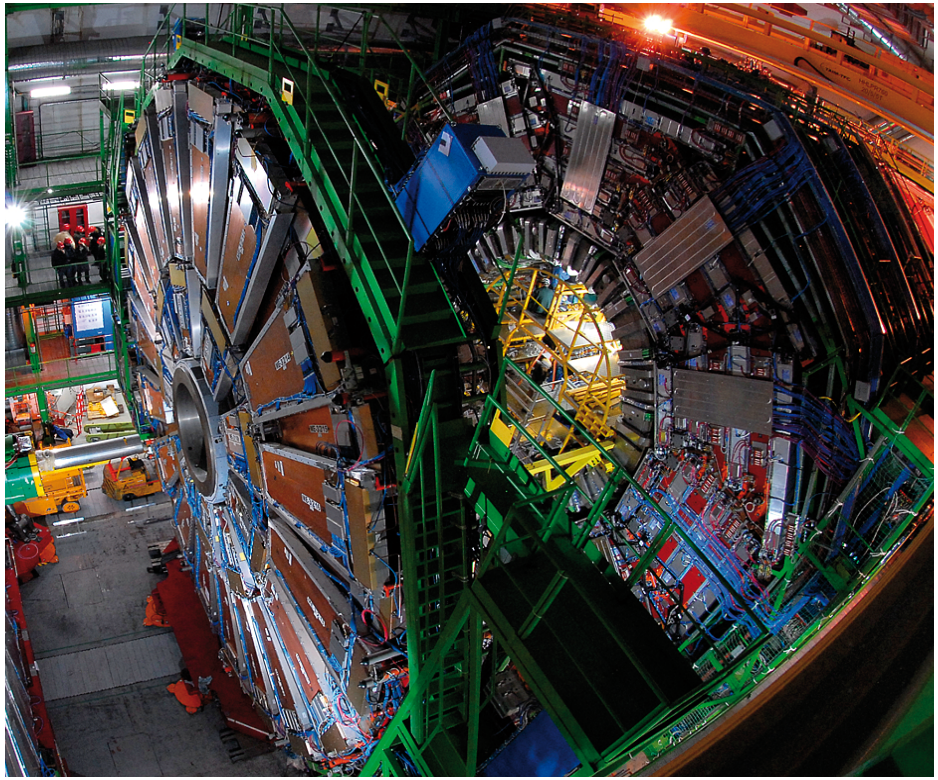
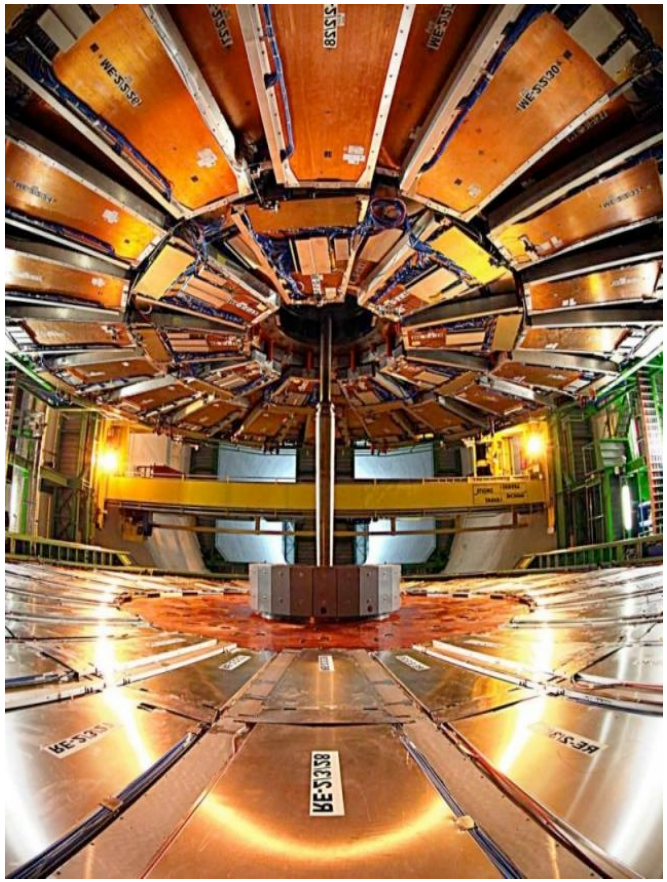
# Overview of US CMS Phase 2 Upgrade Program

HEP PI Meeting
June 17, 2014 Washington, DC

John Cumalat (University of Colorado)





# Outline

- Phase 2 Physics Program
- Challenges of High Luminosity and Radiation Damage
- CMS Plans for Phase 2
- Overview of planned detector upgrades
  - Pixels, Silicon Tracker
  - ECAL
  - HCAL
  - Muons Endcap
  - L1-Trigger
- Towards a U.S. CMS plan for upgrade program
- Conclusions

# HL-LHC Physics Program

## Exploitation of the Higgs Boson

- Coupling and property measurements

| L ($fb^{-1}$) | $\kappa_\gamma$ | $\kappa_W$ | $\kappa_Z$ | $\kappa_g$ | $\kappa_b$ | $\kappa_t$ | $\kappa_\tau$ | $\kappa_{Z\gamma}$ | $\kappa_{\mu\mu}$ | $BR_{SM}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 300 | [5, 7] | [4, 6] | [4, 6] | [6, 8] | [10, 13] | [14, 15] | [6, 8] | [41, 41] | [23, 23] | [14, 18] |
| 3000 | [2, 5] | [2, 5] | [2, 4] | [3, 5] | [4, 7] | [7, 10] | [2, 5] | [10, 12] | [8, 8] | [7, 11] |

- Di-Higgs searches with the aim of Higgs self coupling measurement
- Vector boson scattering measurements

## Exploring new BSM Particles

- Measurement of properties
- Turn evidence into discovery
- Find related evidence

## Discovery of BSM Physics

- Direct search for SUSY and other BSM scenarios
- Dark Matter searches
- Substantial increase in reach (~20%)

## Standard Model Measurements

- Precision measurements (e.g. $m_W, \sin\theta_W, \alpha_s$)
- Search for rare SM processes, enhanced by BSM (e.g. $B_{s,d} \to \mu\mu$)
- Differential measurements of W, Z, di-boson, Top, and Higgs

# 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

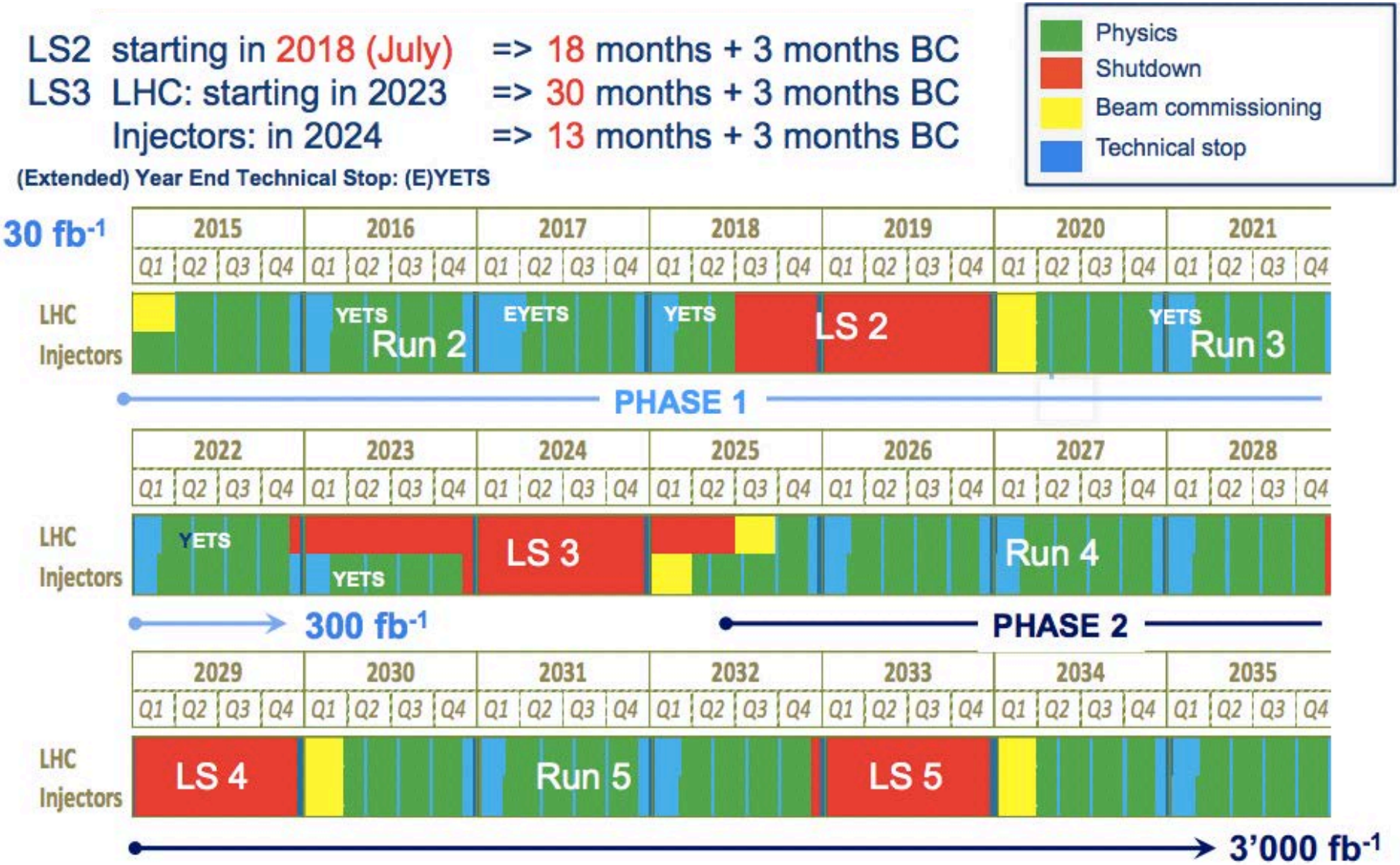
**Phase 2 upgrades**: ≳ 5 x $10^{34}$ Hz/cm$^2$ luminosity leveled, <PU> ≳ 140
Reach total of 3000 fb$^{-1}$ in ~10 yrs operation

- 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, muons, enhanced tracker coverage

# LHC Roadmap: Schedule beyond LS1

LS2 starting in 2018 (July) => 18 months + 3 months BC
LS3 LHC: starting in 2023 => 30 months + 3 months BC
Injectors: in 2024 => 13 months + 3 months BC

(Extended) Year End Technical Stop: (E)YETS




by Frederick Bordry

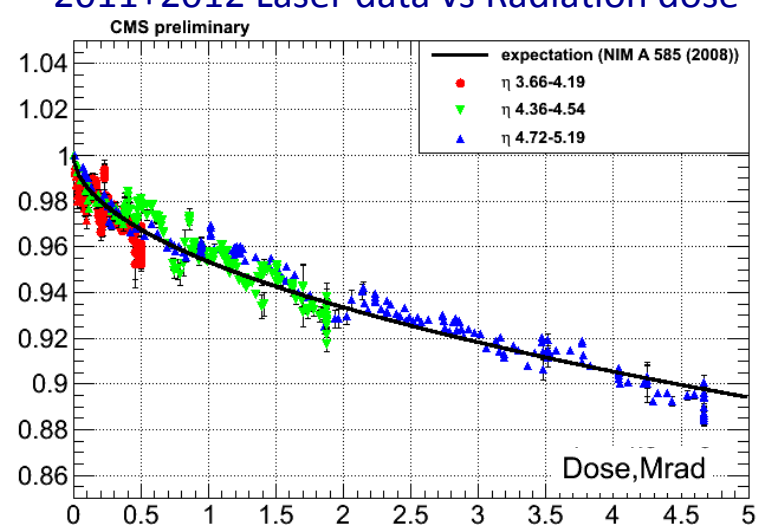
# LHC to HL-LHC - The Challenge

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

- 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 continued attention to maintain calibration
  - Eventually limits the performance-lifetime of the detectors
  - Considerable test beam, GIF and test beam running to evaluate materials

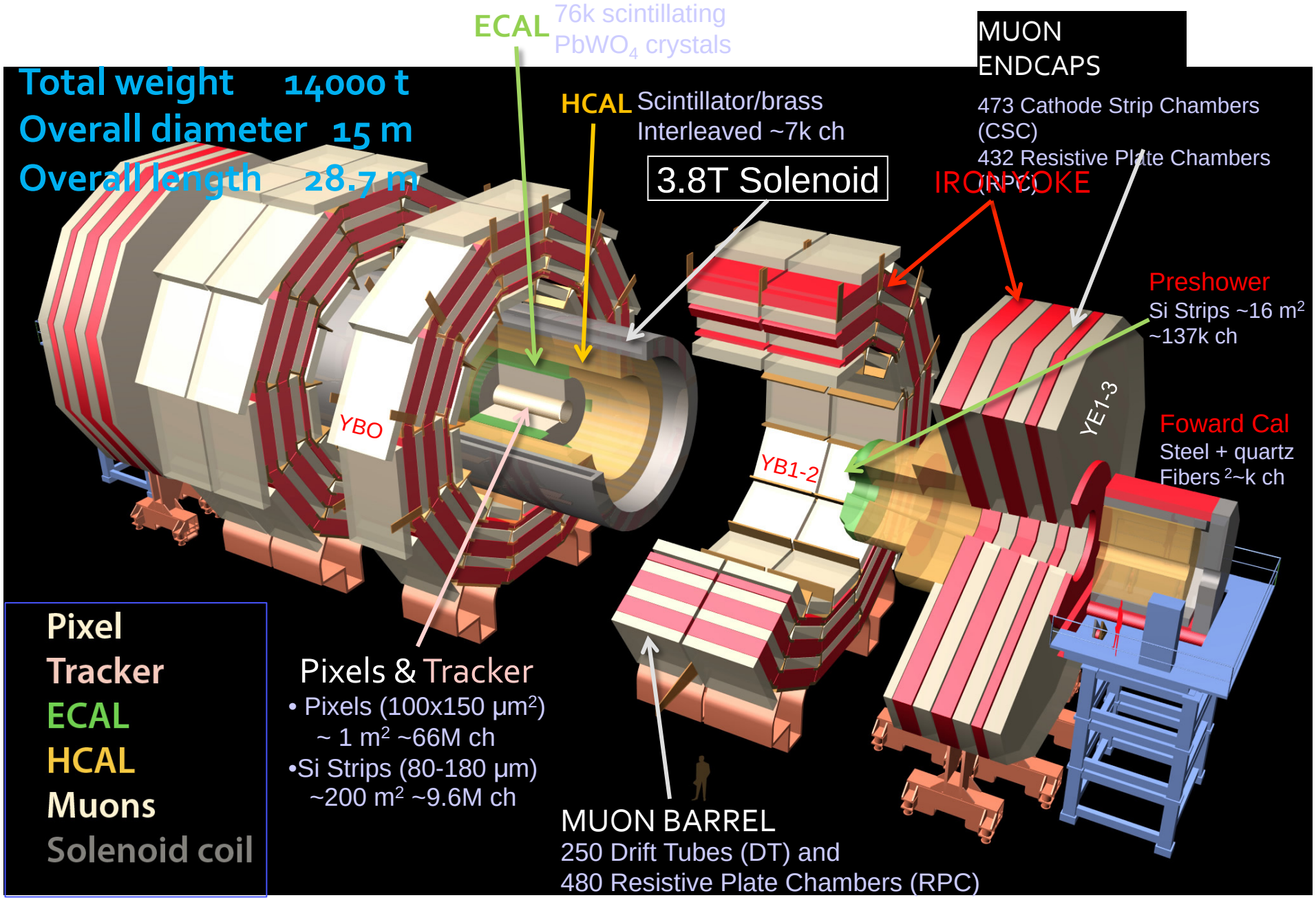
Observed signal loss in HF quartz fibers, 2011+2012 Laser data vs Radiation dose



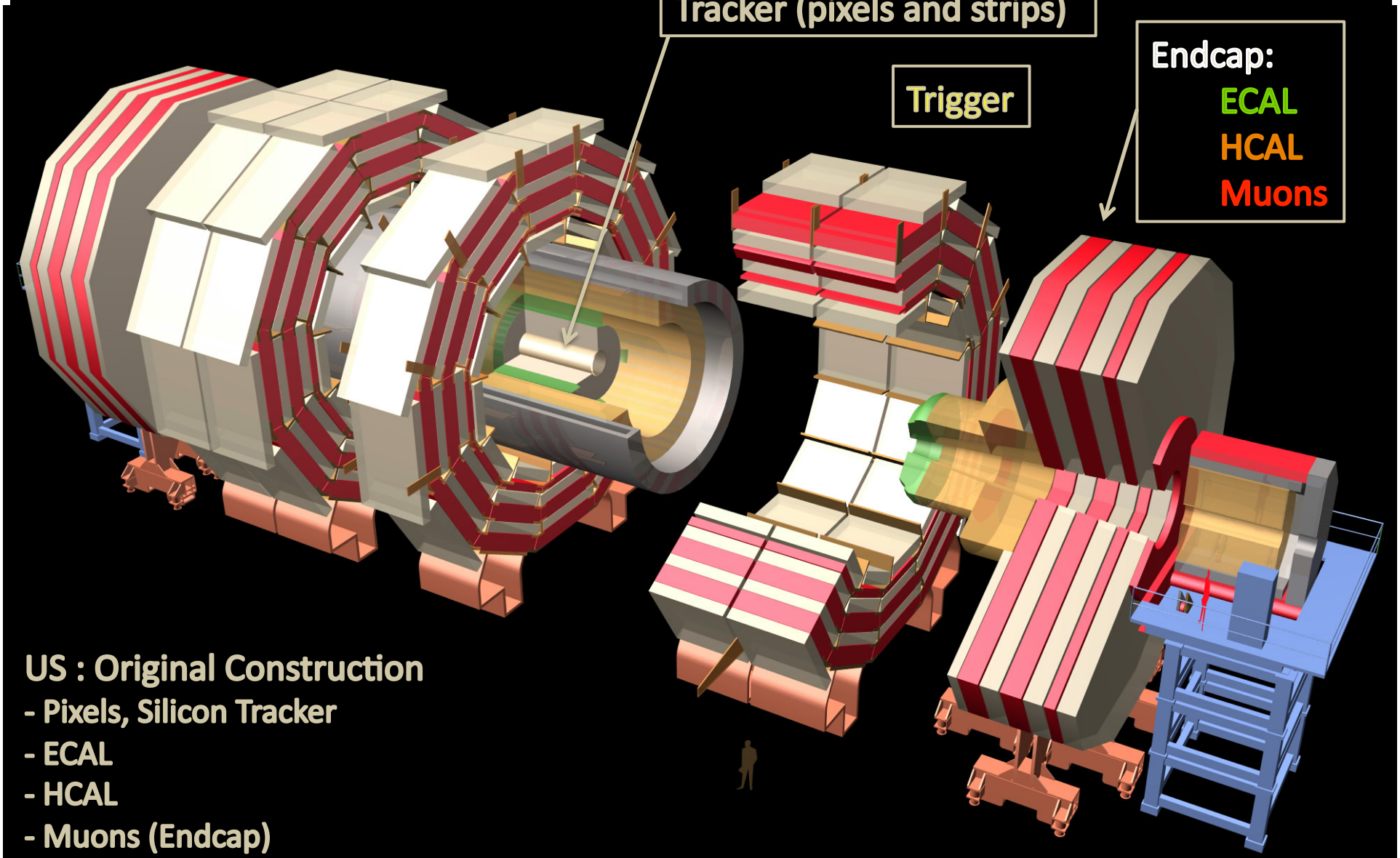
# Manpower Challenges

- **Important challenges for CMS in next several years:**
  - **Analyze Run 1 and Run 2 data**
  - **Construct and commission the Phase 1 Upgrade**
  - **Do R&D for the Phase 2 Upgrade <- Focus of this talk**
  - **Set up the Phase 2 project**

# CMS Detector



# CMS

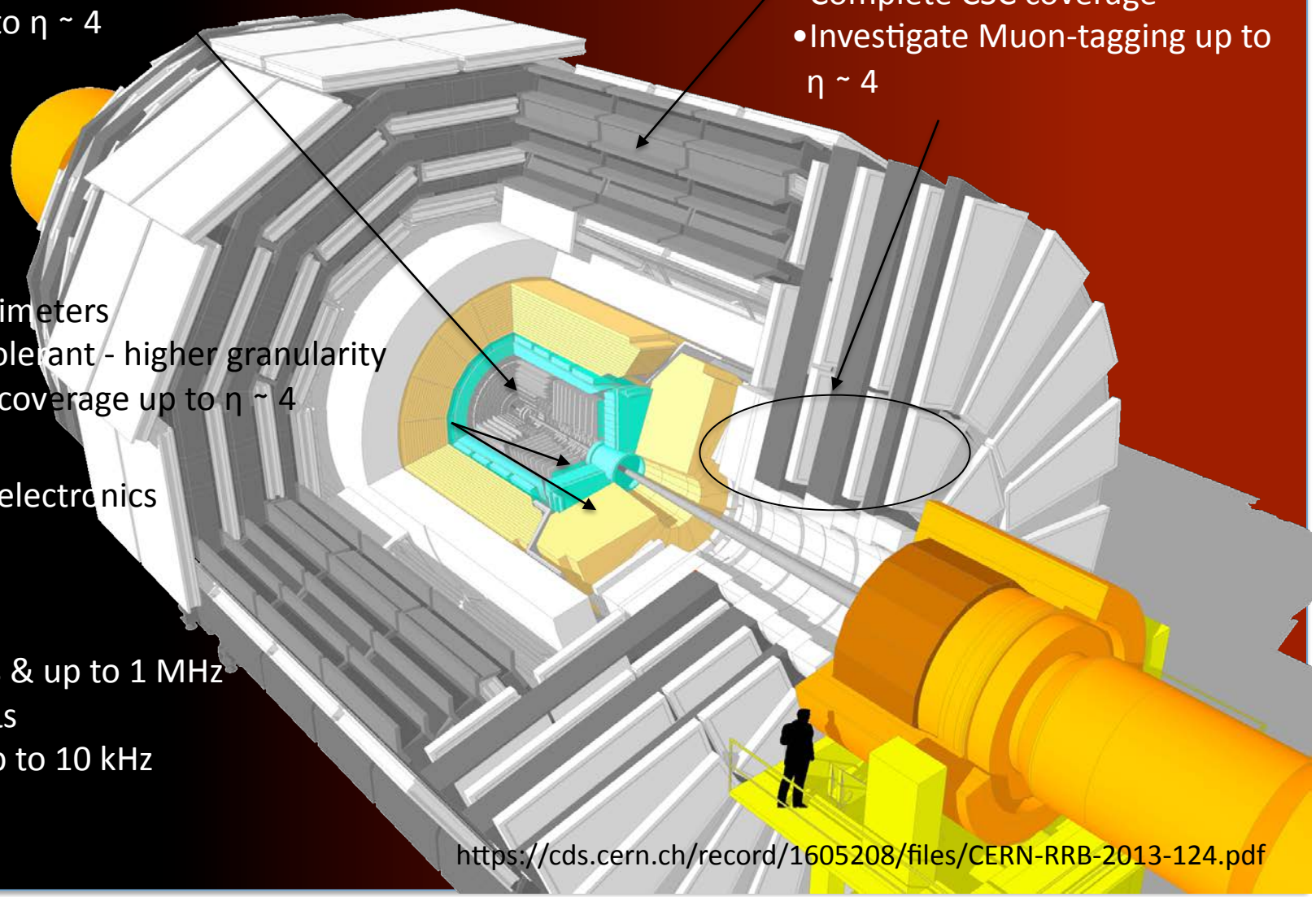



US : Original Construction
- Pixels, Silicon Tracker
- ECAL
- HCAL
- Muons (Endcap)
- L1-Trigger
- Software Framework

# CMS Phase 2 Upgrades: mitigate PU and rad. damage

Tracker: Pixels and Strips → Inner and Outer
- Radiation tolerant - high granularity - less material
- Tracks in hardware trigger (L1)
- Coverage up to η ~ 4

Muons
- Replace DT FE electronics
- Complete CSC coverage
- Investigate Muon-tagging up to η ~ 4



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

Barrel ECAL
- Replace FE electronics

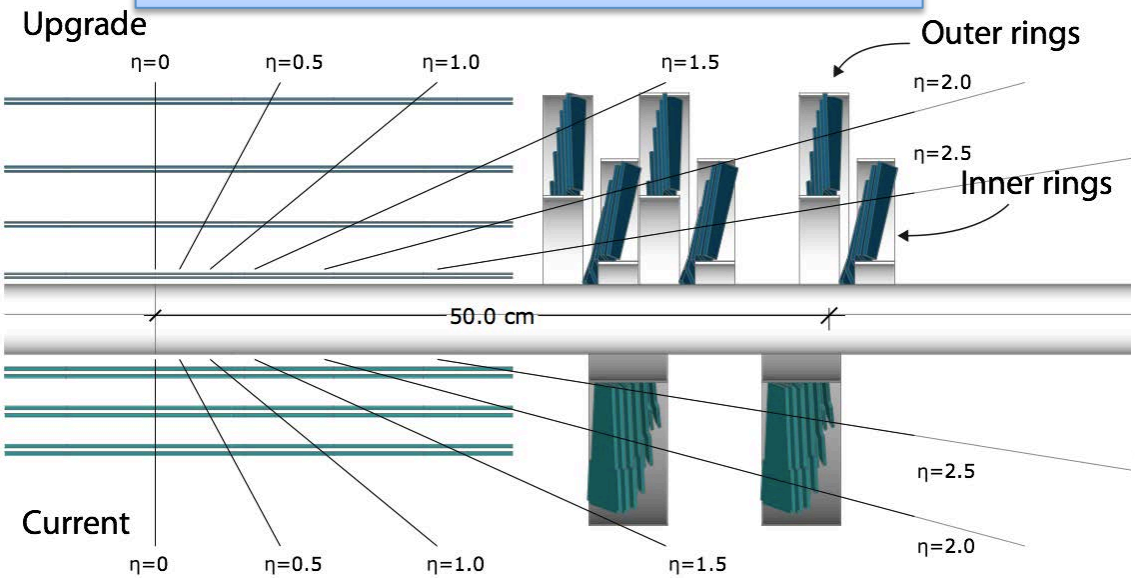
Trigger/DAQ
- L1 with tracks & up to 1 MHz
- Latency ≥ 10μs
- HLT output up to 10 kHz

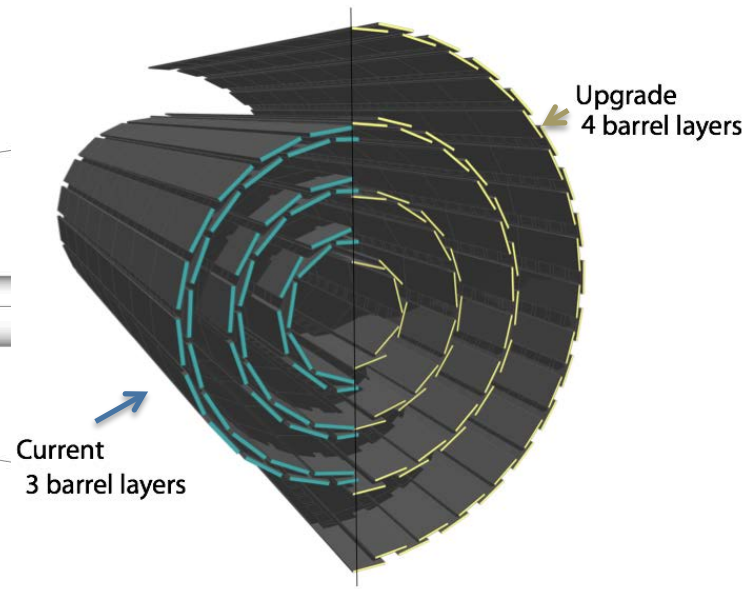
https://cds.cern.ch/record/1605208/files/CERN-RRB-2013-124.pdf

# Phase 1 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

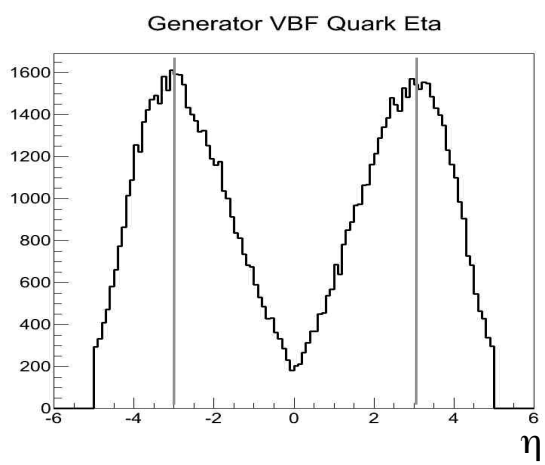
# Longevity of the Phase 1 Detector

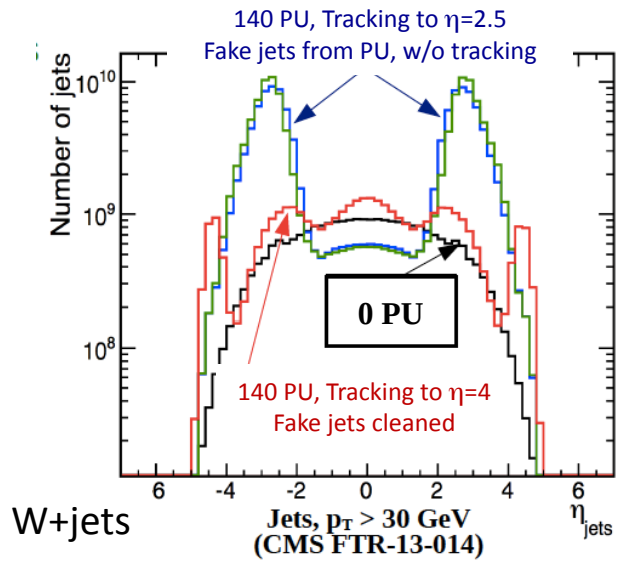
- **Extensive studies of radiation damage for the present detector**
  - Detailed analysis of aging experienced in 2012 & dedicated radiation exposures
  - Damage models developed and benchmarked to data
  - Incorporated into the full simulation of the detector for physics studies
- **Tracker:** Must replace
  - Limitation is leakage current. Cold operation is essential.
  - Tracker will survive to 500 $fb^{-1}$ if operated at -20$^{\circ}$C, but will lose a significant fraction of modules beyond
- **ECAL**: Must replace Endcap Electromagnetic calorimeter
  - Barrel survives to 3000 $fb^{-1}$, but light transmission in the in Endcap drops to few % at high $\eta$, resulting in significant loss of resolution
  - Have extensively investigated ideas for enhanced annealing and/or partial replacement. No solution
- **HCAL**: Must replace/rebuild Endcap Hadron calorimeter
  - Barrel survives to 3000 $fb^{-1}$ (just). Endcap light yield drops to few % over large part of calorimeter by LS3

# 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

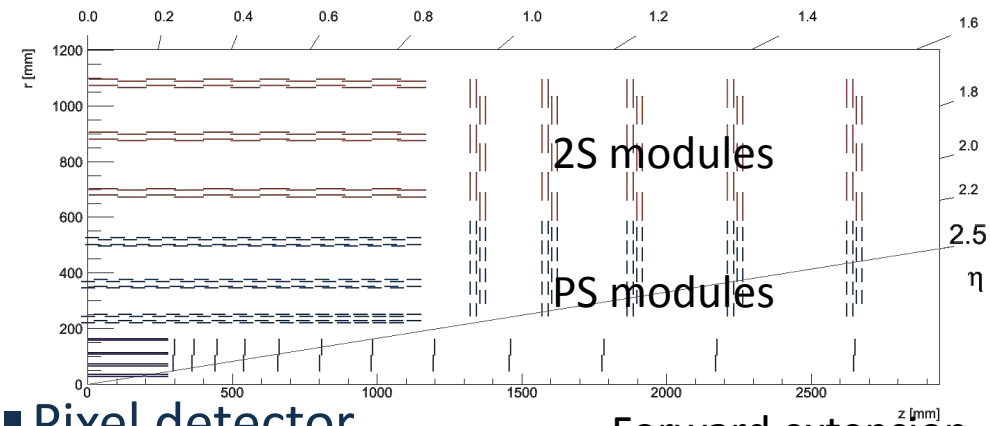
- **Trigger rates will be a major issue. Thresholds for Higgs are well understood. Increasing thresholds will lose physics acceptance**
  - Increase latency to 10μs to allow integrating tracking into all L1 trigger objects
    - improves lepton id, isolation, & PU mitigation through vertex association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

# Phase 2 Upgrades

# Phase 2 Tracker

US: extensive engagement and expertise in Tracker and Track Trigger

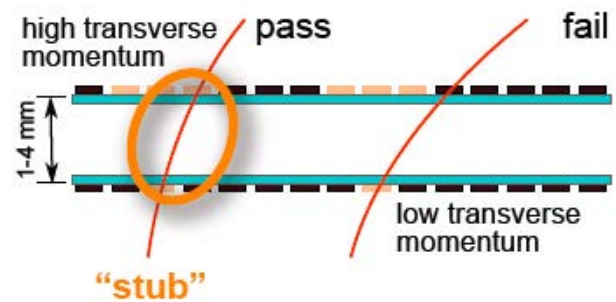
- Outer tracker
  - High granularity: efficient track reconstruction to beyond 140 PU
  - Two-layer "$p_T$-modules" to provide trigger
    - Information at 40 MHz for tracks with $p_T \geq 2$ GeV
  - Improved material budget



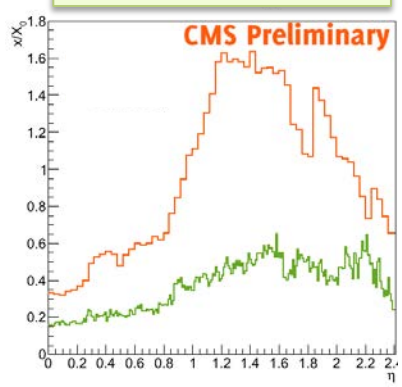

Forward extension

- Pixel detector
  - Similar config as Phase 1, with disks to high η -
  - Thin sensors 100 µm; smaller pixels 30 x 100 µm
  - New ROC, test rad. hardness
- R&D activities
  - All components, prototyping of modules ongoing
  - Track-trigger with Associative Memories, alternatives

Trigger track selection in FE

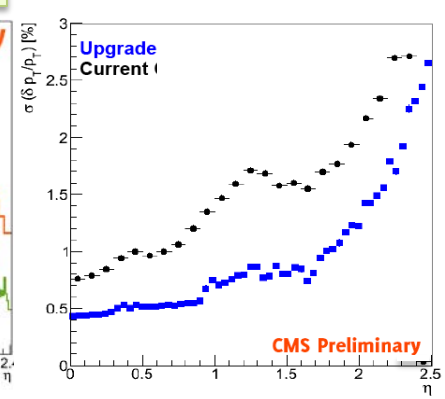



Outer tracker material
Phase 1 & Phase 2

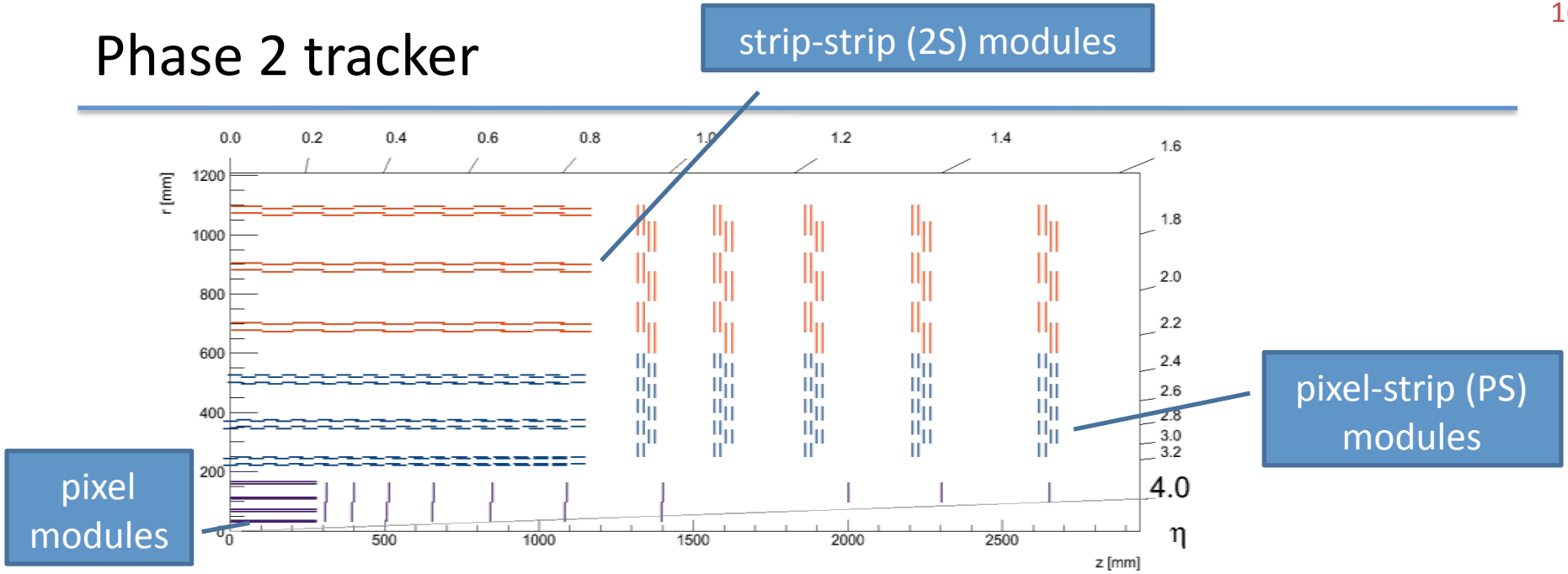



$P_T$ resolution

Single µ $p_T$=10 GeV/c
Transverse momentum resolution



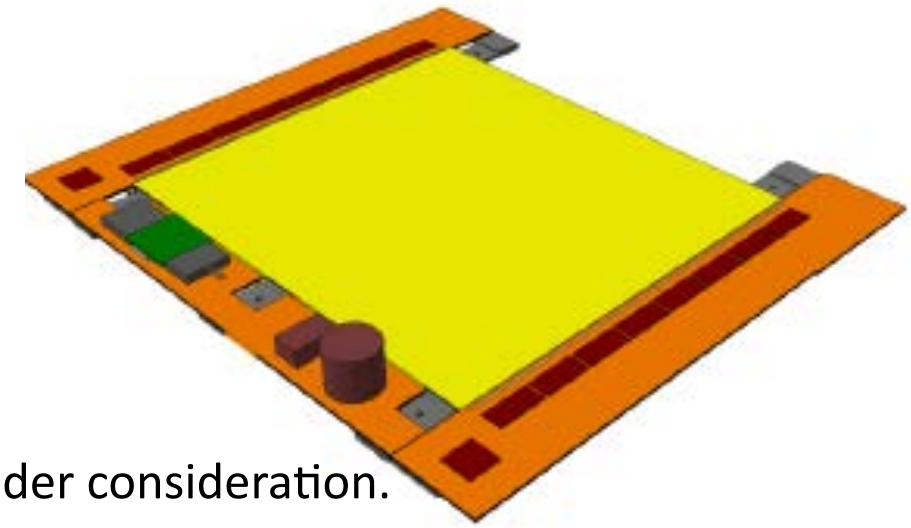
# Phase 2 tracker

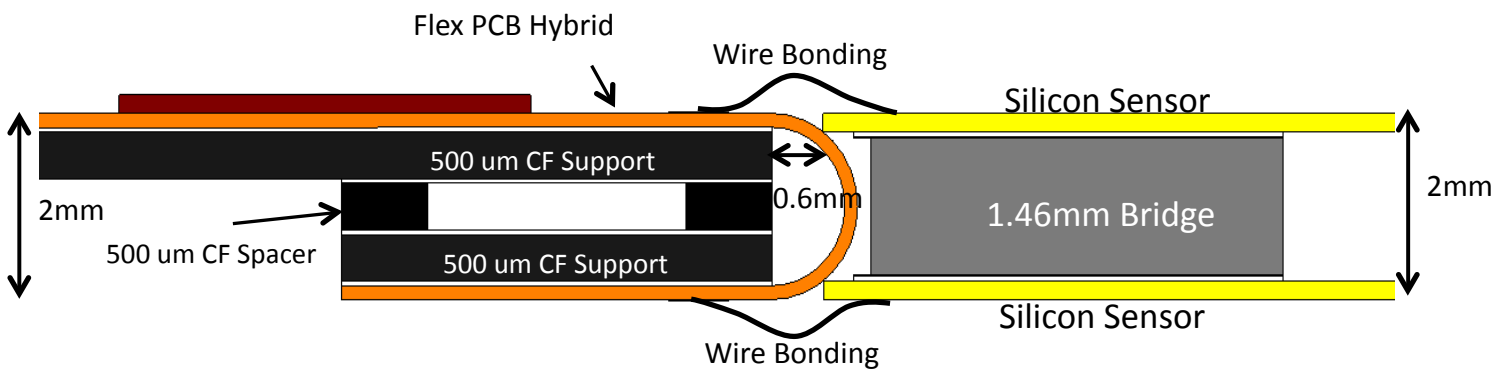



| | 2S modules | PS modules |
|---|---|---|
| radial position | R > 60 cm | 20 < R < 60 cm |
| fluence | $7\times10^{14} n_{eq}/cm^2$ | $1.6\times10^{15} n_{eq}/cm^2$ |
| dose | 80 kGy | 500 kGy |
| sensor area | 10x10 cm² | 5x10 cm² |
| sensor type | AC coupled strips | AC coupled strips |
| z segmentation | 2 rows | 2 rows |
| cell size | 90 µm × 5 cm | 100 µm × 2.5 cm |

# Outer Tracker (2S modules)

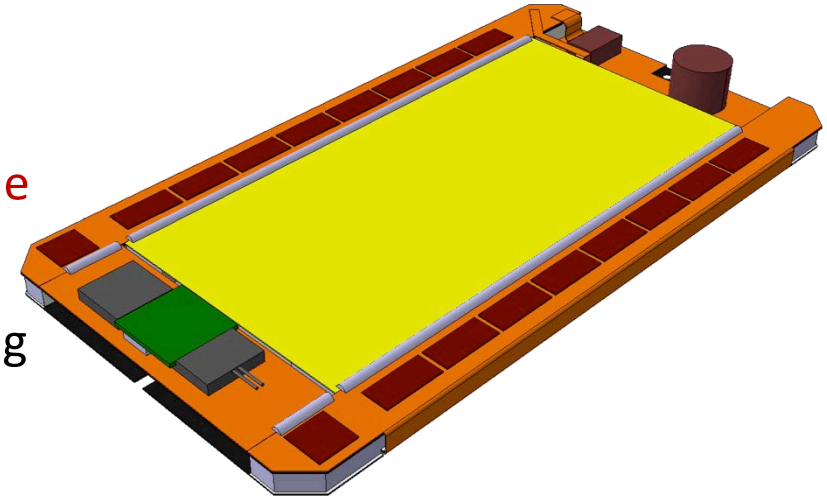
- 2S Modules – doublet of 2x5 cm strips
- 2S design well-advanced
  - CBC chip in UK
  - Module design and prototyping at CERN
  - Module mechanics – CERN/DESY
  - US involvement in design/prototypes under consideration.
  - Sensors – Austria, Germany

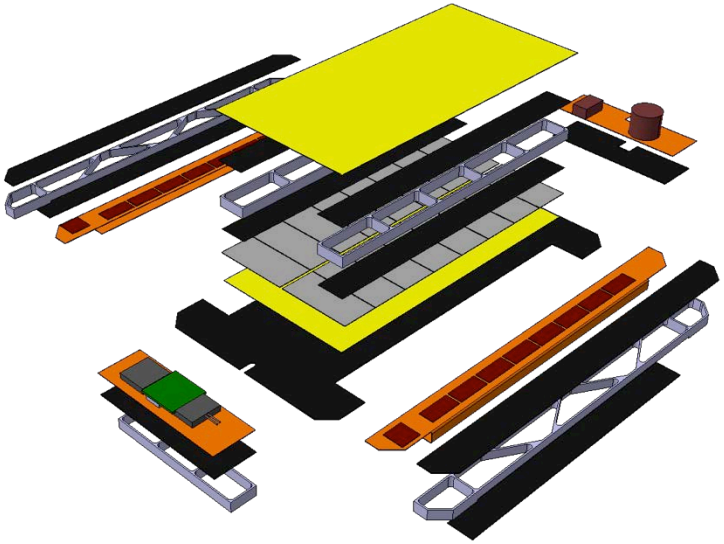




# PS Module

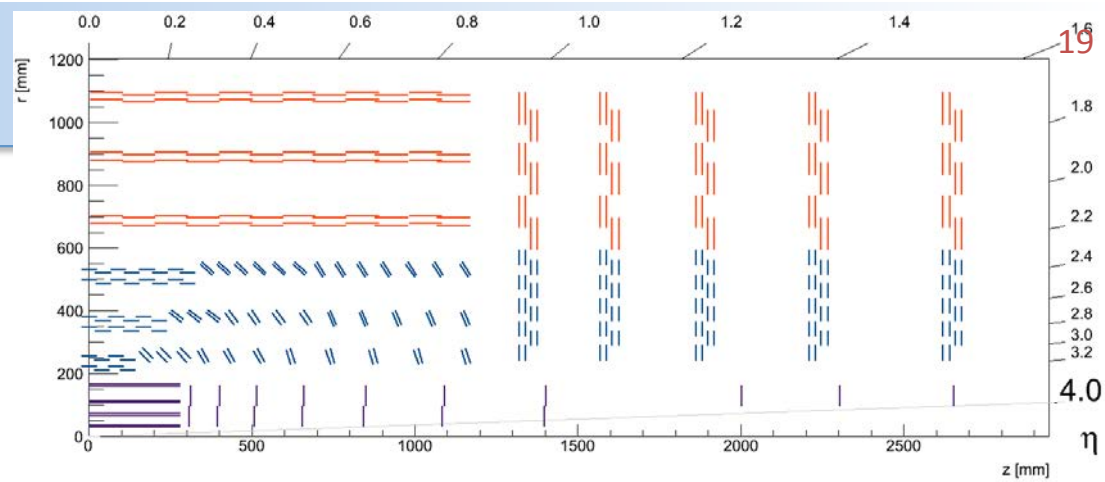
- PS more complex – lots of pieces to the module
  - Design still evolving
  - Looking at carbon foams and thermal testing
- PS chip developed at CERN
  - Initial stage will be small "MaPSA-lite" module
  - US developing dummy assemblies
- Sensor development
  - Thin (200 μ)n-on-p sensors
  - Sensor manufacture @ Infineon, HPK





# Tilted Barrel

- Proposed new geometry
  - Reduces number of modules
  - Complex mechanical support
  - How does it affect L1 track finding?
  - US involvement in the engineering design/prototypes under consideration.



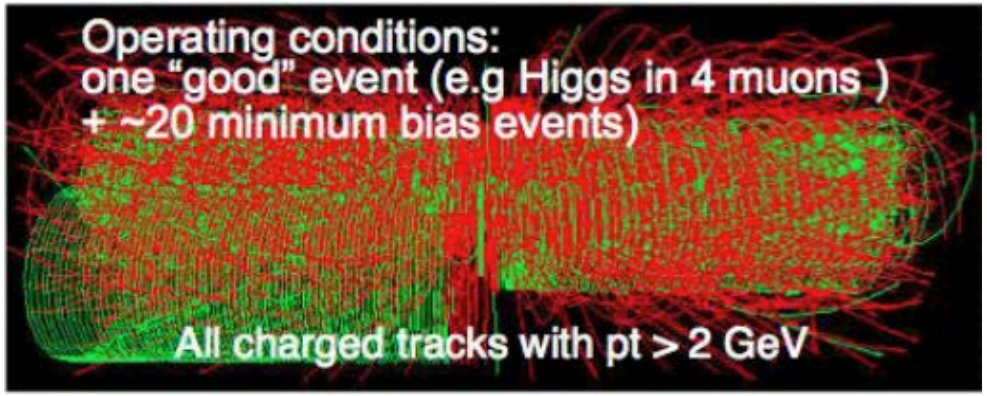
# Track Trigger

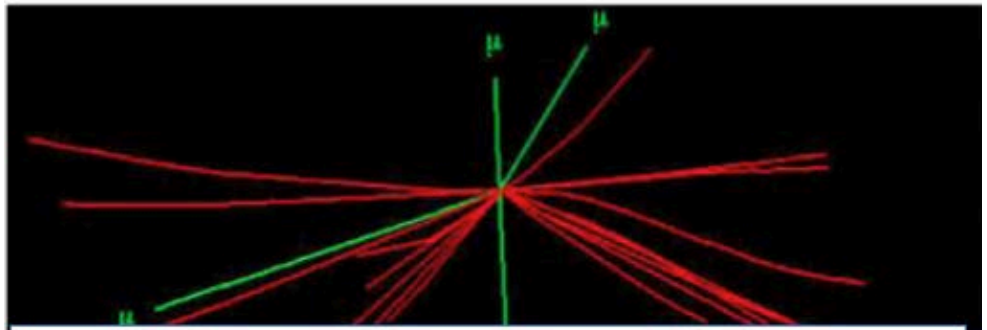
***Silicon based tracking trigger at L1 will be crucial for trigger objects reconstruction at higher luminosity:***

- Electron, Photon, Muon, Tau, Jets
- b-jets, missing ET …. Essential for establishing nature of EWSB, new physics …

*CMS L1 Tracking Trigger:*
*Will need to reconstruct charged particle trajectories "on-the-fly" for every beam crossing (25 ns, or 40 Million beam crossings per second), from an ocean of input data (bandwidth required to transfer up to ~ 50-100Tb/s)*
*This requires extremely fast high bandwidth data communication as well as massive pattern recognition power, with lots of known patterns to be compared against the multiple input data streams simultaneously with near zero latency (~ few μs)* ***This is challenging!***

**140 PU events - only 20 shown here**



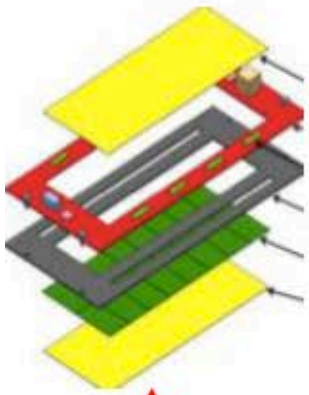
Impact of track reconstruction at L1

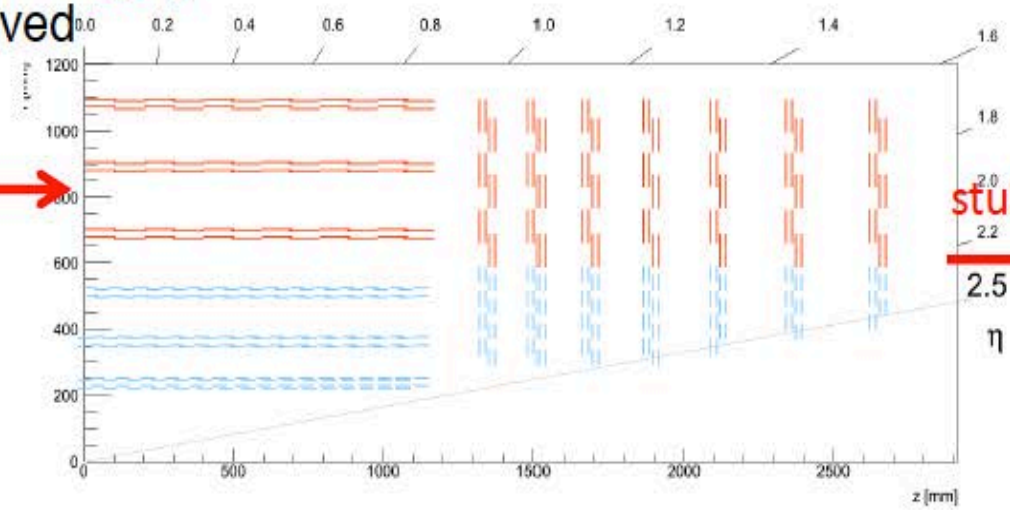
# Module design vs Tracker design vs Trigger Processing

Module Design | Tracker Design | Track Finding

*Pt stub finding reduce the data volume by ~ 10-20, making it possible to transfer the data out for off-detector L1 track finding*

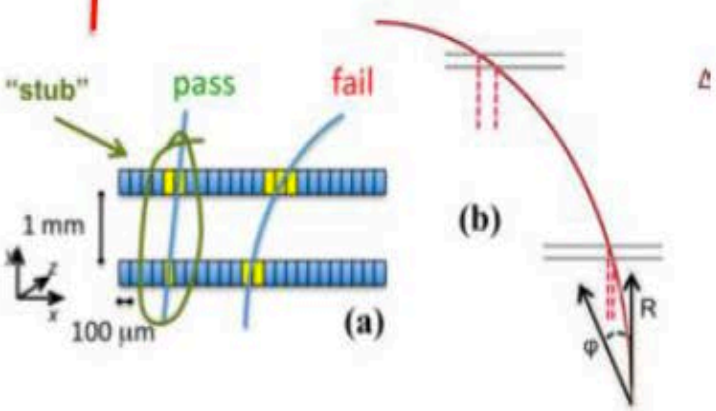
~15K modules involved






Back-end
Off-detector
Track Finding

*CMS new tracker design*



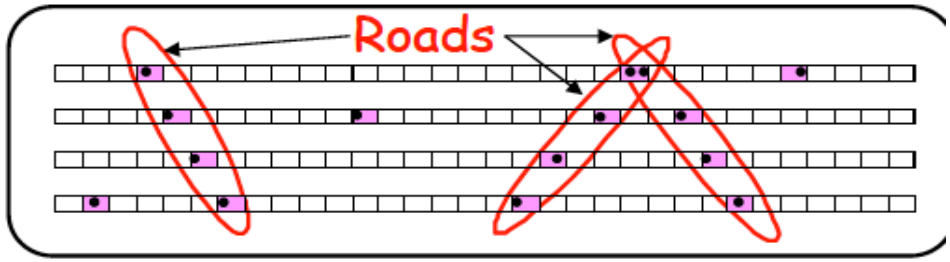

***Working assumptions:***

~15K fibers to trigger,
3.2Gbps payload each,
~ 50 Tbps input bandwidth

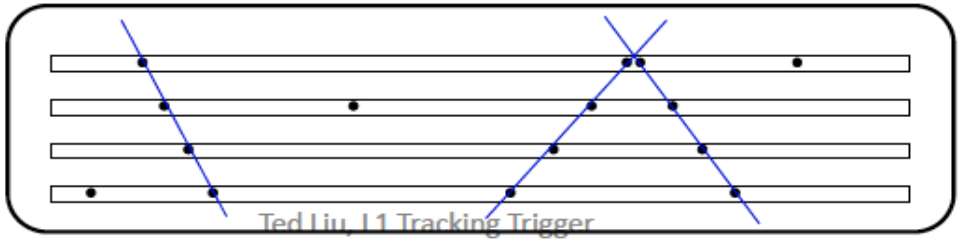
Block synchronous data transfer scheme …

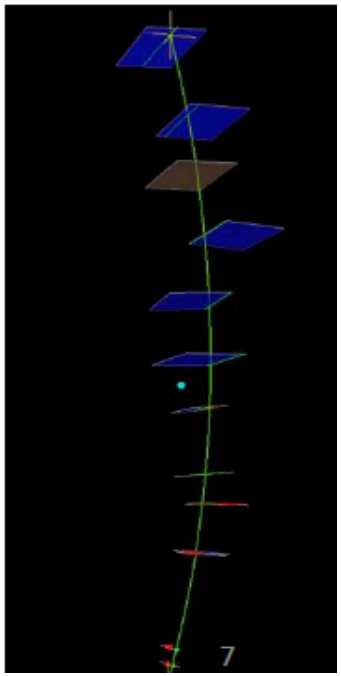
# Associative Memory + FPGA

Pattern Recognition
Associative Memory
approach



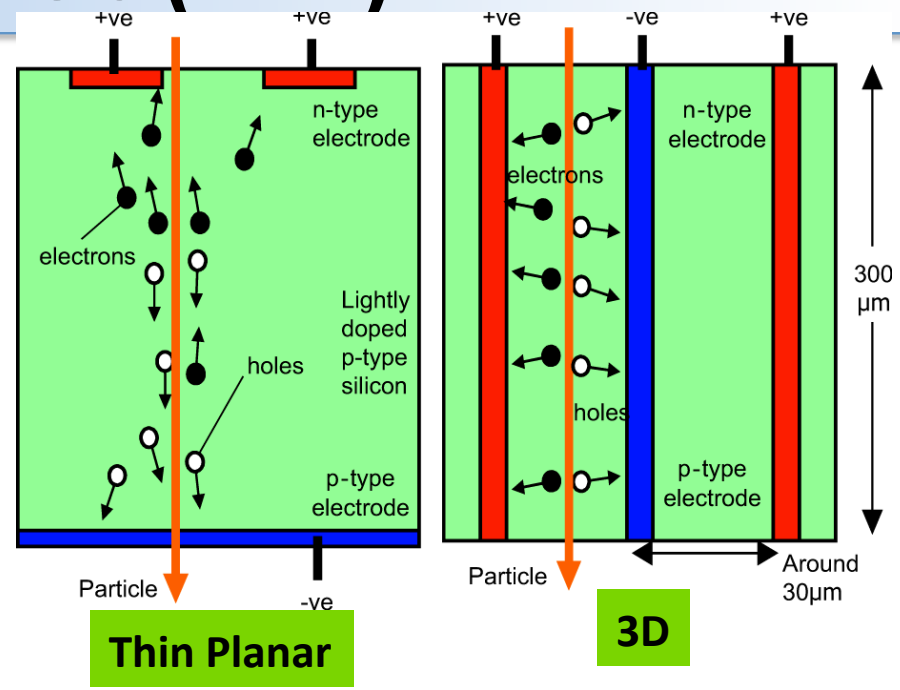

- Pattern Recognition using Associative Memory (AM):
  - Massive parallel processing to tackle the intrinsically complex combinatorics of track finding algorithms, *avoiding the typical power law dependance of execution time on occupancy*
  - solving the pattern recognition in times roughly proportional to the number of hits, making the downstream task much easier
  - Usually requires custom ASIC
- The Track Fitting stage (in FPGA) after AM:
  - Examples: linearized track fitting, Hough transform … etc
  - The more powerful the AM stage, the less demand on TF/FPGA
  - The more powerful the TF/FPGA, the less demand on AM

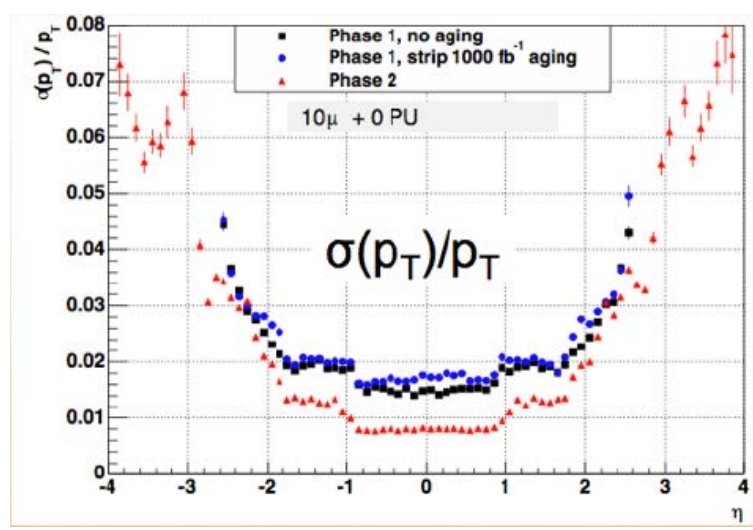




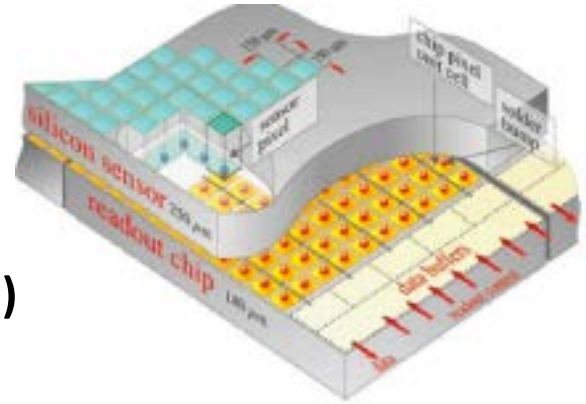
# Forward Pixels (FPIX)

- Radiation tolerance is a big issue: Thin planar sensors (~150um); very fine pixel pitch (25x100um, or 50x50um). Tested sensors from HPK.
- 3D sensors are another option, diamonds etc. should be paid attention to – follow advances in (RD42). Several 3D sensors characterized, tested in FNAL test beam.
- Preserve detector-on-rails idea so that inner layer(s) could be replaced during YETs
- Design is Phase-1 type design of 4 BPIX and 3 FPIX, then consider adding 7 extra forward disks to extend coverage from eta of 2.5 all the way to 4.0
- **Still very much in the R&D phase**. Design is not yet finalized.
- Simulations are well underway, but have established tracking performance with 140 PU.



# FPIX Readout Chips (ROC)




- Critical to improve the radiation hardness + the threshold.
- **Extremely challenging requirements (ATLAS/CMS)**
- Small pixels: 50x50um (25x100um)
- Large chips: >2cm x 2cm ( ~1 billion transistors)
- Hit rates: ~2 GHz/cm$^2$
- Radiation: 1 GRad, $10^{16}$ neutrons/cm$^2$**(unprecedented)**
- Trigger: 1MHz, 10us (~100x buffering and readout

- Low power -Low mass systems
- Baseline technology: 65nm CMOS (high Density/low power) – used in industry/auto.
- Full scale demonstrator pixel chip in 3 year R&D program – goal is a full sized pixel array chip in 2016, followed by pixel chip tests, radiation tests, beam tests, etc

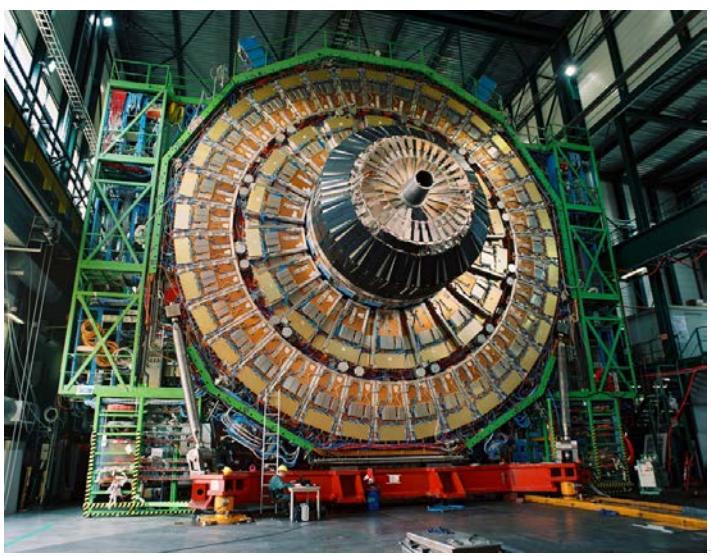
- There is also a ROC designed by FNAL for 30 x 100um pixels in 130nm process. It is 4.8 x 4.8 mm$^2$ with much lower threshold (~1000 electrons). Depending on the fabrication results, will try to move to 65 nm process.
- Another starting point could be the current PSI46dig chip (lower threshold < 2000 electrons) but ported to 130nm.
- Anecdotal evidence that 130nm is more radiation hard than 65nm, but this requires further study – radiation tests ongoing.
- **Very much a R&D program.**

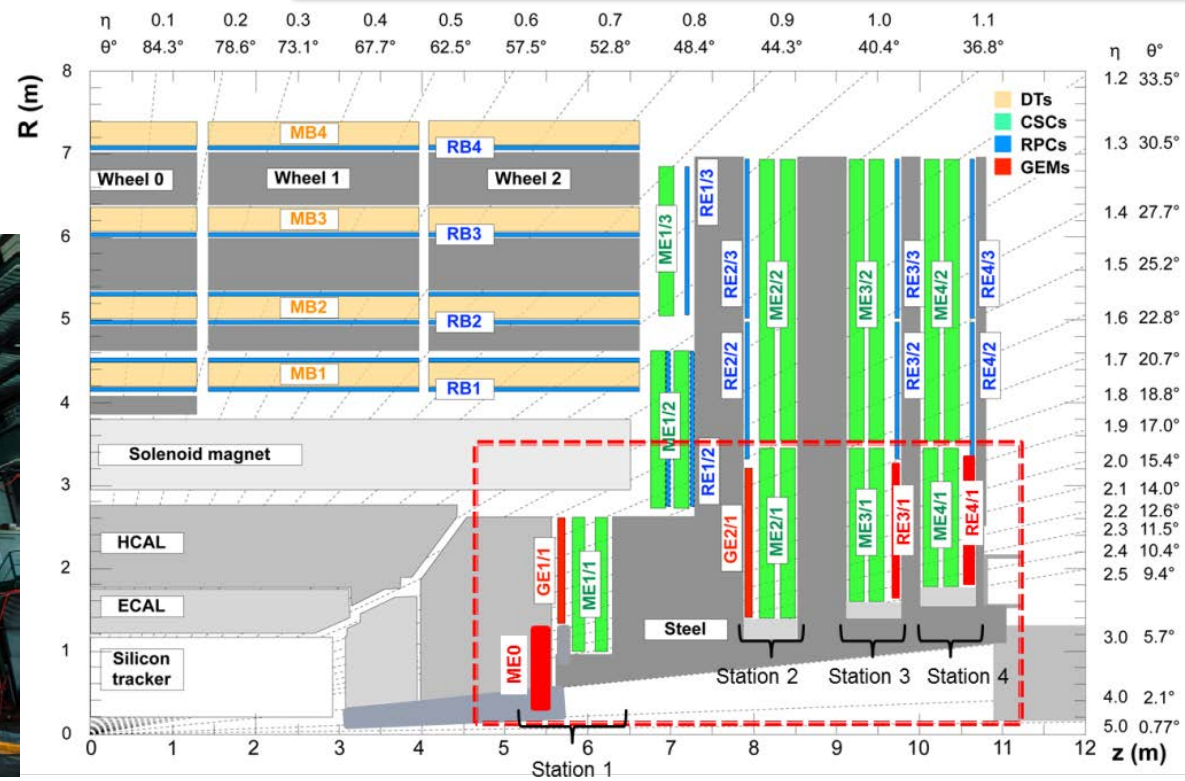
# Forward muon system

- **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 < |η| < 2.4
    - GEM / Glass-RPC
  - Investigating muon tagging beyond |η| = 2.4

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

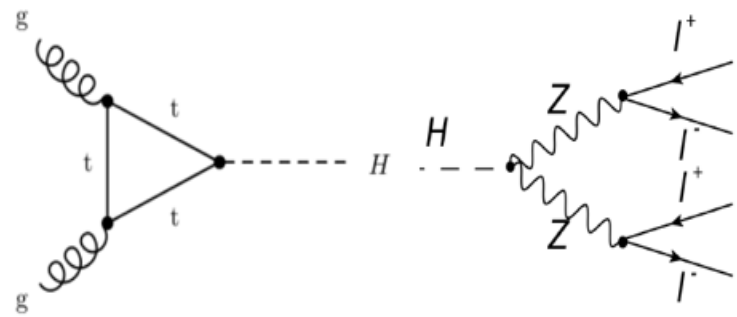
- **R&D activities well underway in CMS for GEM and Glass-RPCs**





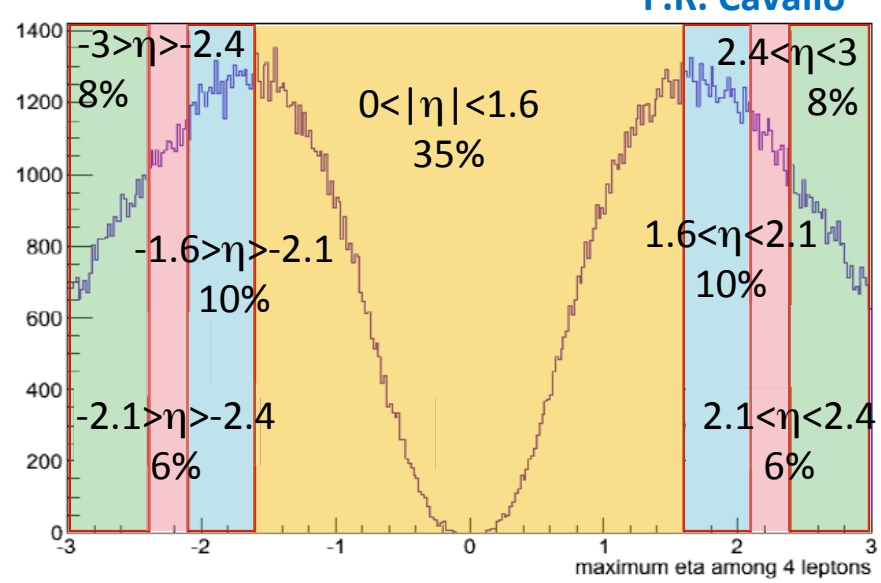
# Motivations for muon extension

- **Tagging for |η|>2.4**
  - With tracking coverage to η=4, and with coverage of endcap to η=4, it's quite a bargain to verify muons over 1.6 units of eta with a single muon station.




  - H→4μ acceptance increase ~30% for η coverage to 3.5, ~40% for η to 4.0
    - With endcap only to 3.0, the physics gains can still be substantial

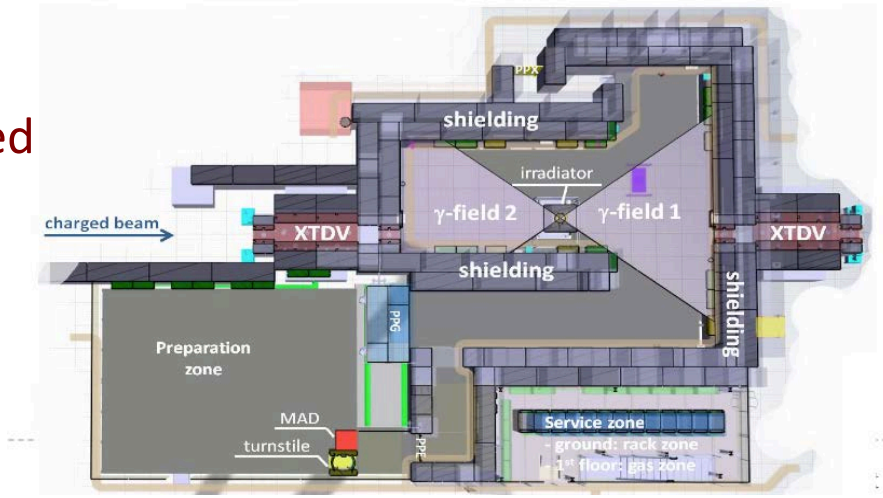
F.R. Cavallo



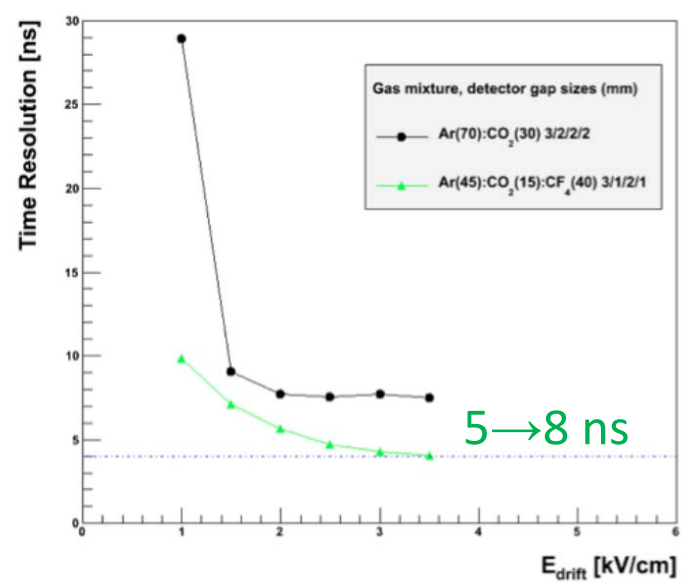
# Muon upgrades (3-fold)

## 1. Consolidation

- RPC, CSC, DT, GEM chambers to be tested for aging at 5x higher rates/6x higher doses in the GIF++ facility starting early 2015



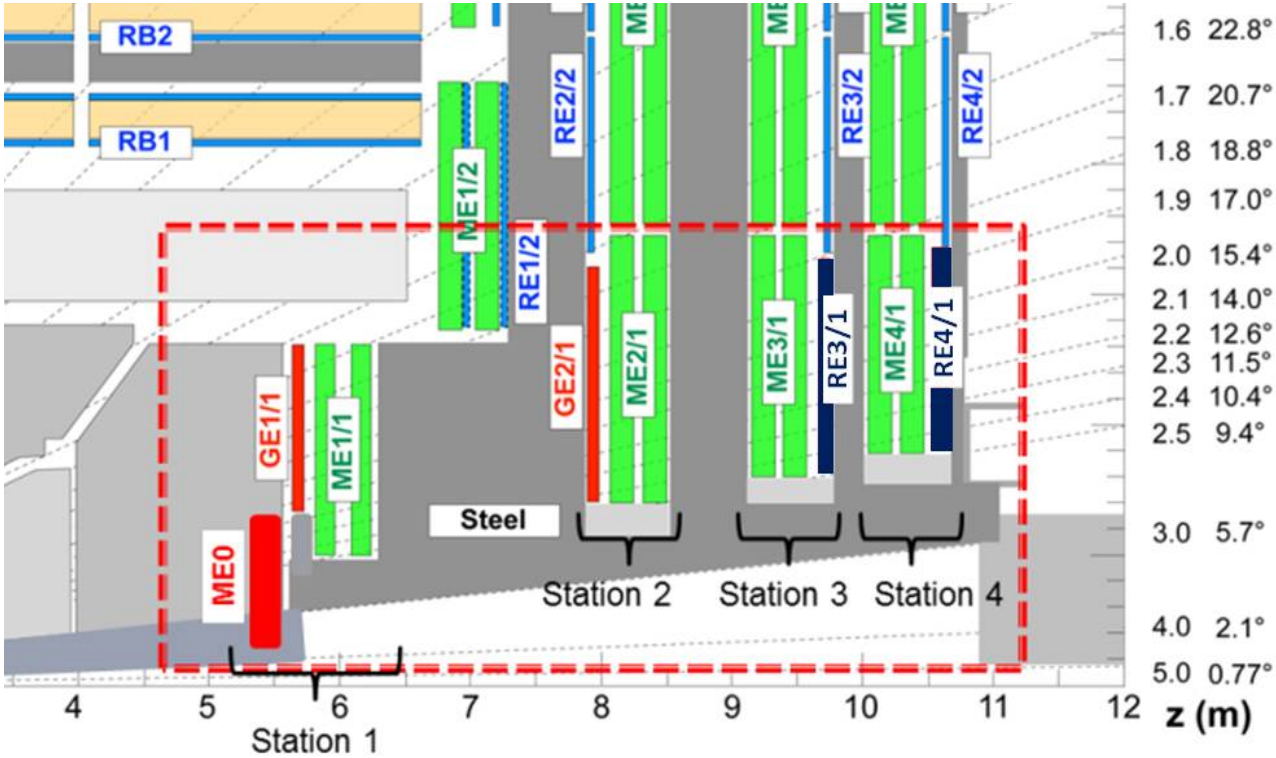

- RPC eco-friendly gas studies (non-trivial!) Replace a small number of leaking barrel chambers?
- $CF_4$ in CSC (10%) and GEM (40%) gas mixtures; in CSC to reduce aging, in GEM to reduce drift times



# Muon Enhancement

## 2. Muon enhancement in forward 1.6<|η|<2.4 region

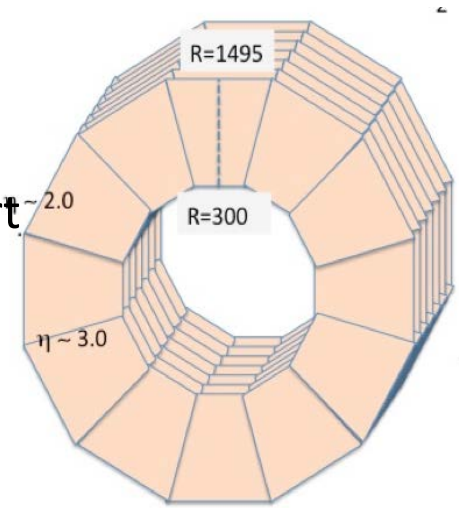
- Addition of small GEM and RPC muon detectors in all four stations; GEMs two layers, RPC one layer (double-gap)
- For redundancy and trigger

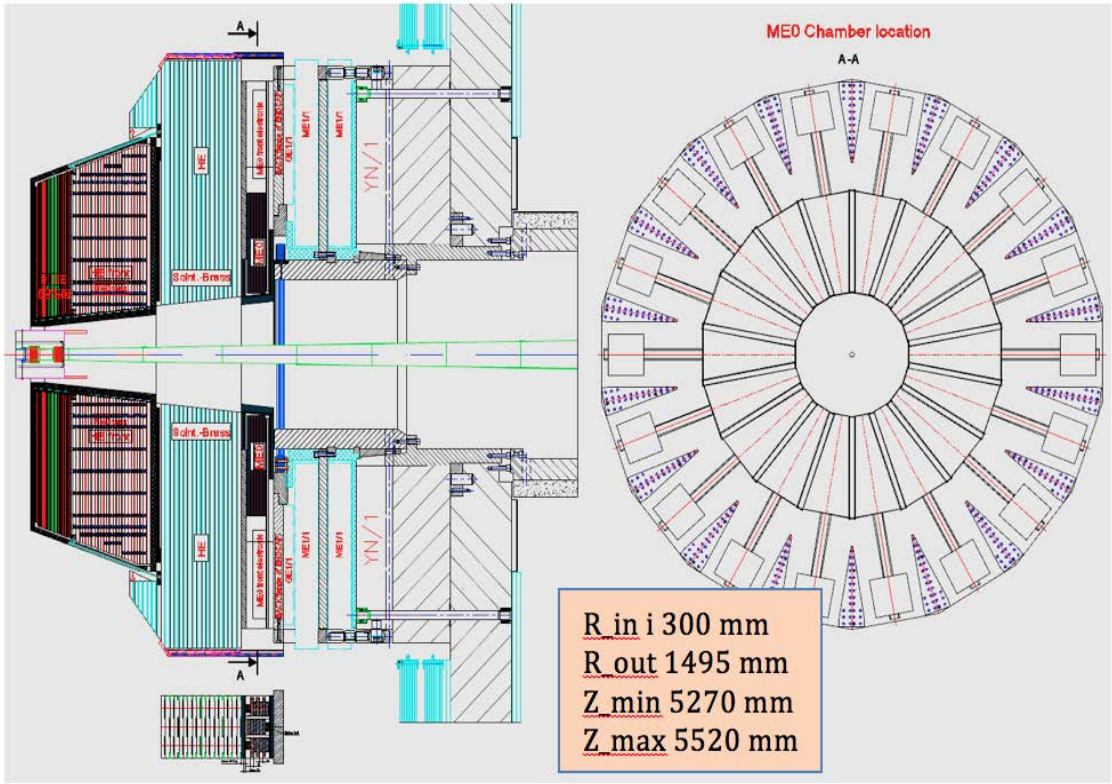


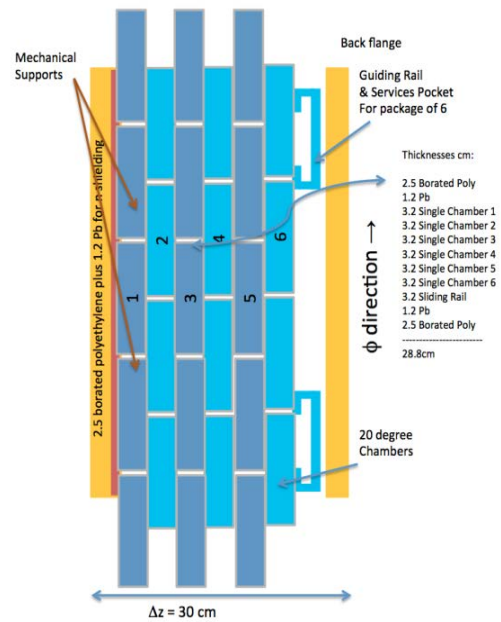
# Muon Extension

## 3. Muon extension of coverage |η|>2.4

- ME0: one GEM station in back of rebuilt endcap
- Min |η|: have to contend with services, mechanical support
- Max |η|: cover as much as possible modulo inner shielding
- Six layers to cope with backgrounds by analogy with CSC



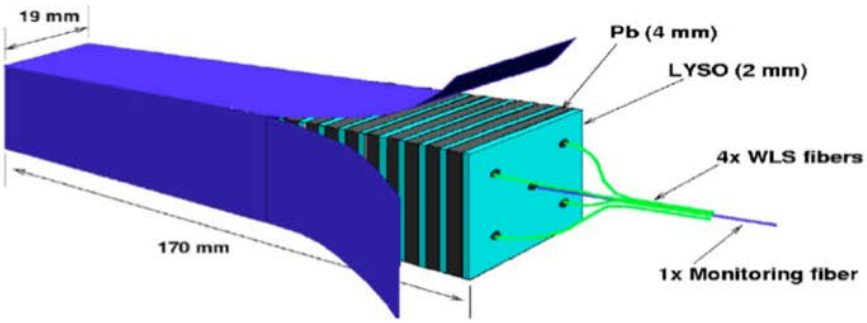



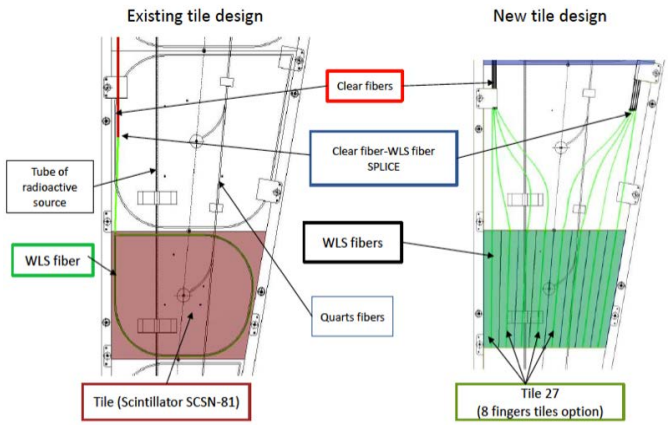
# Phase 2 Endcap Calorimetry

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

- Two approaches
- Maintain standard tower geometry - develop radiation tolerant solutions for 3000 $fb^{-1}$
  - **Shashlik** EE towers (crystal scintillator: LYSO, CeF3)
  - **HE rebuild** with more fibers, rad-hard scintillators



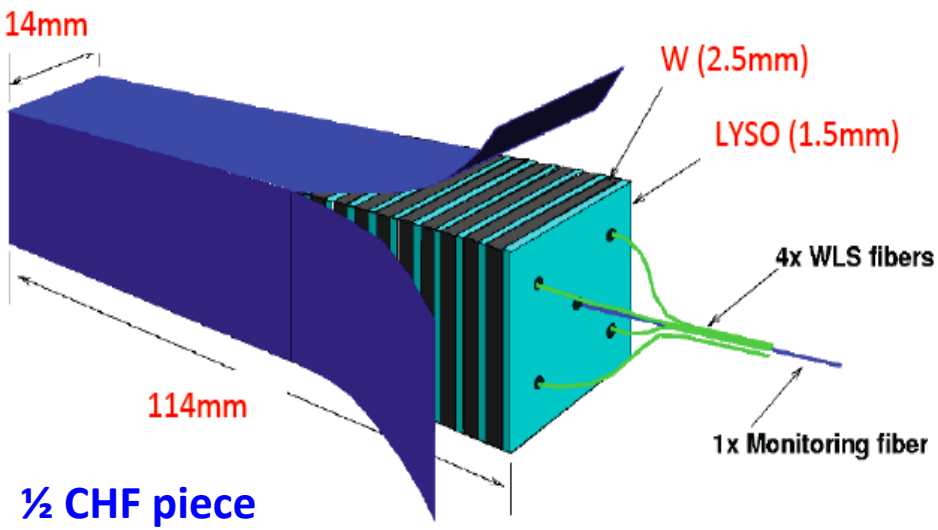

Hadron Endcap Rebuild




o R&D well underway

- Alternative geometry/concepts
  - **High Granularity Calorimeter** (HGCal)
  - Dual fiber read-out: scintillation & Cerenkov
    - ✓ **(Downselected @ Upgrade Week in Karlsruhe)**
- Explore options for PU mitigation with **fast timing**

# Shashlik Module




½ CHF piece

Materials:

- Absorber: W
- Active Material: LYSO(Ce) (primary)
- Active material: $CeF_3$ also under study

Structure:

- 2.5 mm W plates (28 per module)
- 1.5 mm LYSO(Ce) plates (29 per module)

Module Dimensions:

- Transverse Size: Front Face 14 x 14 $mm^2$
- Length 114 mm

Readout:

- WLS Capillaries (4 per module)
- Calibration Fiber (1 per module)
- GaInP Photosensors (4+1 per module)

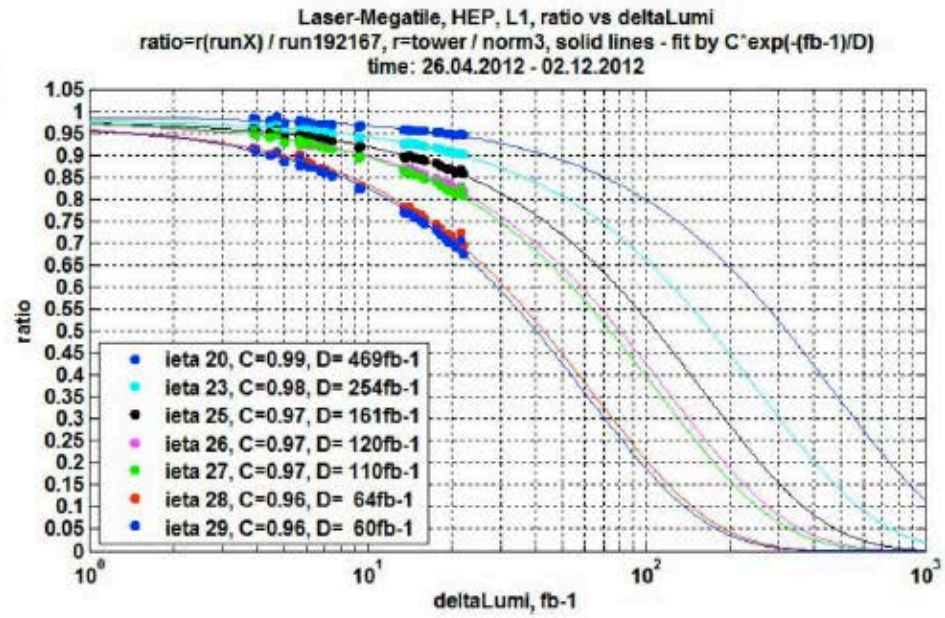
Segmentation in depth: Unsegmented except for the proposed extraction of a signal near shower max

**Shashlik module is very small to minimize pileup; essential a Moliere radius in size**

# HE Rebuild

- The current HE detector needs to be replaced during LS3
  - The analysis of the 2015-2016 data will show if an intervention is needed during LS2
- A new HE would be part of a separate-function calorimeter, combined with the shashlik EE
  - A brass+scintillator HE would be also necessary to cover the rear hadronic compartment of an HGCAL
  - Considering the possibility of a tungsten or brass extension to improve the performance of the current detector

**Laser data, HE layer 1**




**30% Light-yield loss after 22/fb**
**~10 times our prediction**

US CMS effort ongoing in four approaches
- Crystal fibers
- Plastic scintillators
- Liquid scintillator
- Coated quartz plates

# HGCAL – Silicon-based Calorimetry

Alternative to Shashlik and HE rebuild

Electromagnetic Calorimeter:

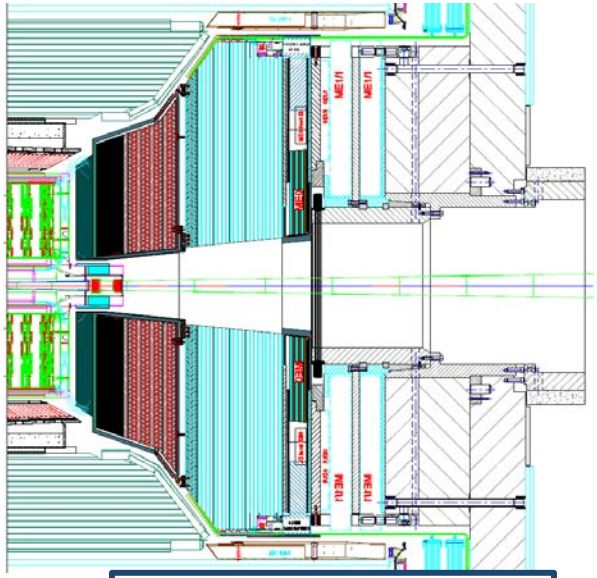
- 30 samplings of tungsten/lead/copper total of 25 $X_o$
  - 11 layers of 0.5 $X_o$/10 layers of 0.8 $X_o$/10 planes of 1.2 $X_o$.
  - Pad size 0.9 $cm^2$ for first 20 layers, 1.8 $cm^2$ for the last 10 layers.
- 420 $m^2$ of silicon pad detectors.
- **7M channels.**

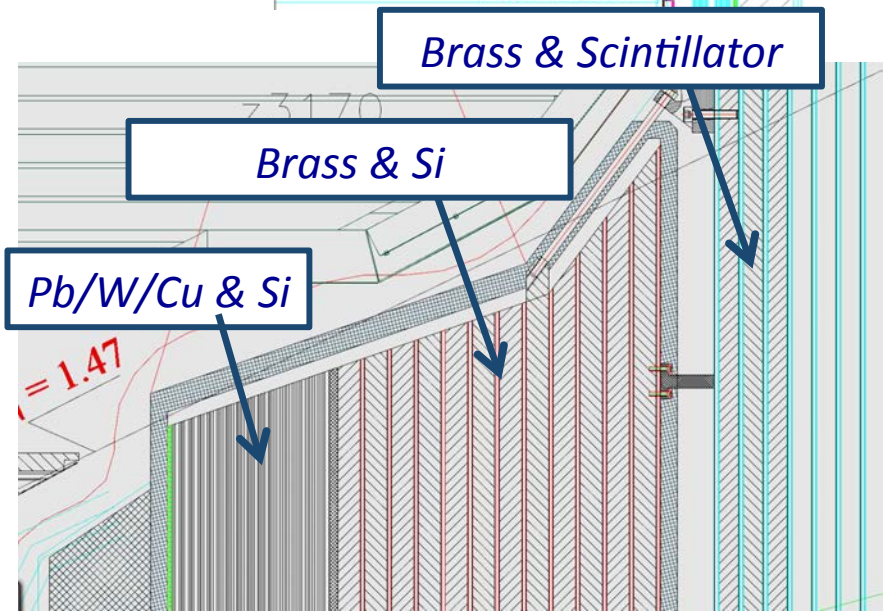
Front Hadronic Calorimeter

- 4 interaction lengths.
- 12 layers of brass/silicon each 0.33λ.
- Pad size is 1.8 $cm^2$
- **3M channels.**

Backing calorimeter

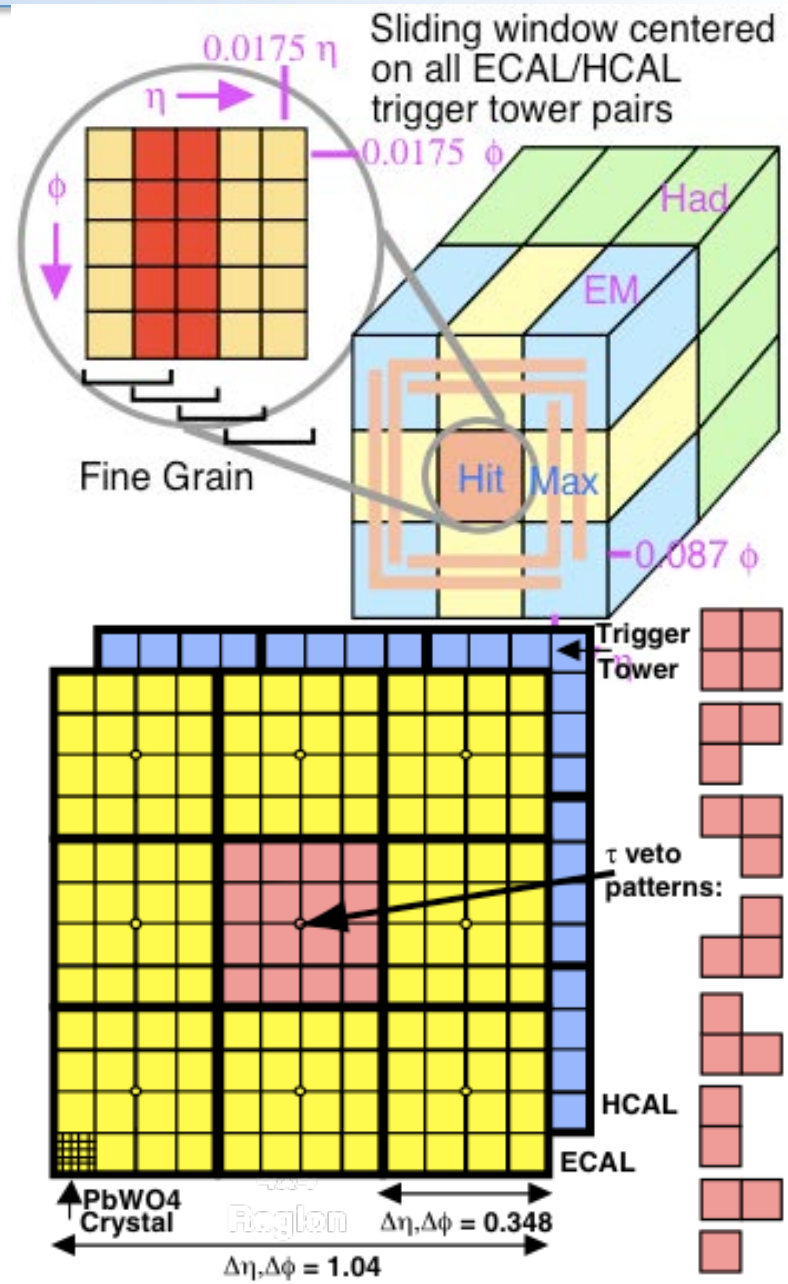
- Five interaction lengths (e.g. sampling of 0.5λ).
- Radiation levels are lower so can use plastic scintillator.





# CMS Phase 2 Trigger

- **Replace ECAL Barrel and Endcap Front End electronics**
  - Allows L1 latency of 10 – 20 μsec
  - Provides individual crystal level (not 5x5 sums) trigger information
    - ✓ Improved spike rejection in EB
- **L1 Accept rate of 500 kHz – 1 MHz**
  - Provides more acceptance and lower thresholds
- **Tracking Trigger**
  - Leptons: $P_T$ cut & isolation, Jets: Vertex
- **New L1 Trigger (Calorimeter, Muon, Global) to incorporate Track Trigger**
  - Finer calorimeter cluster trigger, muon & calorimeter seeds for track match
  - Also incorporate additional muon chambers for $|\eta| > 1.5$ (e.g. GEMs)
- **HLT Output Rate of 10 kHz**
  - Limit from Downstream Computing



# CMS Phase 2 Upgrade Planning

- Enable ramp up of US efforts on Phase 2 R&D as described in the Technical Proposal (2014).
- US should be involved in the targeted program where it matches our interest and capabilities.
- Organize along the lines of program with deliverables (ie rad hard fibers, etc.)
- Establish a good system to evaluate R&D progress.
- Maximize US participation and input to Phase 2 Technical Design Reports in 2016/17.

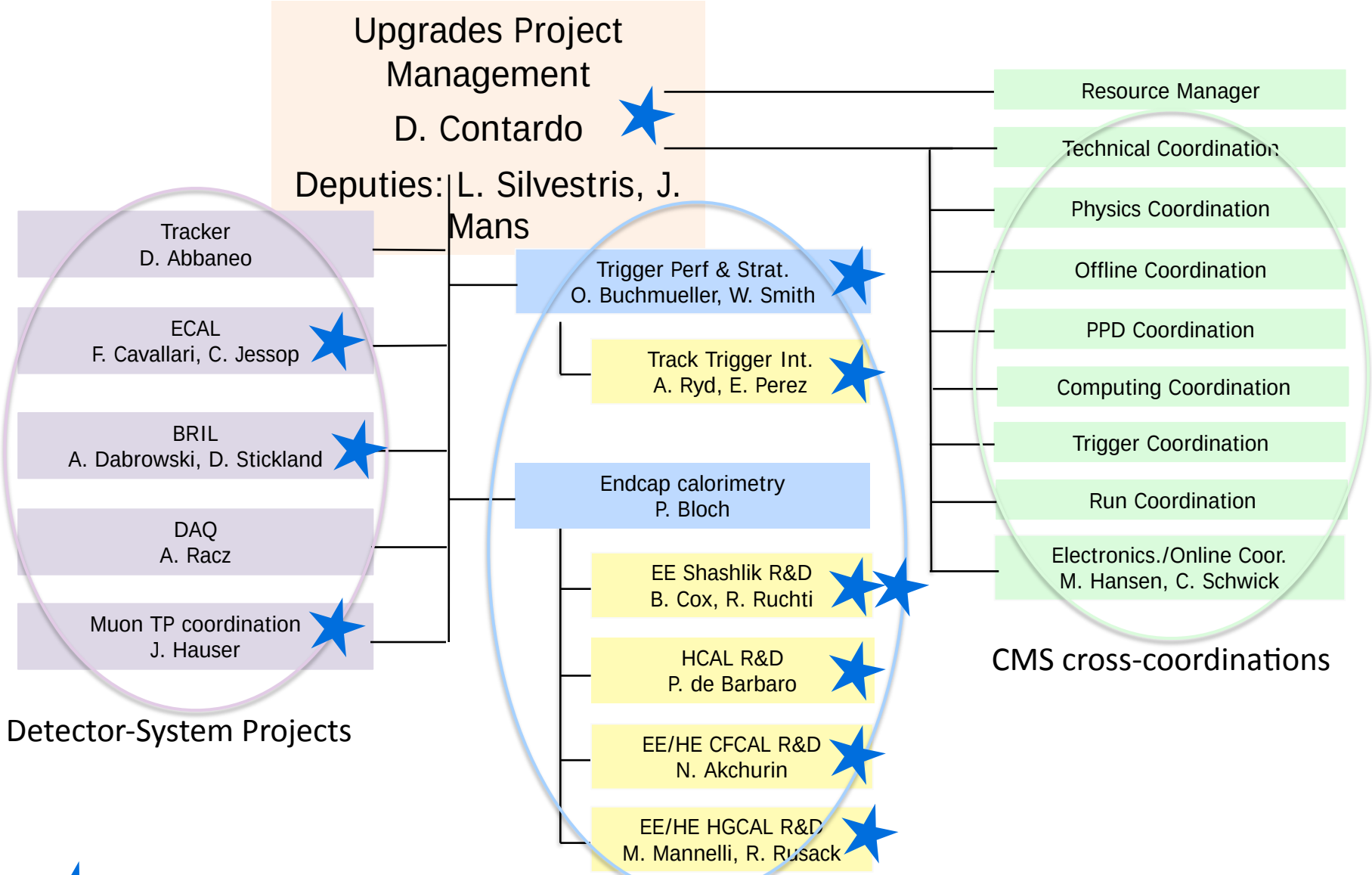
Subsystem (elected) Institution Board Representatives now serving as community organizers.

Lenny Spiegel: Tracker/Pixels + Track Trigger

Ivan Furic & Paul Karchin: Trigger/DAQ + Muons

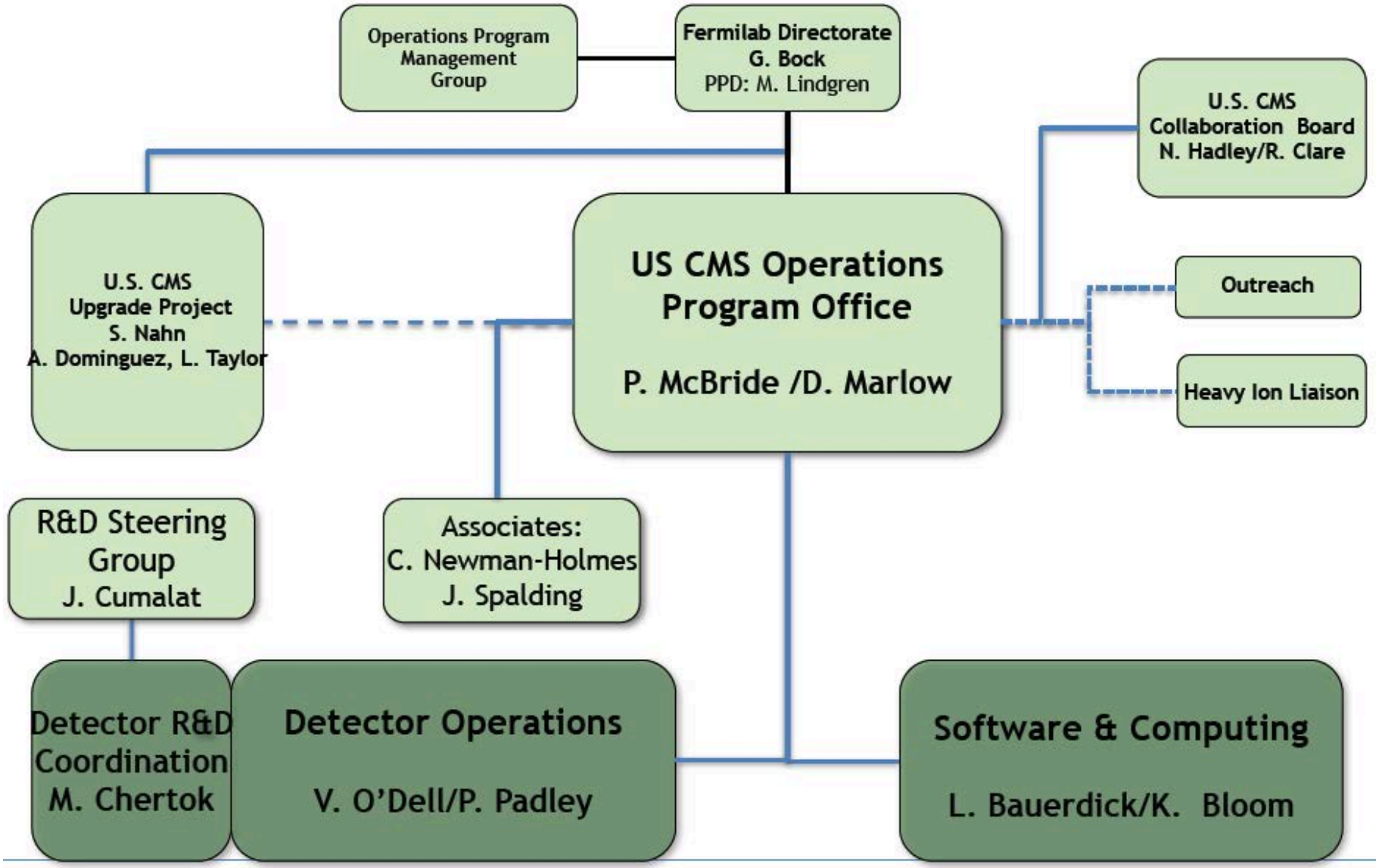
Manfred Paulini: Calorimetry/Fast Timing

# CMS Phase 2 Upgrade Organization




★ = U.S. CMS, several are Technical Proposal editors

# US CMS Management Overview



# Concluding Remarks

- Phase 2 Upgrade is essential to capitalize on the extensive physics potential of the HL-LHC
- Much to do!
- 2014 Phase 2 R&D funding decisions in place
  - Roughly 50% SOWs finalized and approved
  - Start next year's planning this summer, review recent R&D progress
- Engaging of U.S. CMS community in full swing
- CMS Phase 2 planning in parallel
  - Preparing technical proposal, expressions of interest from collaboration
  - U.S. CMS is in synch with this process
- Maximize U.S. CMS input to Technical Design Reports (2016/17) and beyond

# Backup Slides

# R&D Proposal Review Process

- **Timeline**: 2013: R&D Steering Committee formed. Call for LOI's: 33 received→detailed review comments, no downselect. Call for Proposals: 26 received. **Tough decisions necessary!**

- **4 Review committees** evaluated proposals regarding: **priority** for CMS upgrade, **US experience** and interest, **urgency** for 2014 funding, **impact** if funding delayed
- **Status**
  - Review committees submitted detailed reports, funding levels determined
  - Input from U.S. CMS Steering Committee and from CMS Upgrade Manager
  - PIs contacted with award amounts, asked to update budgets and R&D scope to match available funding
  - Many SOWs are now in place.

# Steering and Review Committees

- **R&D Steering Committee**
  - **Spiegel, Stuart, Cumalat (SC Chair), Jindariani, Karchin, Hill, Hauser, Paulini, Sulak, Bornheim, Anderson, Spalding, Furic, Smith, Marlow, Mcbride, Chertok, O'Dell, Newman-Holmes, Hadley, Bortoletto, Butler**
  - **A few names may change this year**
- **Review committees: (RED is Chair, BLUE is non-US)**

**EMU:** Karchin (IBR), Apollinari, DellaValle, Hill

**CALO/TIMING:** Sulak (IBR), Anderson, Butler, Hirosky, Jindariani, Tabarelli de Fatis, Spalding

**TRACKER/PIXEL:** Spiegel (IBR), Bacchetta, Christian, Stuart, Cumalat

**TRIGGER/DAQ:** Furic (IBR), Saltzberg, Buchmuller, Smith

Review committees did excellent work, so their reward will be more work

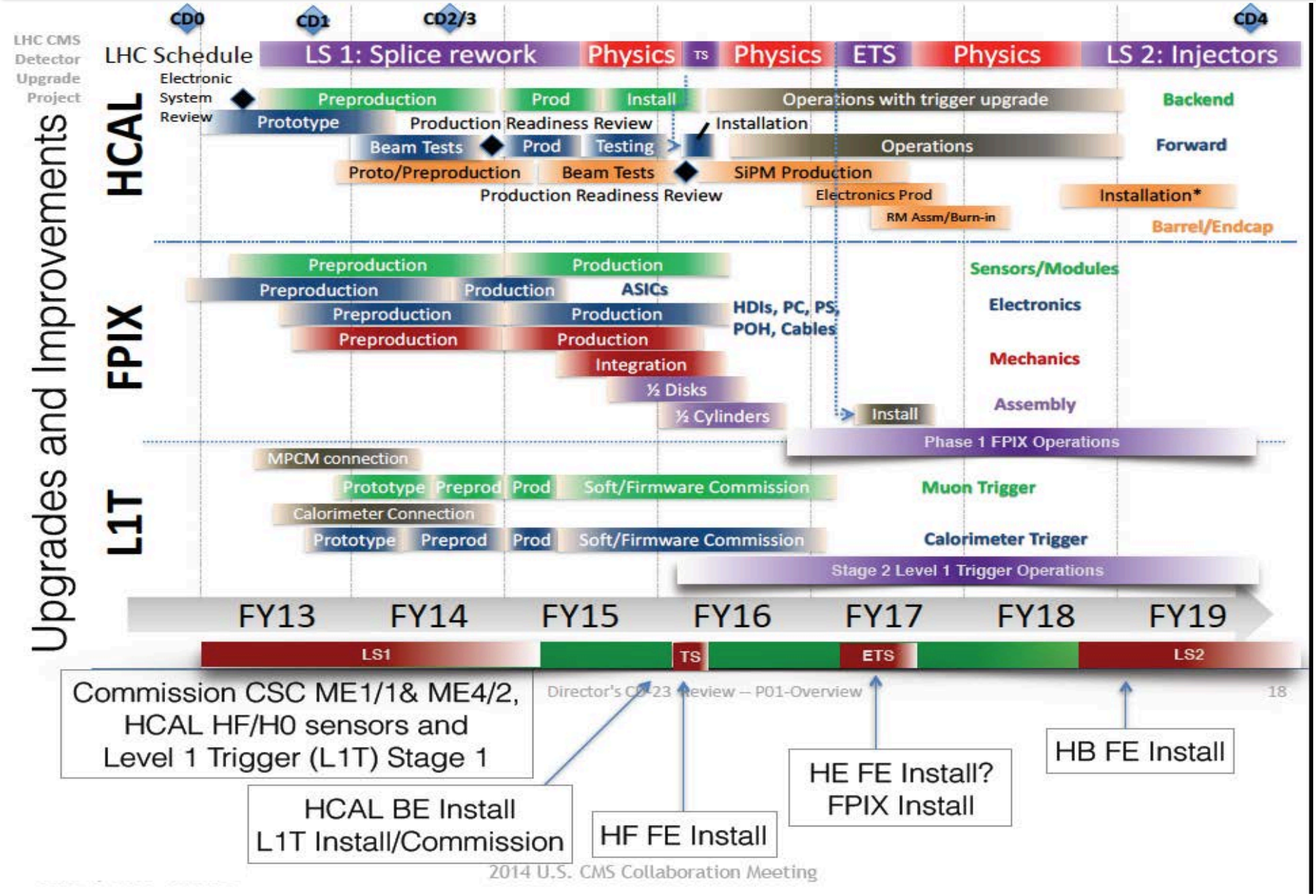
# Schedule for 2015 funding - for SC discussion

- June: Collaboration meeting, last week
- Aug 1: 2015 proposals and budgets due, send to review committees
- Aug-Sept: updates at Friday meetings, others
- Sept 15: review committee reports due
- Oct 1: Funding decisions
- Then, revised budgets, SOWs, ...

Goal: all funding in place 1/1/15

# LS1 and Phase 1

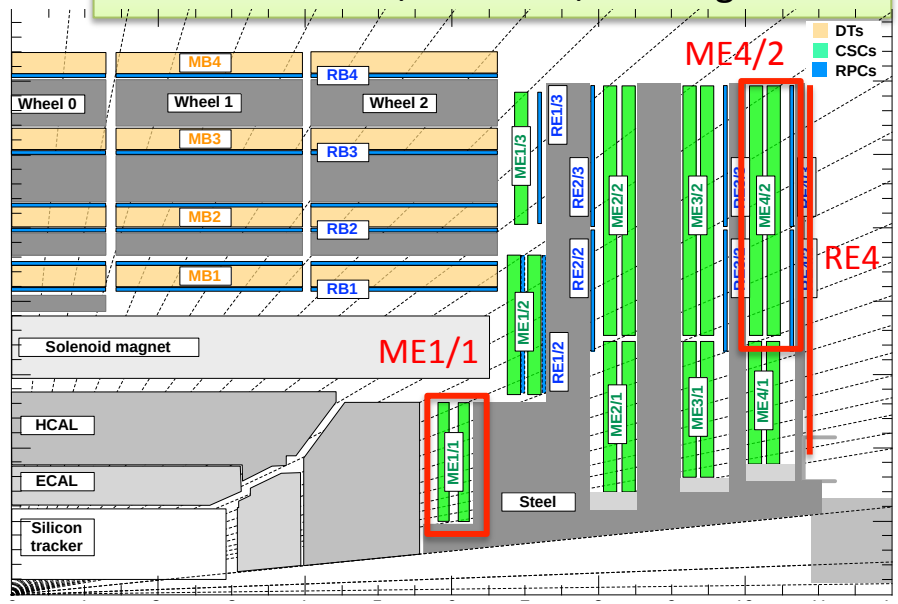
# LHC Schedule



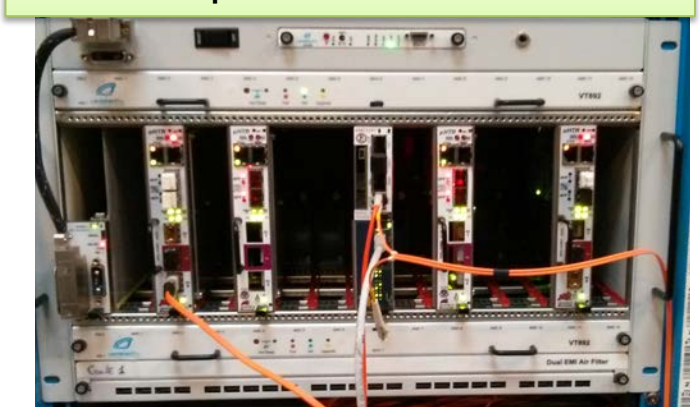
# Long Shutdown LS1 (2013-14)

- 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 (-20$^{o}$C 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$^{34}$ cm$^{-2}$s$^{-1}$
  - Muon endcap system
    - ME1/1 electronics (unganging) US
    - ME4/2 completion of stations & shielding
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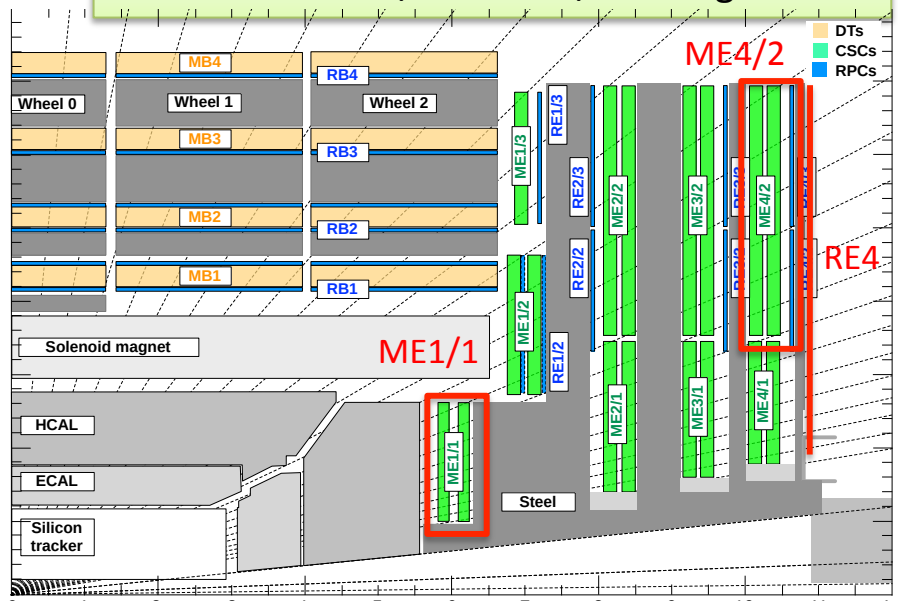



Slice test: µTCA BE electronics for HF

# L1 Trigger

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

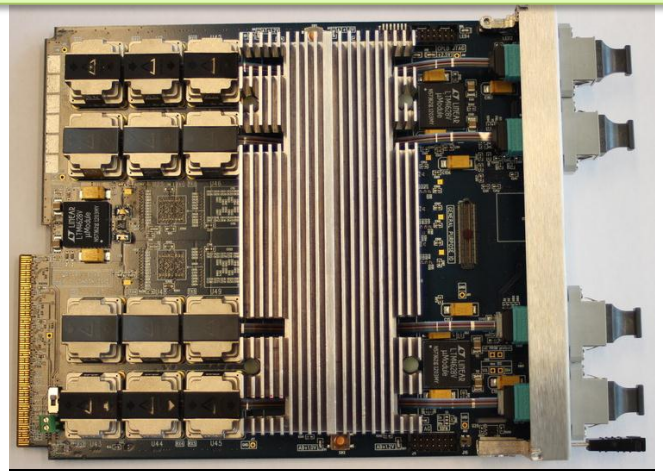
- Architecture based on powerful FPGAs and high bandwidth optical links
- Upgrade entire L1 Trigger: Calorimeter, Muon and Global
- **Based on only 3 types of boards – all using Virtex-7 FPGA** 2 of them developed in US
- Trigger inputs split during LS1 to allow full commissioning of new trigger in parallel 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

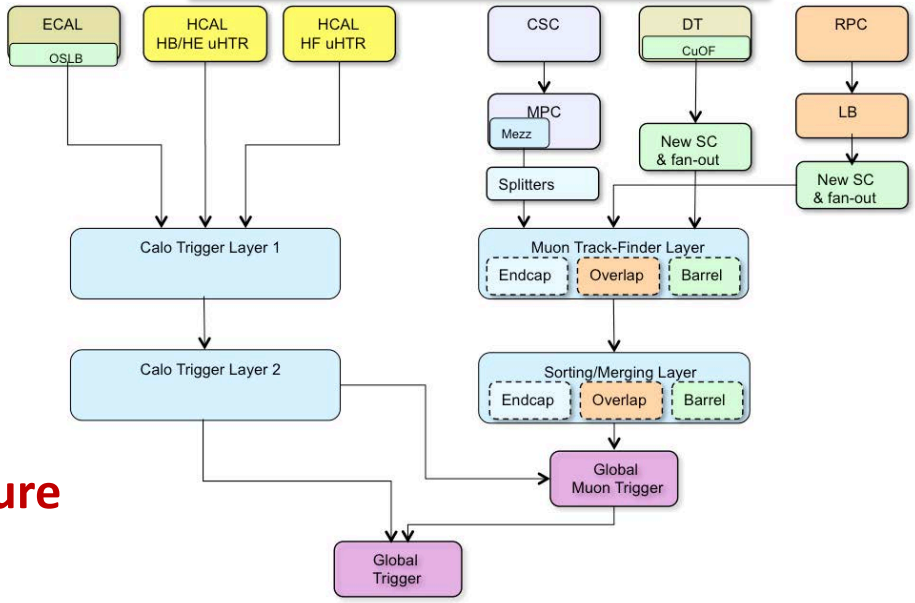
US: algorithms and software

**Phase 2 upgrade will build on this architecture**

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



Level 1 Trigger Upgrade

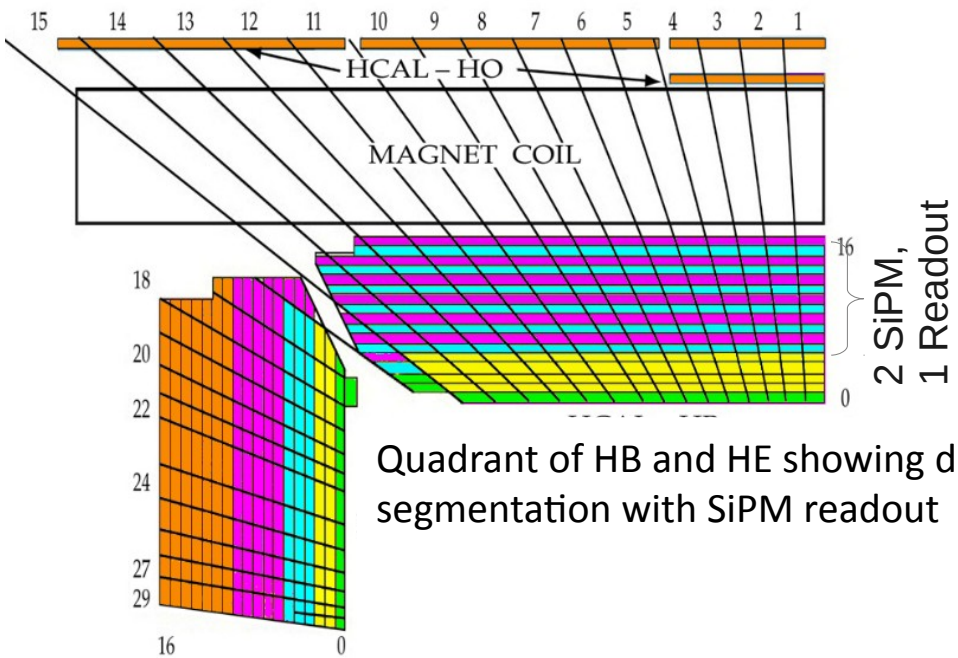


# HCAL-Phase 1

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

US: extensively involved / lead role

- 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

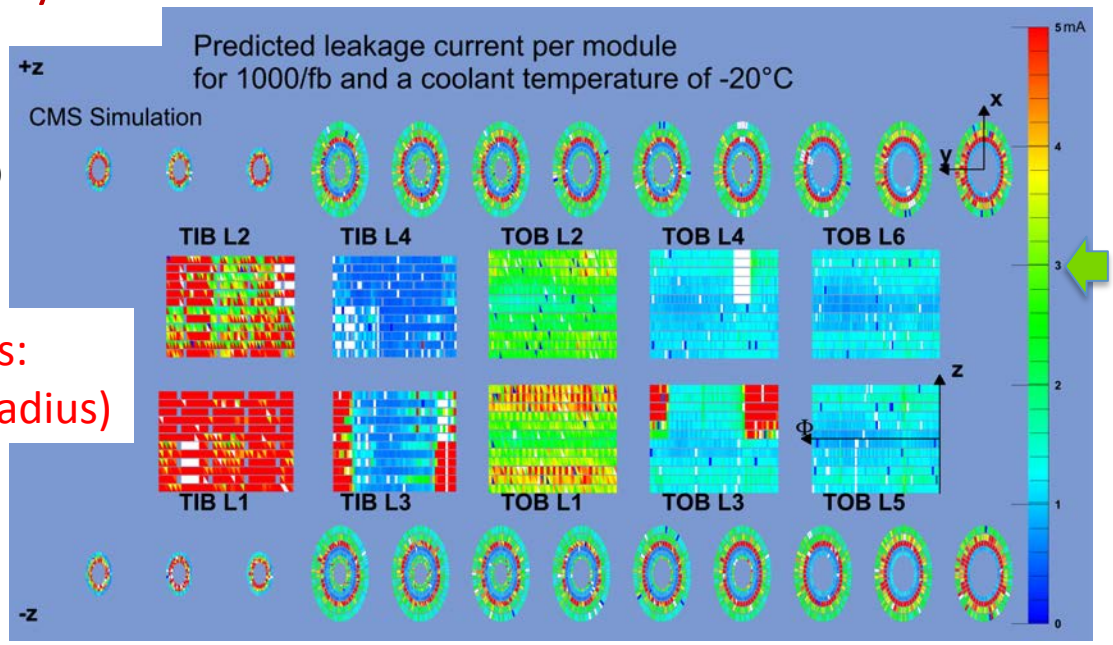
# Longevity of the Phase 1 Detector

- **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)



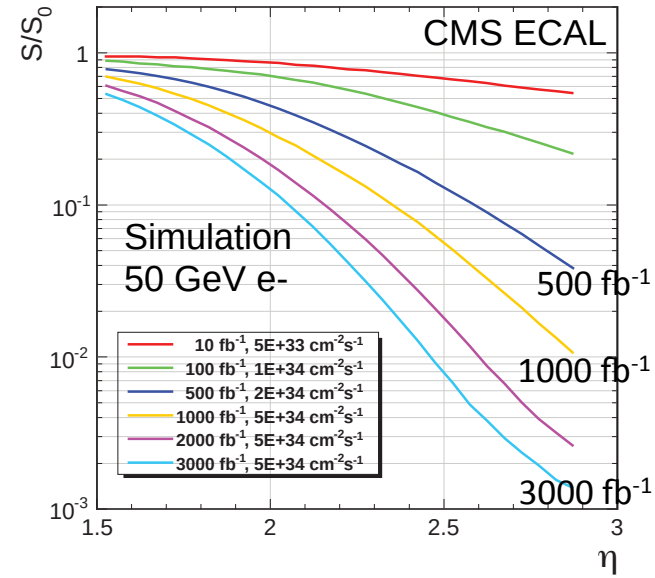

Operational limit ~ 3mA

Risk thermal runaway

# Longevity of Phase 1 Detecto

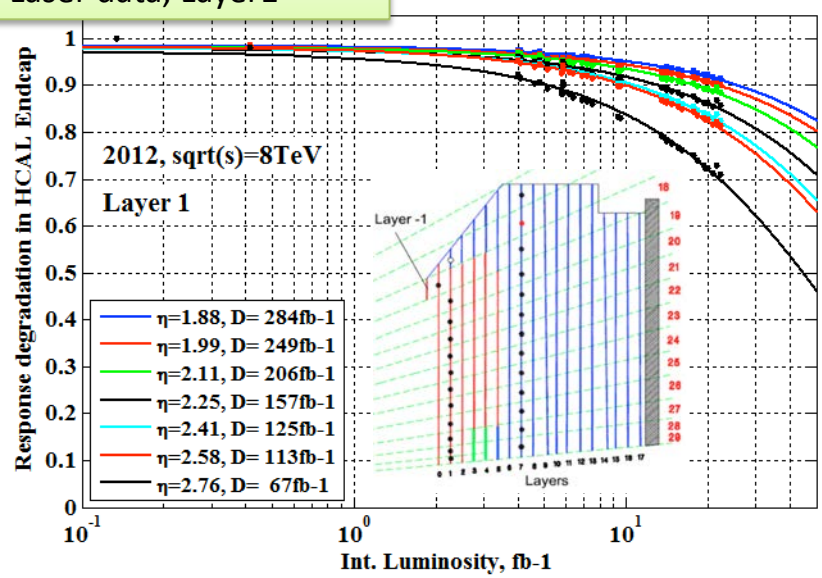
- ECAL: Must replace Endcap calorimeter
  - Barrel survives to 3000 fb$^{-1}$, but light transmission in the in Endcap drops to few % at high η, resulting in significant loss of resolution
  - Have extensively investigated ideas for enhanced annealing and/or partial replacement. No solution
- HCAL: Must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

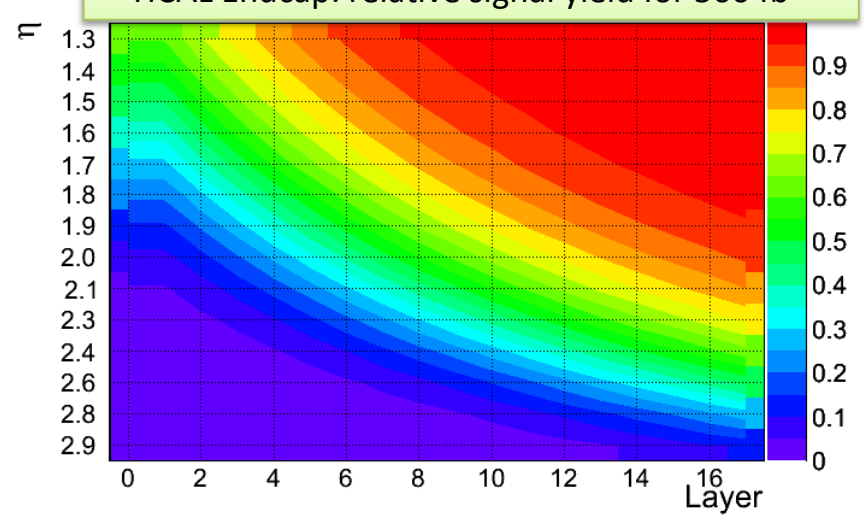



(Phase 1: improved S/N and depth segmentation, and can replace worst tiles in LS2 if needed to reach LS3)

Response degradation in HE, 2012 Laser data, Layer1




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



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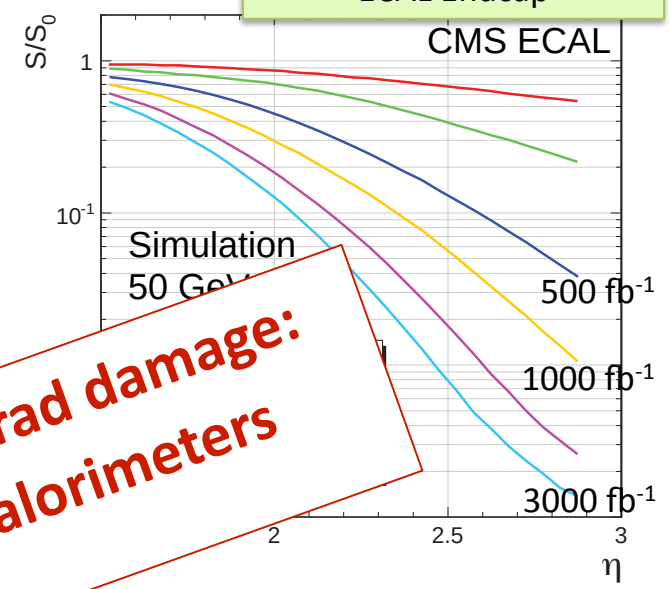
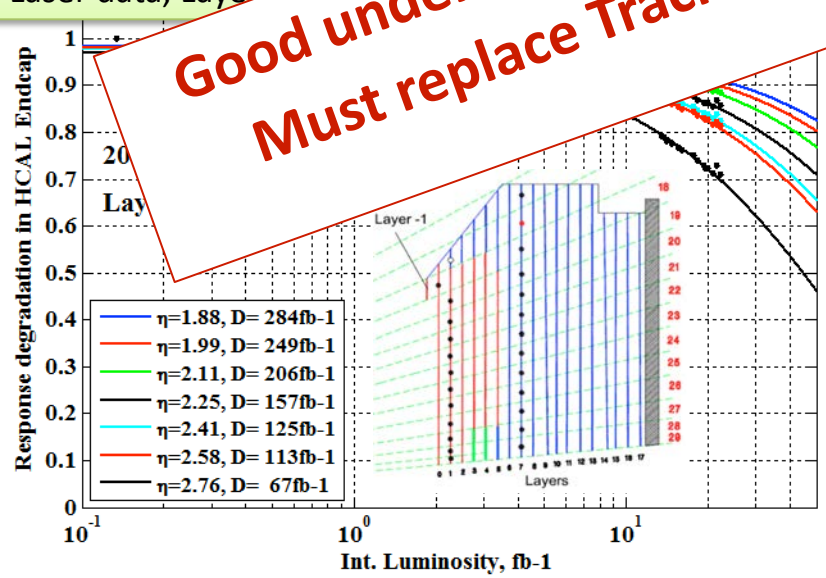
Relative light yield in ECAL Endcap

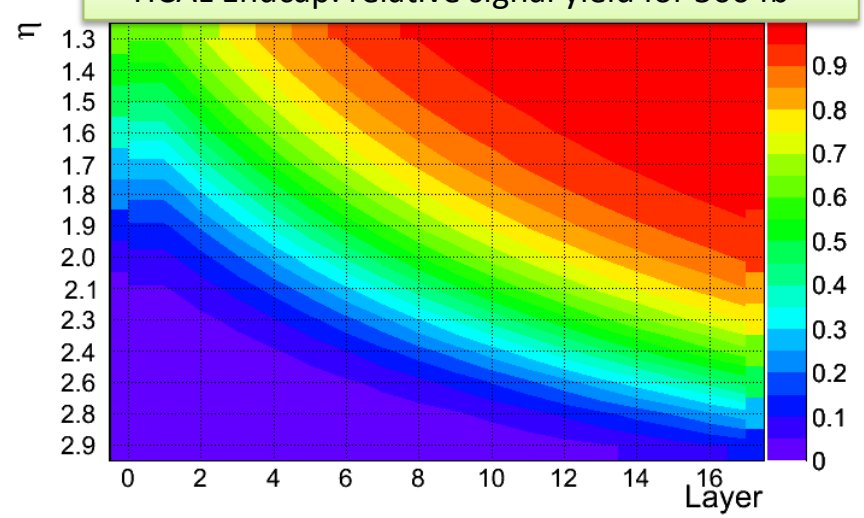



- **HCAL:** Must replace/rebuild Endcap calorimet
  - Barrel survives to 3000 fb$^{-1}$ (just). Ende
    drops to few % over large part
    ...entation, and can replace worst tiles

**Good understanding of performance/ rad damage:**
**Must replace Tracker, and Endcap calorimeters**

Response degradation in HE, 2012 Laser data, Layer1




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