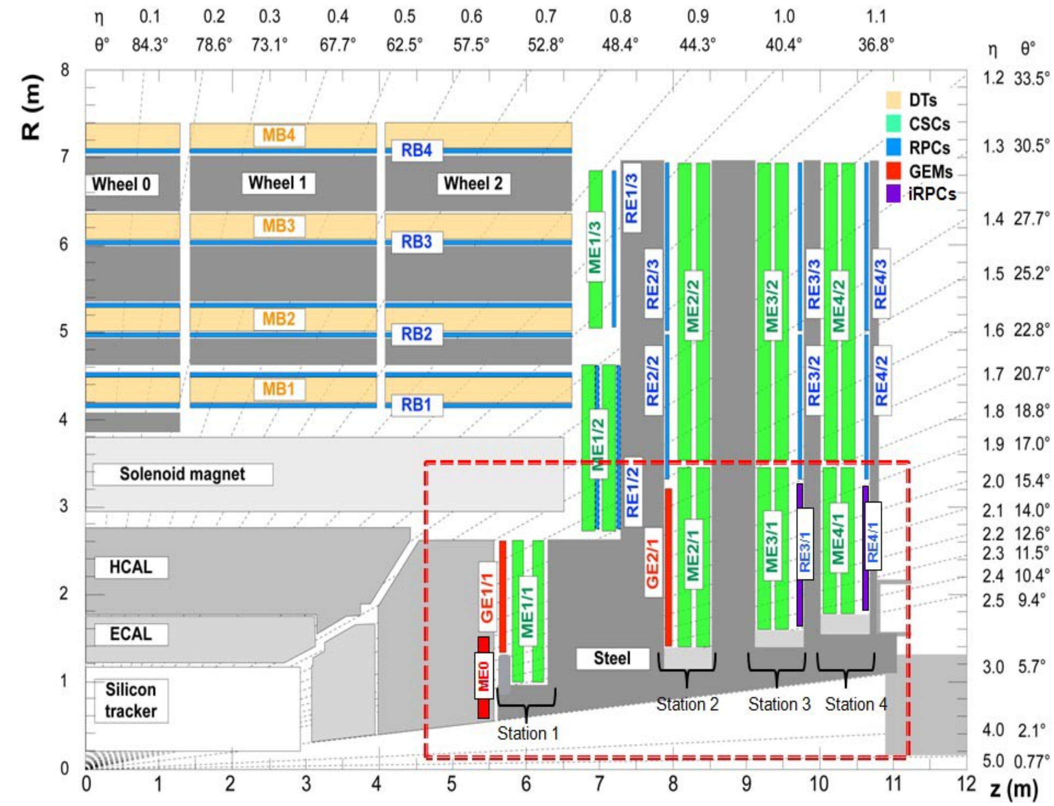


Trigger primitive, feature extraction done off detector using FPGA . U.S delivers complete block of readout

Foresee a common development with EB, HB and EndCap Calorimeter backend – i.e use the same cards as EB but modified and form combined ECAL+HCAL trigger primitives.

CMS Muon Upgrade Scope

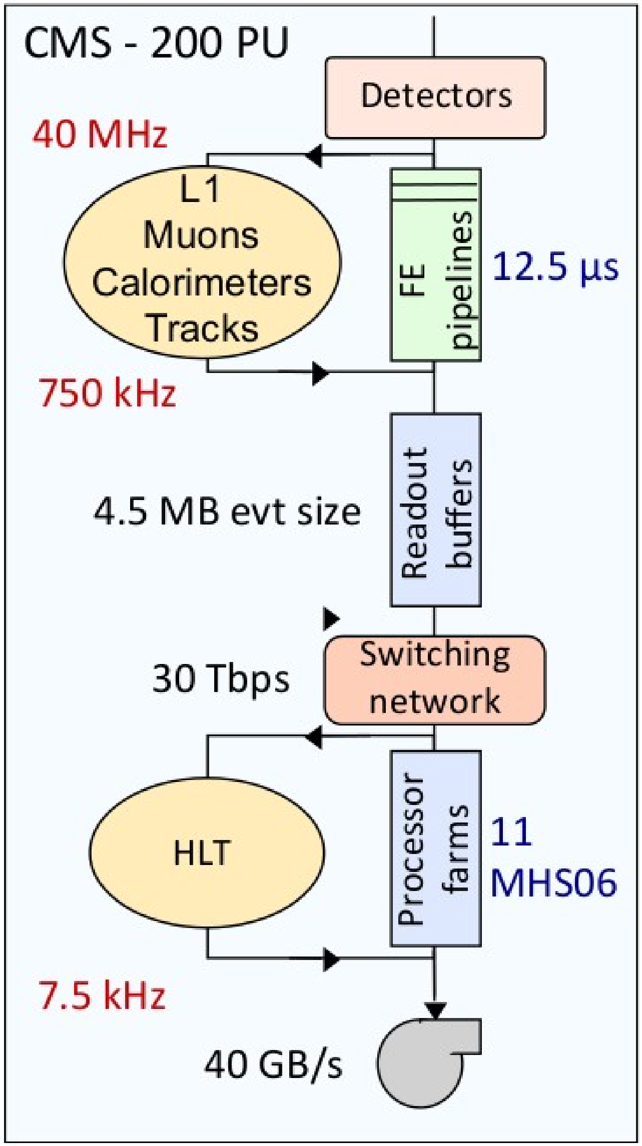
- Barrel readout electronics upgrade (no U.S. involvement)
- Forward muon upgrades maintain trigger, extend offline coverage
- Endcap Muon Cathode Strip Chambers (CSC):
  - Upgrade ME2/1 off-chamber electronics to cope with data volume/bandwidth
- New Gas Electron Multiplier (GEM) detectors:
  - GE1/1 and 2/1 work with CSC ME1/1 and ME2/1 to maintain muon trigger
  - ME0 works with ME1/1 to maintain trigger and extends offline coverage η=2.4 to 2.9



U.S. has historically a strong involvement in the forward muon trigger and CSCs
We focus in Phase-2 on CSC off detector electronics and GEM-CSC trigger and DAQ electronics

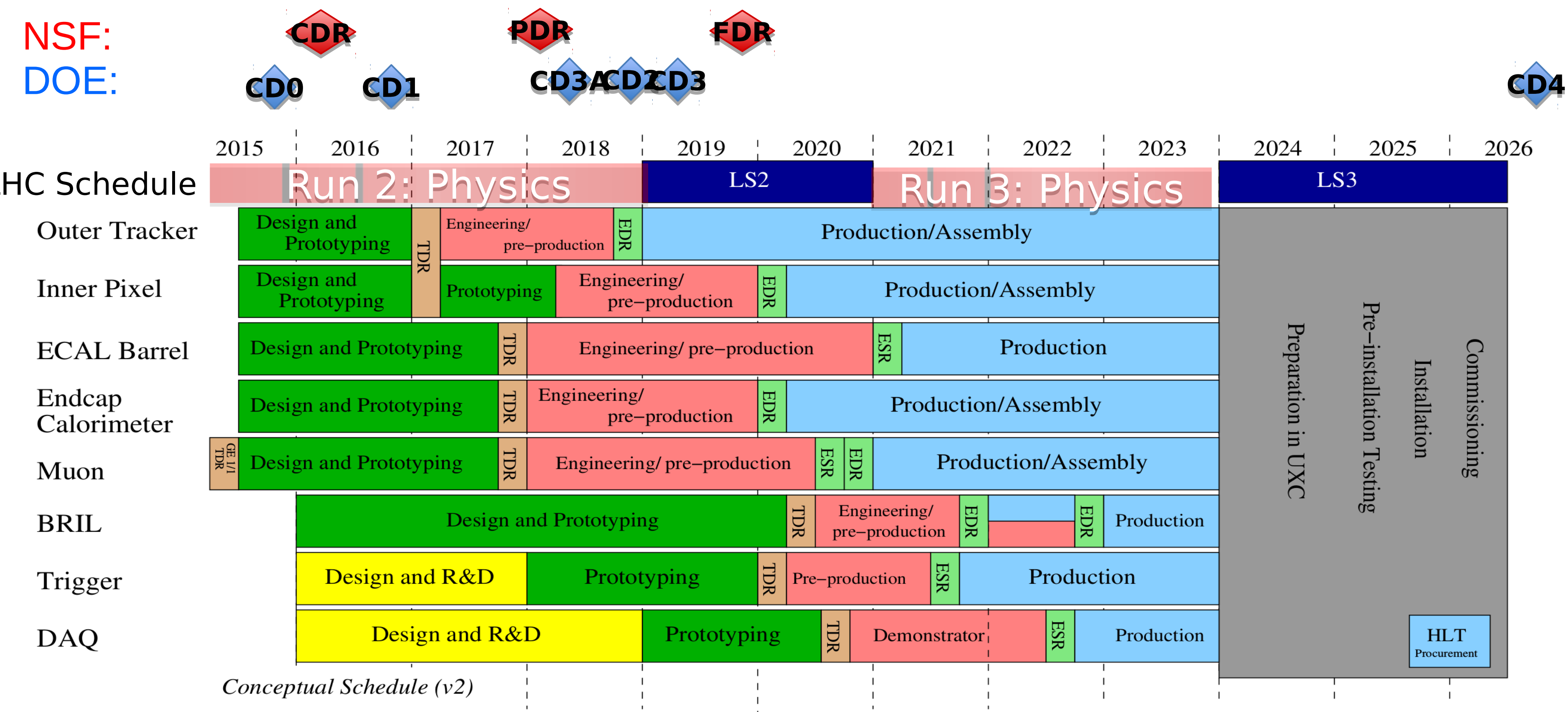
L1Trigger/HLT/DAQ

- L1Trigger
  - High BW and powerful processing boards: 12.5 μs latency and 750 MHz (currently ~3 μs and 100 kHz)
  - First layer to match detector information
  - Second layer to produce Trigger objects
    - Including track trigger
- DAQ
  - Similar event builder, HLT, and storage as present. Increase band width – 800 links at 100 Gbps with 30% occ. will produce 30 Tbps event building throughput.
- HLT
  - Processing power scales as PU times L1 rate – need increase of a factor of 50 with respect to Run 2 when operating at <PU>=200.



U.S. CMS willl continue its role in trigger and DAQ – plan to deliver ~50% of L1 trigger

CMS HL-LHC Upgrade Schedule



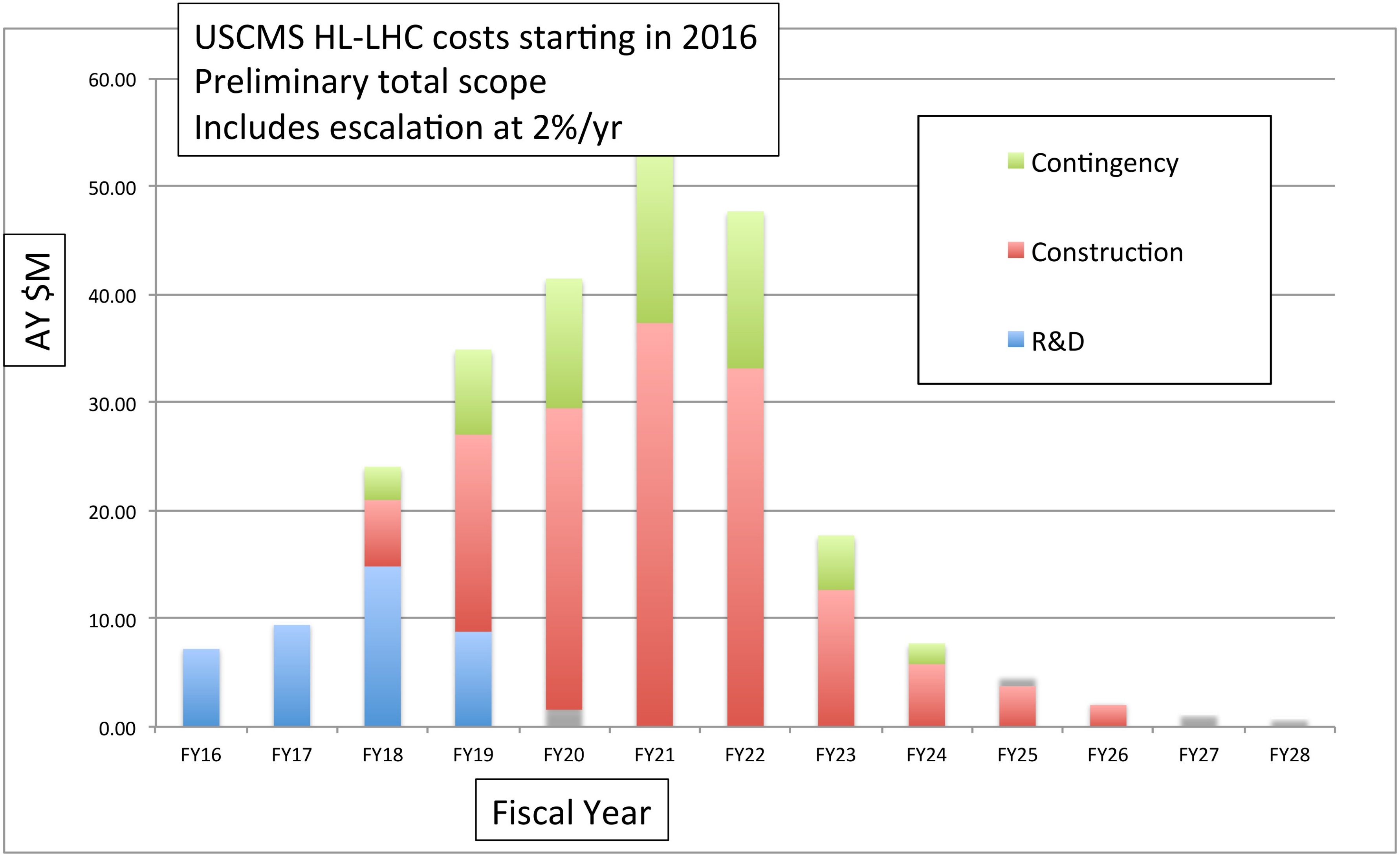
Major subproject TDRs scheduled for completion in 2017
Available for NSF PDR and DOE CD2/3 reviews

U.S. CMS Project Costs

Sub Project	Construction Cost ($M) (no contingency)	R&D and OPC Cost ($M)
Project Office	24.80	2.53
Tracker	75.09	22.16
Barrel Calorimeter	7.74	4.19
Endcap Calorimeter	27.70	8.00
Muon System	5.06	1.52
Trigger	8.00	2.70
DAQ	1.55	
Total	149.94	41.10

- Assuming 50% contingency on everything in the construction project (except project management) gives a total of $212.51M
  - The guidance from DOE and NSF is a construction project with a total cost of $134.75M+$75M = $209.75M
- For R&D and OPC we expect to have $35-36M available
  - Working on updating budgets/scope to align R&D/OPC costs

Preliminary Total Cost Profile



- FY18 and FY19 start of DOE OPC and TEC – early procurements, e.g. sensors for outer tracker and high granularity calorimeter
- FY20 and FY21 NSF MREFC funds available

Summary

- The HL-LHC upgrade addresses 3 of the 5 science drives identified in the P5 report and is ranked the highest priority near term large scale project
- The HL-LHC upgrades for CMS has to address many challenges:
  - High occupancy (Pileup)
  - Large data rates
  - Harsh radiation environment
- CMS are planning a series of upgrades to address these challenges
  - Tracker:
    - Higher granularity
    - Selective readout of p_T>2 GeV for L1 trigger
    - Forward pixel extension
  - Calorimeter
    - HGC with 3D reconstruction of electromagnetic and hadronic showers
    - Barrel calorimeter readout and cooling
  - Muons
    - Updates to electronics and extending forward coverage
  - Trigger/HLT/DAQ
    - Increased bandwidth at both L1 and HLT stages
    - Inclusions of tracking in the first (L1) trigger stage
- The U.S. contributions are well matched and aligned with the international CMS needs and expectations

Backup

U.S. CMS Costs for Construction Project

		Total	NSF	DOE	ORE fractio	CORE MCH
402.00	**Totals, no contingency**	**149.94**	**55.07**	**94.87**	**0.27**	**64.70**
402.01	**Project Office**	**24.80**	**6.10**	**18.70**		**6.75**
402.01.01	Project Management	17.30	3.60	13.70		
402.01.02	Common Infrastructure	7.50	2.50	5.00	0.27	6.75
402.02	**Tracker**	**75.09**	**33.06**	**42.03**	**0.31**	**33.66**
402.02.02	Management	0.50	0.30	0.20	0.00	0.00
402.02.03	FPIX	25.50	25.50	0.00	1.00	11.60
402.02.04	Outer Tracker	40.16	2.46	37.70	0.24	18.46
402.02.05	Track Trigger	8.93	4.80	4.13	0.50	3.60
402.03	**Barrel Calorimeter**	**7.74**	**5.20**	**2.54**	**0.40**	**4.40**
402.03.02	Management	0.30	0.30	0.00	0.00	0.00
402.03.03	ECAL Barrel	4.90	4.90	0.00	0.30	3.00
402.03.04	HCAL Barrel	2.54	0.00	2.54	1.00	1.40
402.04	**Endcap Calorimeter**	**27.70**	**0.00**	**27.70**	**0.24**	**13.80**
402.04.02	Management	0.50		0.50		
402.04.03	Sensors and Modules	12.30		12.30		
402.04.04	Casettes	5.60		5.60		
402.04.05	Backing Cal	2.90		2.90		
402.04.04	Electronics & Services	6.40		6.40		
402.05	**Muon Systems**	**5.06**	**5.06**	**0.00**	**0.08**	**1.69**
402.05.02	Management	0.31	0.31	0.00	0.00	0.00
402.05.03	CSC	1.03	1.03	0.00	1.00	0.30
402.05.04	GEM	3.72	3.72	0.00	0.15	1.39
402.06	**Trigger**	**8.00**	**5.65**	**2.35**	**0.50**	**3.66**
402.06.02	Management		0.08	0.08		0.00
402.06.03	Calo Trigger		1.50	1.86		1.87
402.06.04	Muon Trigger		2.33	0.00		0.90
402.06.05	Track Correlator		1.74	0.41		0.89
402.07	**DAQ**	**1.55**	**0.00**	**1.55**	**0.04**	**0.74**
402.07.02	Management	0.05		0.05		
402.07.03	DAQ	1.50		1.50	0.13	0.75

Totals applying 50% contingency on everything except project management is $133M DOE, $79.5M NSF.

The CORE costs are in MCHF with respect to the technical proposal and the scoping document. These were calculated using the same inputs at the TP. The CORE fractions are calculated with respect to the middle scenario (Scenario 1).

The overall core fraction with respect to middle scenario (Scenario 1) is ~27%

For the reference design, this would represent 24.4%, for the lowest scoping scenario 31%.

The proposed work would change a bit between the full scope scenario and Scenario 1, however for the lowest scope (Scenario 2) we would have to rework the project significantly.

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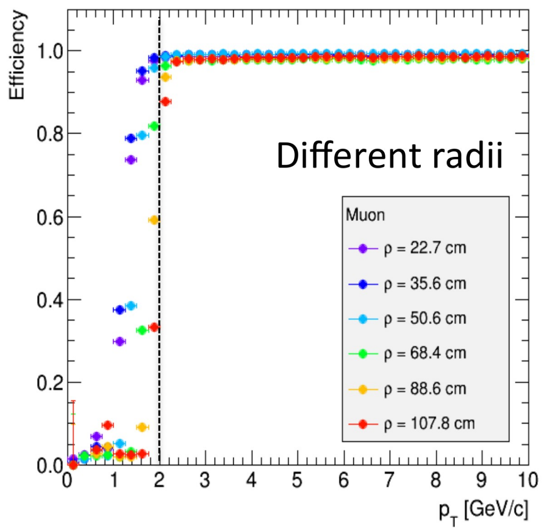
Scoping Scenarios

Scoping Scenario 2: Total CORE cost 208.3 MCHF

Upgrade configuration of $\simeq$ 208 MCHF cost			
De-scoped item	**Operation and performance impact**	**Cost reduction (MCHF)**	**recoverability**
Tilted modules in the outer tracker	Track-trigger resolution	3.9	No
No Muon endcap stations 3 and 4	Redundancy, efficiency and resolution	2.0	Yes
No replacement of CSC stations 3 and 4 readout	Efficiency at trigger rate $\geq$ 500 kHz	2.5	Yes
HLT/DAQ power	Trigger rate $\lesssim$ 300 kHz	8.0	Yes
No Muon endcap stations 2	Redundancy, efficiency and resolution	4.0	Yes
No Muon extension to $\eta \simeq 3$	Muon acceptance	4.5	No
HGC 18-9 layers	Energy resolution, pileup mitigation, shower pointing, timing	13.0	No
No Pixel extension $\eta \simeq 4$	Pileup, jet tagging and Missing ET	7.7	Yes
No replacement of Muon DT minicrates	Efficiency and trigger rate $\lesssim$ 300 kHz	6.1	Yes
One less layer in outer tracker barrel	Track-trigger efficiency	5.0	No
TOTAL cost reduction		**56.7**	

- Includes all of scenario 1 plus removing: tracker and muon η extensions, full layer of barrel (outer) tracker, additional endcap calorimeter layers
- Large impact in Higgs measurements, missing E_{T}, discovery potential

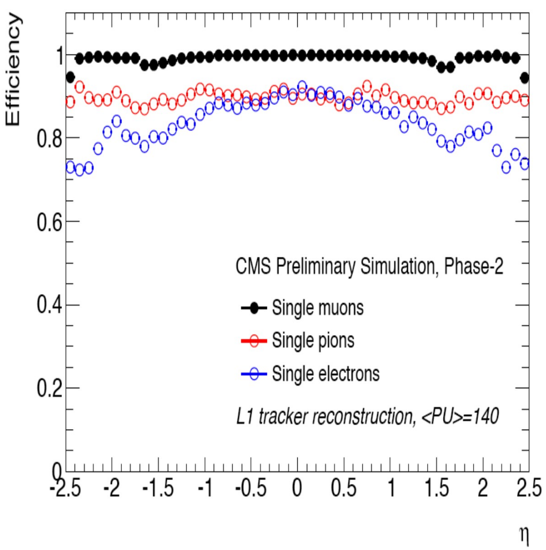
L1 Tracking Performance

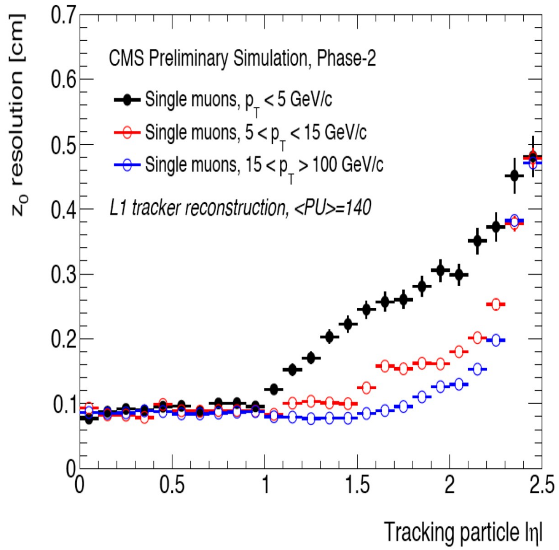


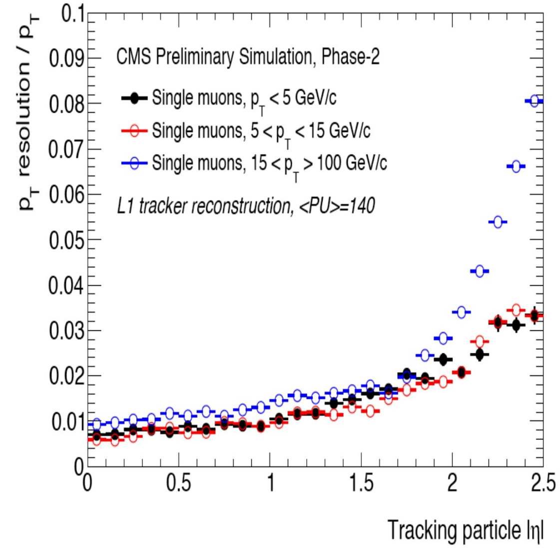
High B-field allows to measure bending of tracks in few mm spacing between two sensors of a module

- Selective readout of track hits down to $P_T \simeq 2$ GeV reduce Band Width for readout at 40 MHZ
- 3 techniques investigated for track reconstruction

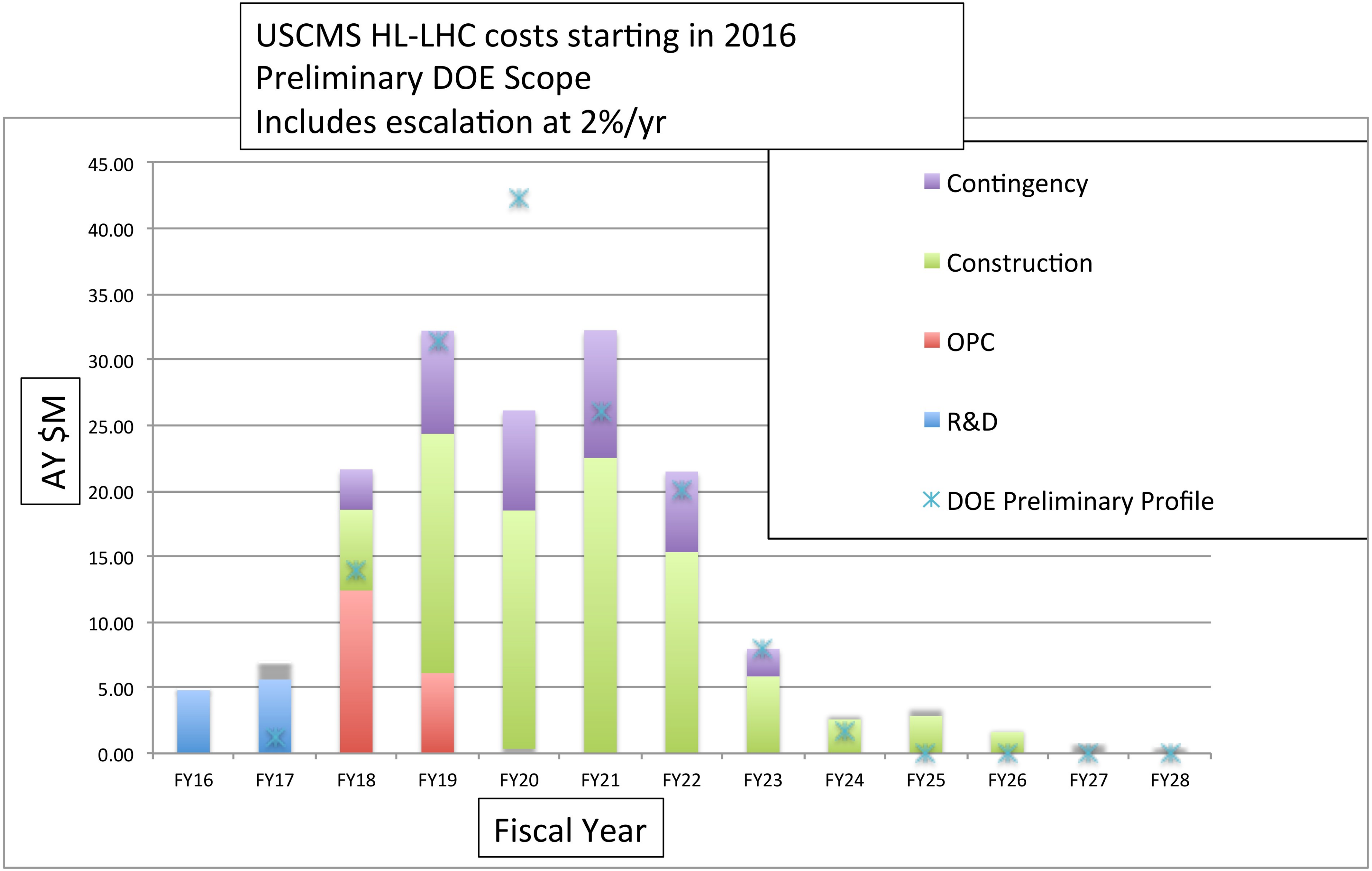
L1 Track Trigger reconstruction performance



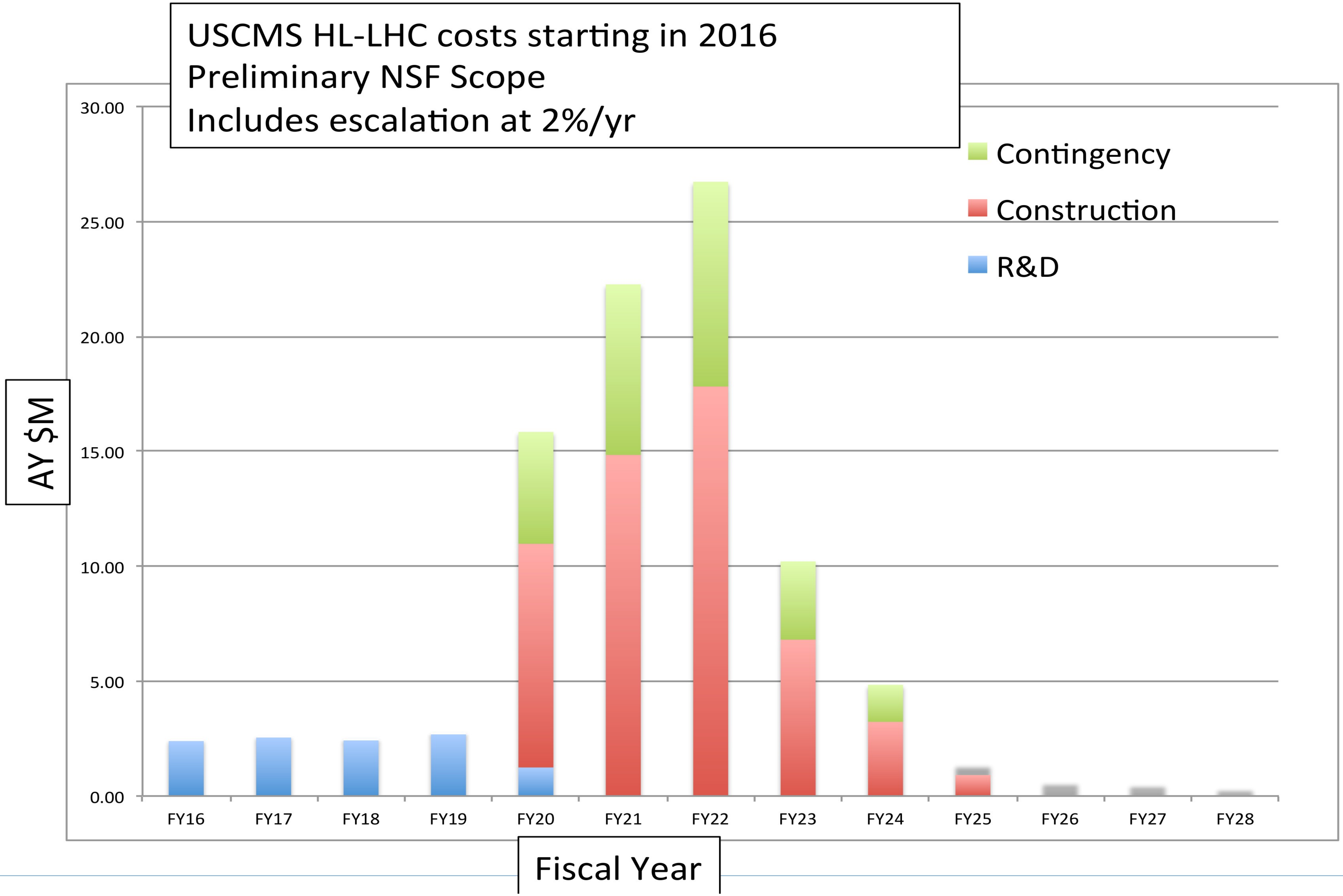




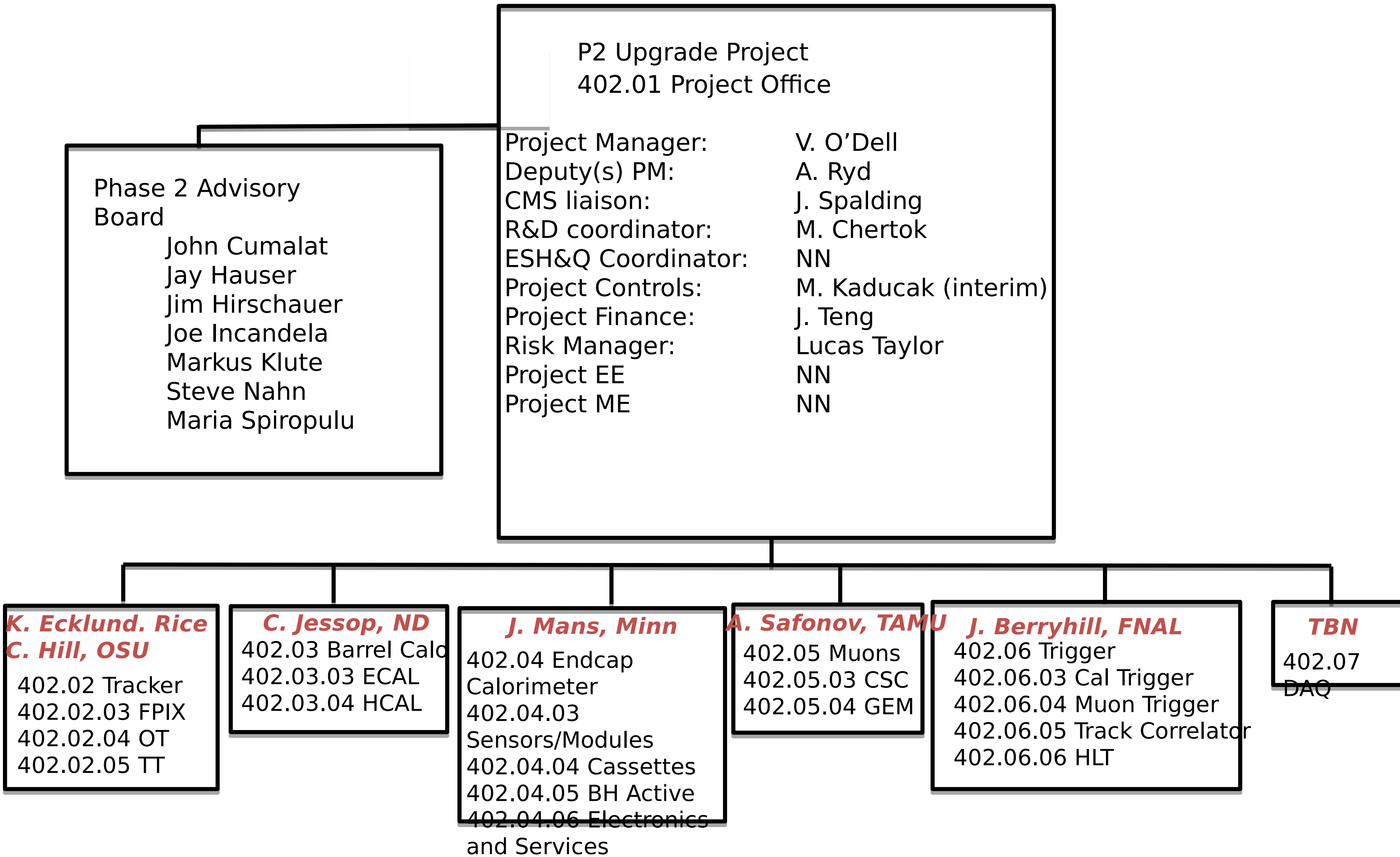
DOE Cost Profile



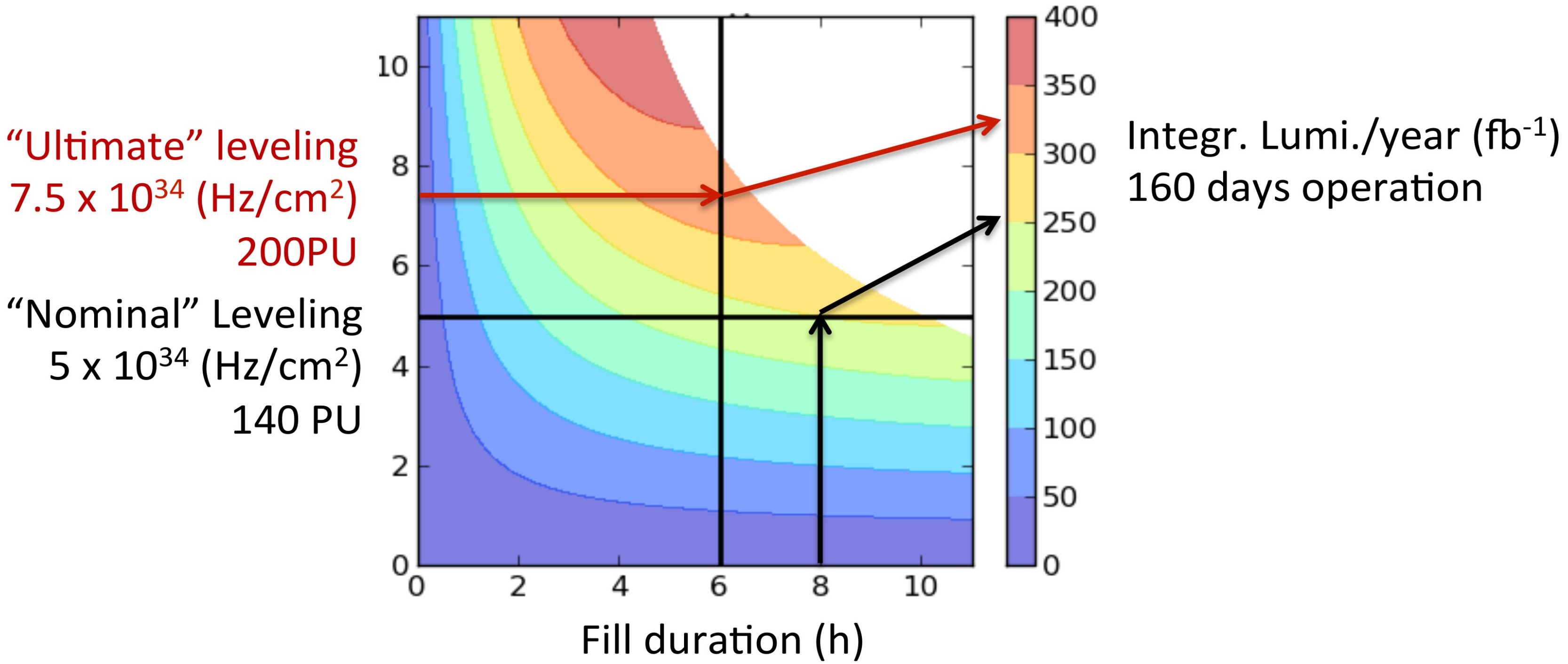
NSF Cost Profile



U.S. CMS HL-LHC Organization



HL-LHC Luminosity Goals



Ultimate luminosity represents ≃30% gain in operation time to reach expected additional integrated luminosity of ≃ 2500 fb^{-1}

CMS upgrades enable operation at 200 PU, target Phase-I performance at 140 PU, allowing moderate degradation up to 200 PU, and radiation tolerance ≥3000 fb^{-1}