# The CMS Phase 2 Upgrade

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CMS collaboration
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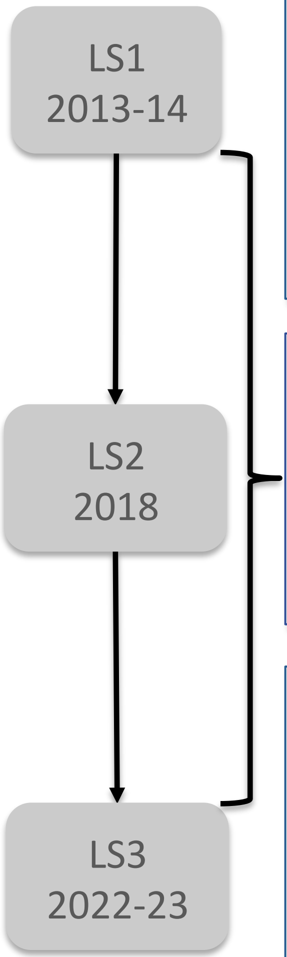
# CMS Upgrade program




**LS1 projects:** Complete detector & consolidate operation for nominal LHC beam conditions ~ 13 TeV - 1. $10^{34}$ Hz/cm$^2$ - PU ~ 25

- Complete Muon system (4$^{th}$ endcap station), improve RO of CSC ME1/1 & DTs
- Replace HCAL HF and HO photo-detectors and HF backend electronics
- Tracker operation at -20$^\circ$C
- Prepare and install slices of Phase 1 upgrades

**Phase 1 projects:** Prepare detector for 1.6 x $10^{34}$ Hz/cm$^2$ , PU ~ 40, ~ 200 fb$^{-1}$ by LS2 & 2.4 x $10^{34}$ Hz/cm$^2$, PU ~ 60, ~ 500 fb$^{-1}$ by LS3

- New Pixel detector (ready for installation in 2016/17 Year End Technical Stop)
- HCAL upgrade: photodetectors and electronics (HF 2015/16 YETS, HB/HE LS2)
- New L1-trigger systems (Calorimeter - Muons - Global) (ready for 2016 data taking)

## This presentation

**Phase 2 projects:** Major upgrades for HL-LHC era

$\gtrsim$ 5 x $10^{34}$ Hz/cm$^2$, PU ~ 125, ~ 3000 fb$^{-1}$ in ~ 10 years operation

- Driving considerations and proposed sub-system upgrades
- Conceptual designs and technical solutions considered

# Process to develop the scope of Phase 2 upgrades

- Driving considerations
  - Study of Phase 1 detector longevity
  - Simulation studies to define upgrade requirements and evaluate detector and physics performance at high rates and PU
  - Development of cost effective conceptual designs and technical solutions
  - Constraints from experimental areas and scope of work during LS3

- CMS will document the overall scope for Phase 2 in a Technical Proposal, anticipated in 2014, including:
  - Description of conceptual designs of the upgrades and the supporting physics performance studies
  - Scope of work, timeline and cost estimate

- TDRs for the major sub-detectors and systems will follow by ~ 2016

# Longevity of Phase 1 detectors

- CMS was designed for 10 years operation, accumulating ~ 500 $fb^{-1}$
- While a longevity margin was incorporated into the design and technologies of the original detectors, specific systems will require replacement
- Studies of radiation damage are based on test beam and in-situ data allowing performance projections for HL-LHC

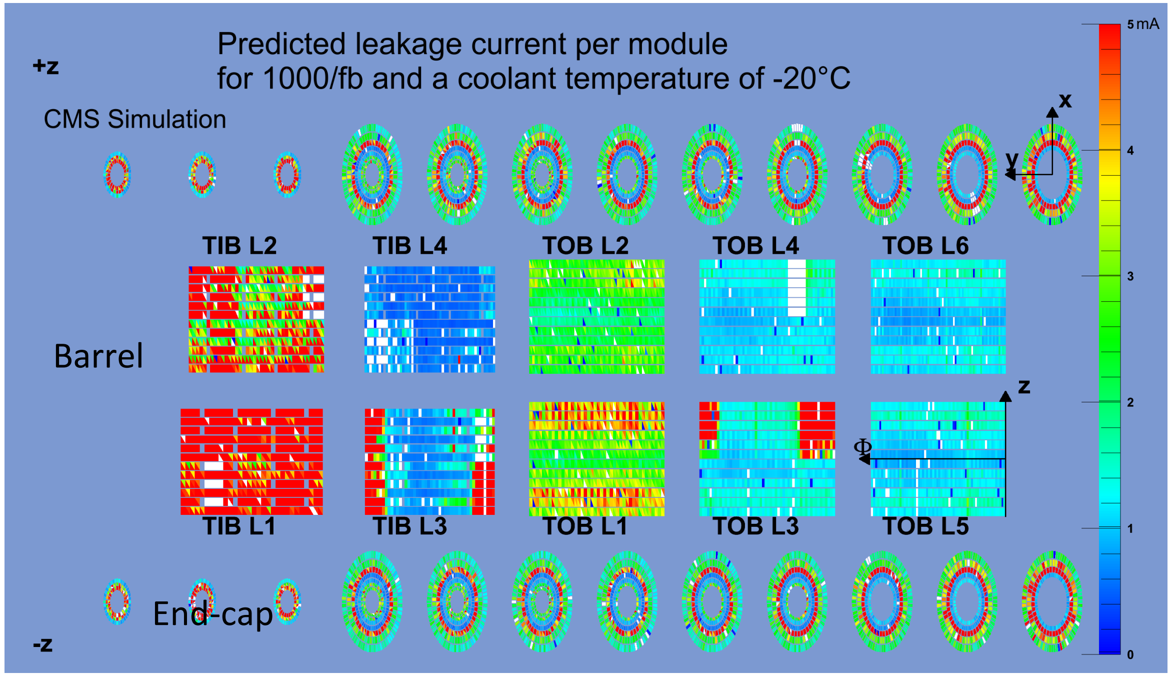
# Longevity of Phase 1 Tracker

- Strip tracker module leakage current & S/N degradation are well reproduced by radiation damage model
  - Projections demonstrate that the tracker will survive 500 $fb^{-1}$ if operated at -20◦C after LS1, but will start to lose modules beyond
- Pixel Phase 1 detector will be built to sustain ~ 500 $fb^{-1}$ with a replacement of the inner-most layer

→ Must replace the full Tracker in LS3

Map of module leakage current in the outer tracker after 1000 $fb^{-1}$

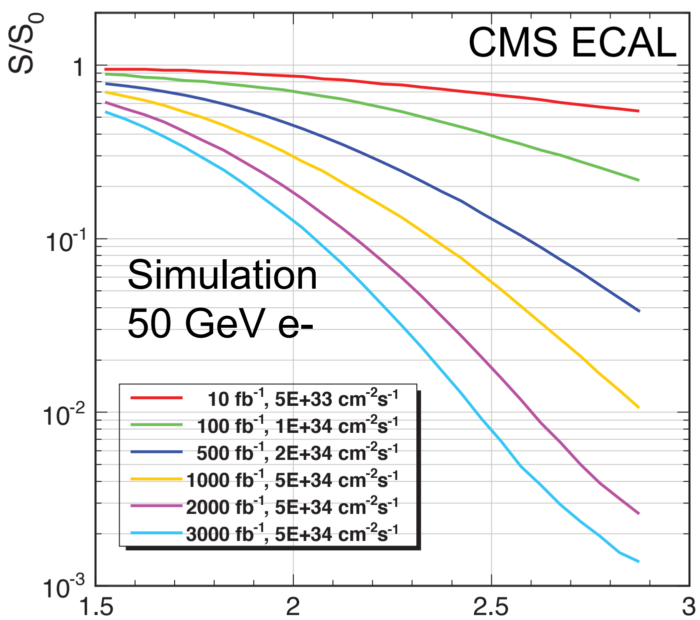
- Specification for leakage current was ≤ 1 mA
- All red and green areas will have operational problems



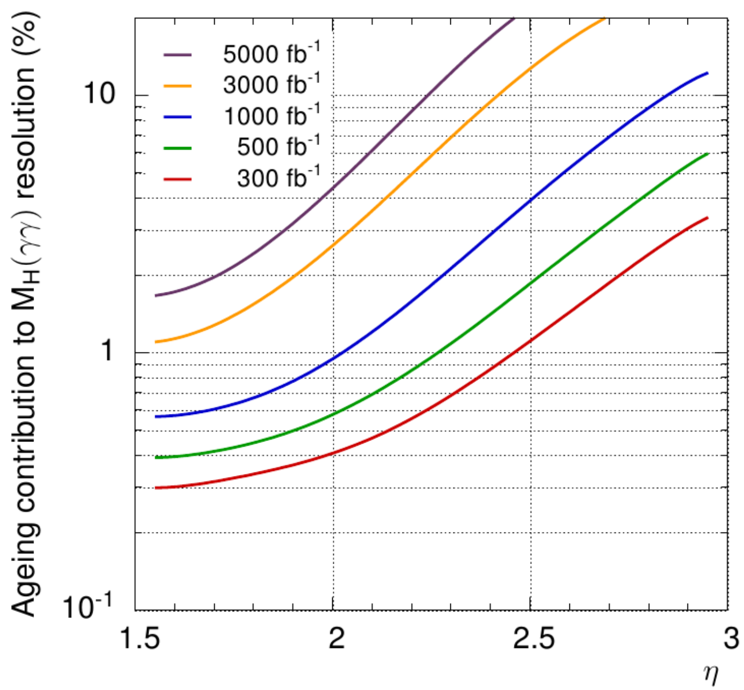
# Longevity of Phase 1 Electromagnetic Calorimeter

- Detailed studies in beam tests, at P5, and from in-situ transparency measurements to understand and model electromagnetic and hadronic radiation damage effects on crystals and photo-detectors (APDs and VPTs).
  - Projections indicate that ECAL barrel will sustain 3000 $fb^{-1}$
  - End-cap will collect ≤ 10% of light at high rapidity after 500 $fb^{-1}$
  - Due to S/N degradation the end-caps will also progressively lose trigger ability

→ The ECAL end-caps need to be replaced during LS3




Crystal Light transmission

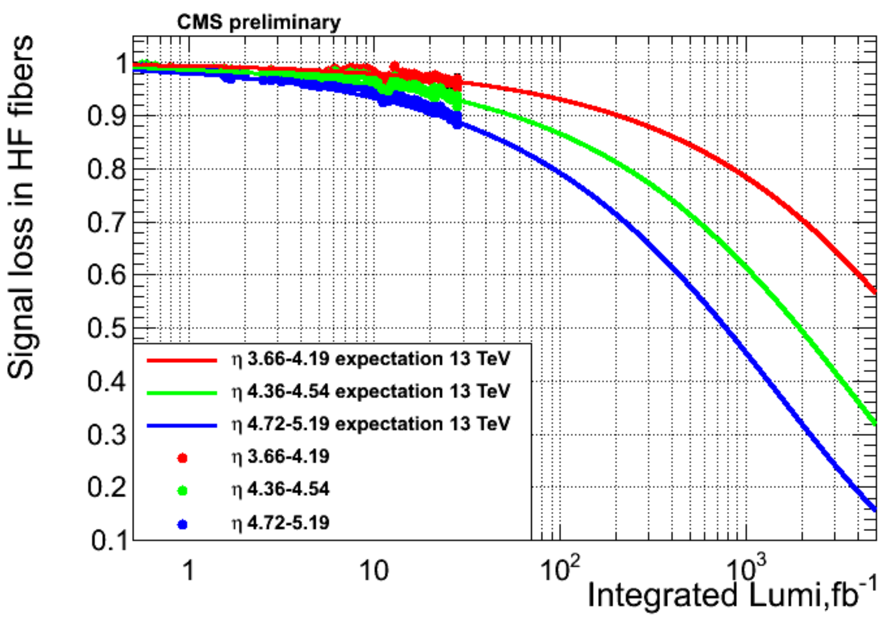


# Longevity of Phase 1 Hadronic Calorimeters

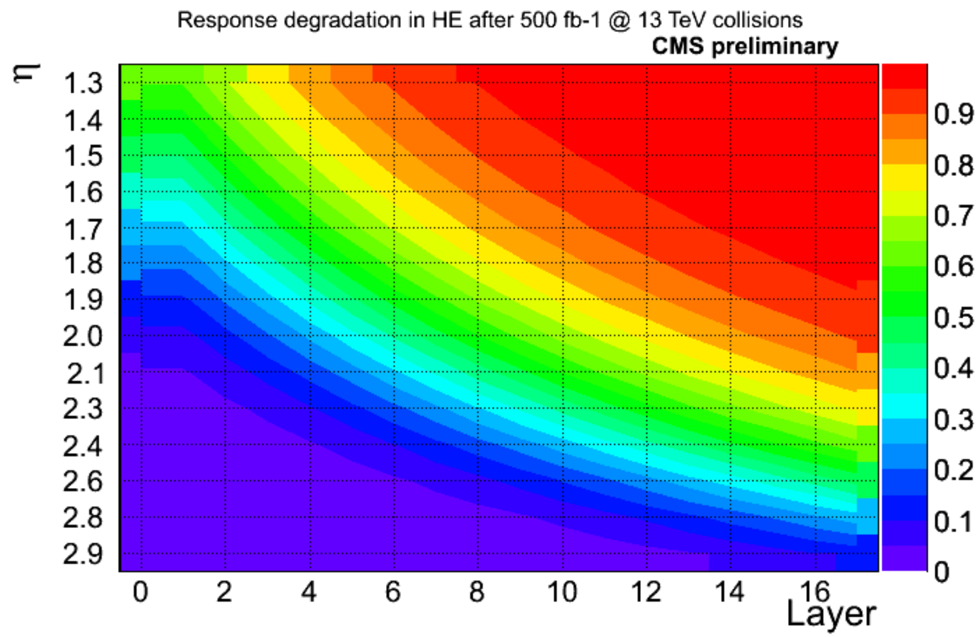
- Radiation damage projections are based on in-situ monitoring of light collection
  - HF will survive 3000 $fb^{-1}$ at least up to $\eta = 4$
  - Projections of light loss indicate that HCAL barrel will sustain 3000 $fb^{-1}$
  - End-caps will start to collect less than 5% of light after 500 $fb^{-1}$ in the forward region and front sampling depths

→ The HCAL end-caps need to be replaced during LS3

HF signal monitoring and projection




HE map of signal yield projection after 500 $fb^{-1}$



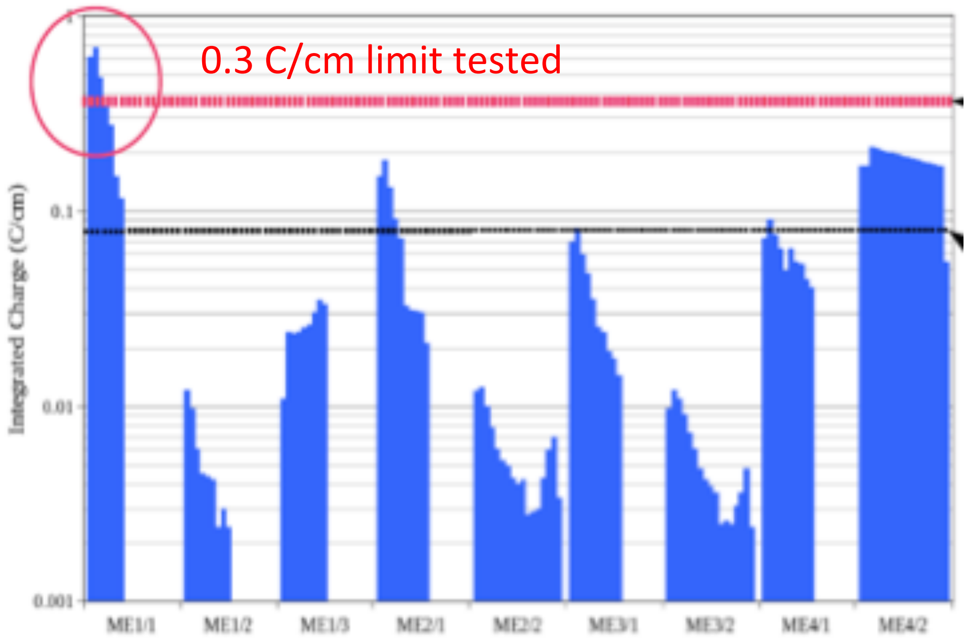
# Longevity of Phase 1 Muon systems

- Measured rates are linearly increasing with luminosity and with a strong η dependence as expected from simulation
- No aging effects have been observed so far
  - Test have been performed up to 0.3 C/cm - only forward CSC station will exceed this limit after 3000fb$^{-1}$ - new tests including readout will be performed at the GIF++ facility to confirm aging properties of all systems

→ The muon systems are expected to sustain 3000 fb$^{-1}$

- Construction tests of the radiation damage to FPGAs in the DT read-out indicate that they need to be replaced for Phase 2 operation
  - The new electronics design will not limit the L1-trigger rate

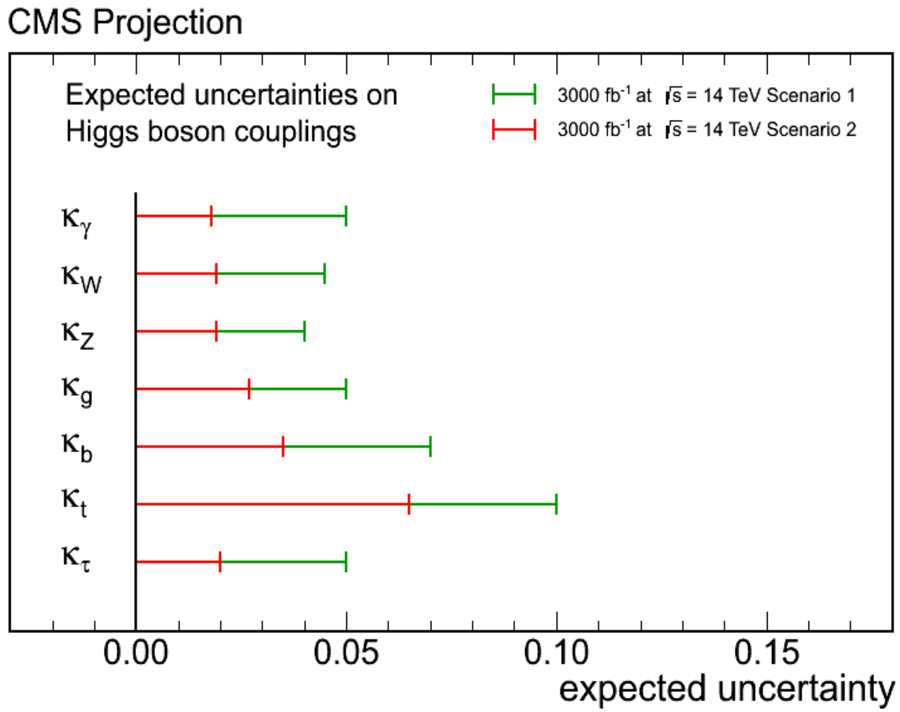
Integrated charge collected in CSCs after 3000 fb$^{-1}$



Requirements from the physics program
Overall upgrade scope including performance aspects
Plans for supporting simulation studies

# HL-LHC physics program

The Physics Program and performance reach at HL-LHC have been documented in the framework of ESPG and Snowmass prospective based on the Higgs boson discovery and current results on New Physics searches




Systematic uncertainties as now, theory scaled by ½ and experimental with √ of Luminosity

- Improving systematic errors is critical for precise measurement of Higgs properties
  → Tracker and Calorimeter performance at high PU is critical to ensure best possible physics object reconstruction
- Measurement of VBF and rare processes is a major physics goal at HL-LHC
  → Trigger acceptance at low Pt & detector coverage are key
  → Jet-tagging and measurement in the forward region needs special attention

# Proposed upgrades and motivations

- Mitigation of PU effect relies on particle flow reconstruction and high tracking performance
  - The tracker replacement will allows to design for the high PU operation
  - We propose to extended the pixel coverage up to $|\eta| = 4$ to match the calorimeter coverage and mitigate PU effect on VBF jet-tagging
  - The end-cap calorimeters replacement will offers opportunity to optimizing energy measurement and segmentation for high PU operation
  - Precision timing measurement in front of calorimeters is investigated as a mean to mitigate PU from neutral particles

# Proposed upgrades and motivations

- To ensure trigger acceptance with low momentum thresholds we propose
  - To implement tracking in L1-trigger - imbedded in the tracker concept
  - New muon stations in the end-cap
  - Increased latency to perform track reconstruction and global trigger algorithms. This will need replacement of ECAL Barrel front-end electronics
  - Modification of the EB and DT FEE readout will also allow L1-trigger rates up to 1 MHz. This will need HLT processing power upgrade

# Proposed upgrades and motivations

- End-cap coverage
  - Replacement of end-cap calorimeters allows to consider extended calorimetry coverage up to $|\eta| = 4$ for uniform measurement in the VBF Jets region (avoiding transition from end-caps to HF) and to increase e/γ acceptance
  - It will also allows extending muon coverage with a Muon tagging station behind the calorimeters, coupled with the pixel extension
  - Studies of implications on infrastructure - radiation and background levels are ongoing

# Physics simulation studies

Simulation studies are evolving to develop requirements and evaluate performance with realistic detector descriptions

- Common benchmark signals agreed with ATLAS (also LHCb and ALICE) for ECFA workshop Oct. 1-3) - CMS uses parameterized simulations at 140 PU (Delphes) ~ 10 studies are in approval Different detector configurations (coverage - granularity - resolution) under study →
- For TP studies will be performed with Fast & Full simulation
  - Significant effort ongoing to implement configurations – reconstruction - analyses → MC production early 2014
  - Will demonstrate upgrade performance for selected representative physics benchmarks (HH → bbγγ, VBF H → ττ)

**Higgs & EWSB:**
- HH to bbγγ (full-simulation)
- HH to bbττ
- BSM Higgs
- VBF -- H to ττ
- H to μ+μ
- H to Zγ
- Tests for CP-odd components in Higgs
- VBS -- WW to lvlv qq, WW to lvqq qq
- VBS -- ZZ to 4lqq

**BSM:**
- Light third generation squark searches
- Electroweak gaugino searches
- Squark and gluino searches in difficult reg
- Study how well we can measure model pa discovered at LHC (300 $fb^{-1}$)
  - 2 specific plausible pMSSM models, c
- Heavy resonance decays to ttbar, VV, lept
- Top partners (Q = 5/3, 2/3, 1/3)
- Monojet + MET (dark matter)

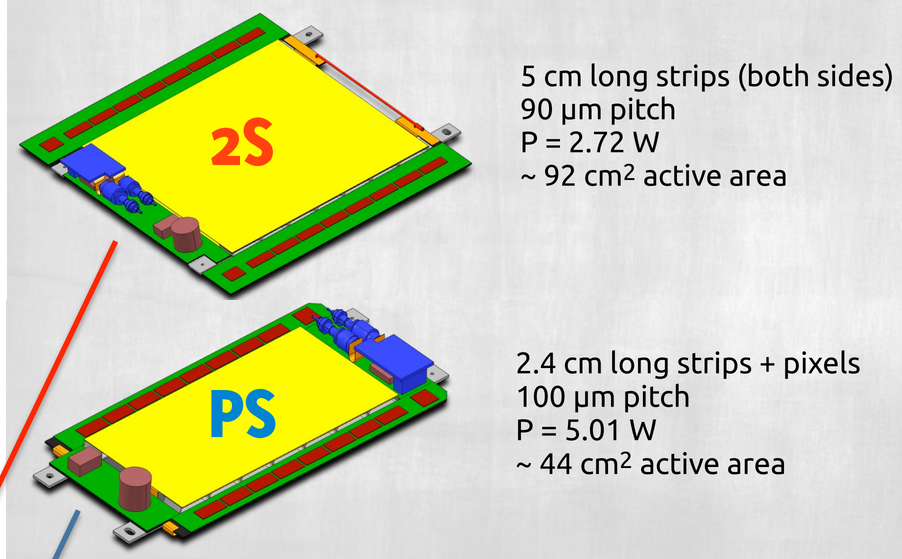
**Heavy Flavor:**
- $B(B^0$ to $\mu^+\mu^-)/B(B^0_s$ to $\mu^+\mu^-)$
- $\Phi_s(B^0_s$ to $\Phi\Phi)$
- CKM angle γ
- $A_\Gamma(D^0$ to $K^+K^-$, $\pi^+\pi^-)$
- $B_d$ to $K^*\mu^+\mu^-$
- t to cX(X=γ, μμ, ee, ...)

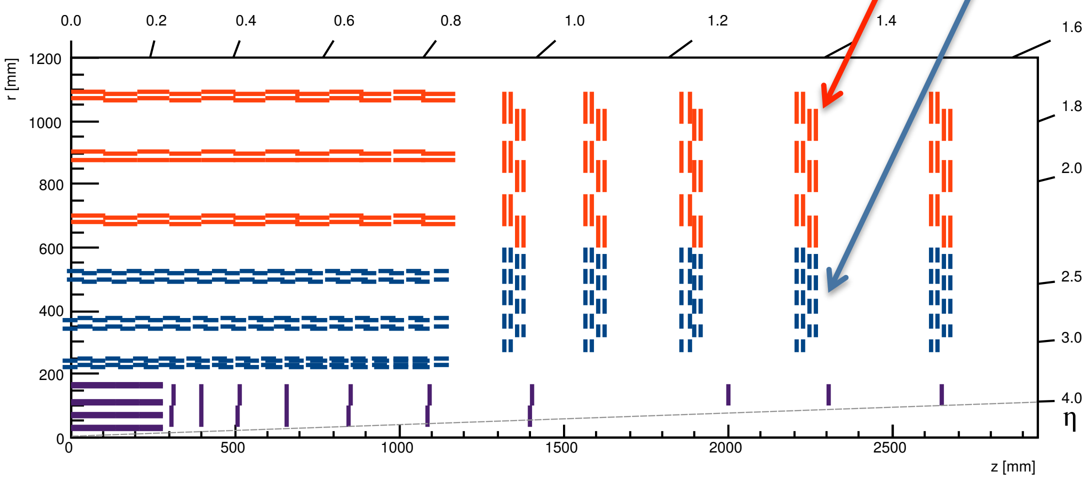
**HI:**
- Low-$p_T$ heavy flavour and charmonium pro
- Multi-differential Upsilon family measurem
- Low-mass and low-$p_T$ dileptons, ρ, ω, con
- Jet physics
  - differential jet, b-jet, di-jet, γ/Z-jet meas

# Conceptual designs and technical solutions

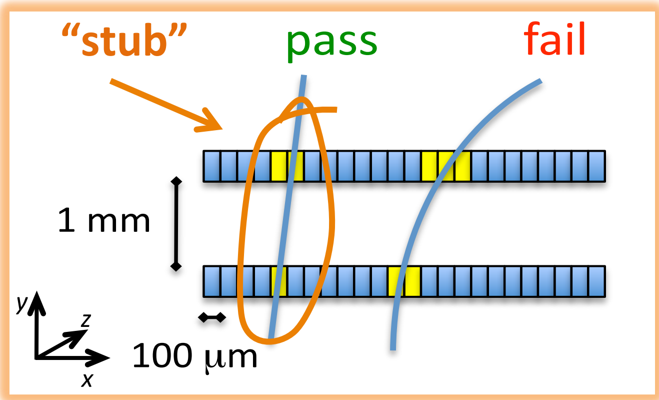
# Tracker: conceptual design

- Outer tracker
  - High granularity for efficient track reconstruction beyond 140 PU
  - Two sensor “Pt-modules” to provide trigger information at 40 MHz for tracks with Pt≥2GeV
  - Improved material budget
- Pixel detector
  - Similar configuration as Phase 1 with 4 layers and 10 disks to cover up to |η| = 4
  - Thin sensors 100 µm; smaller pixels 30 x 100 µm
- R&D activities
  - In progress for all components - prototyping of 2S modules started
  - BE track-trigger with Associative Memories



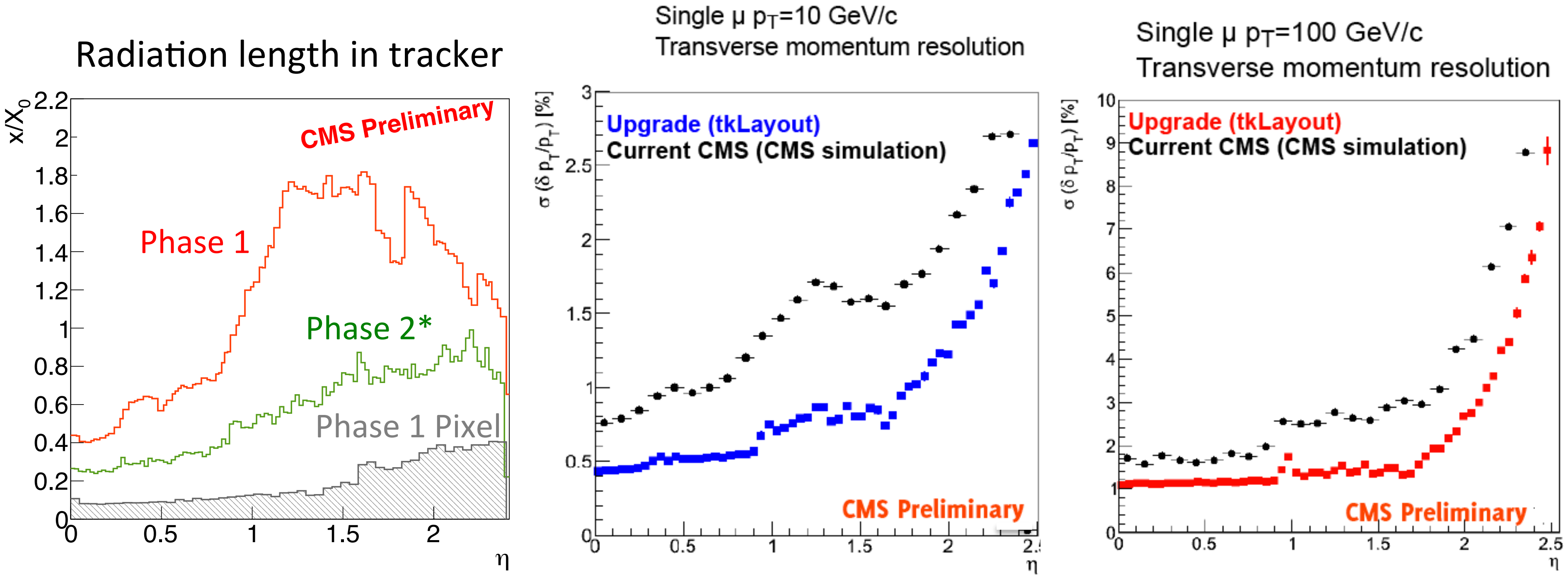




Trigger tracks selection in FE



# Tracker: performance preliminary estimates

- Performance estimated with stand alone simulation tool (benchmarked against CMSSW full simulation) and CMSSW simulations
  - Improved Pt resolution
  - L1- trigger information bandwidth reduced by ~ 10 with Pt-modules



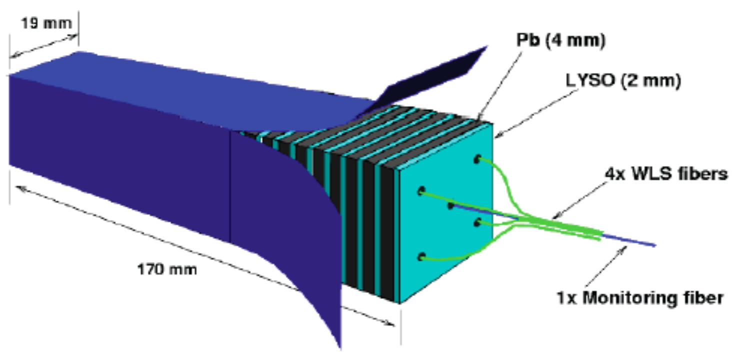

* Pixel MB in Phase 2 is same as in Phase 1

# Forward calorimeters: ECAL tower geometry

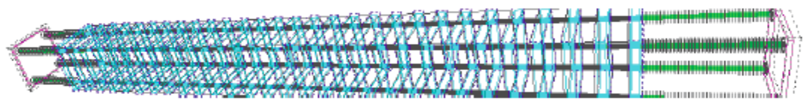
- First approach under consideration:

  Maintain standard tower geometry - develop radiation tolerant solutions for EE and HE to deliver the necessary performance

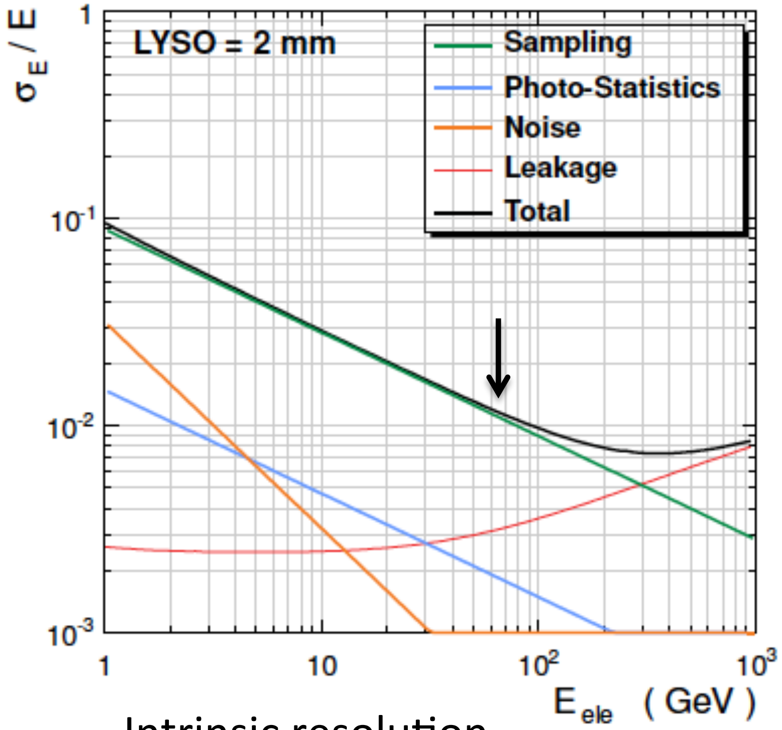
  - Build EE towers, in eg, a strawman Shashlik design:
    - Lead or tungsten absorber - crystal scintillator - LYSO, CeF, WLS in Quartz Capillaries - GaInP photodetectors…




Prototype replacement for EE: Absorber plates could be W or Pb; Scintillation plates can be LYSO or other scintillator options. Fiber readout is likely Quartz Capillaries with WLS cores. Photosensors would be GaAs or GaInP Pixelated Geiger Mode APDs.



Simulation model of the Shashlik structure built using Litrani code



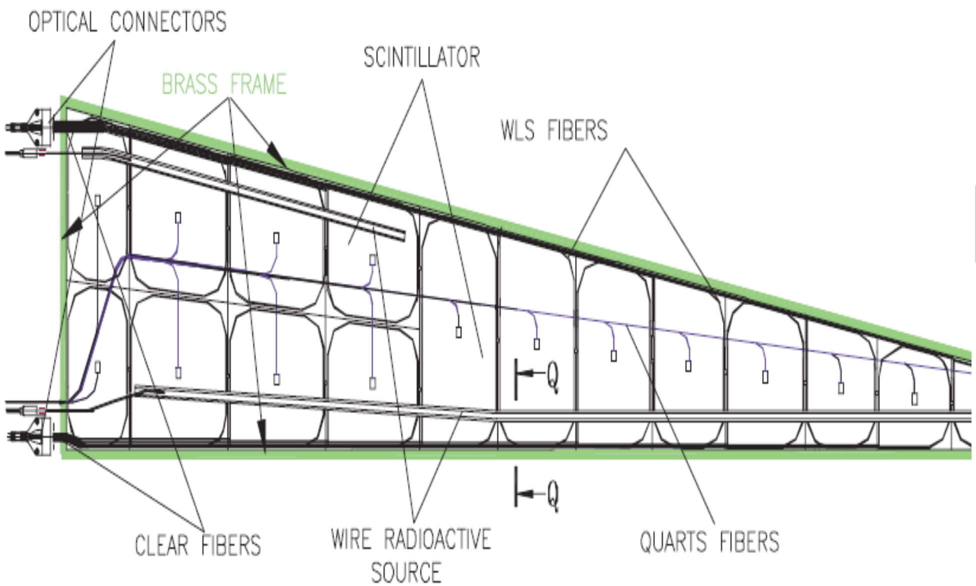

Intrinsic resolution

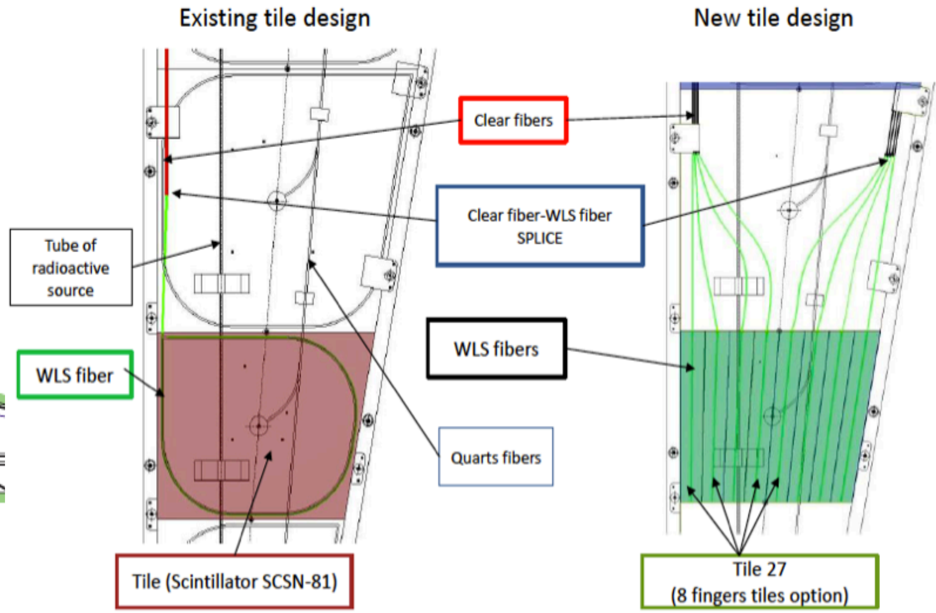
# Forward calorimeters: HCAL tower geometry

- ○ First approach under consideration:

  Maintain standard tower geometry - develop radiation tolerant solutions for EE and HE to deliver the necessary performance

  - Rebuild HE
    - – More WLS fibers
    - – Rad-hard scintillator
    - – Possibly increase transverse segmentation for PU mitigation



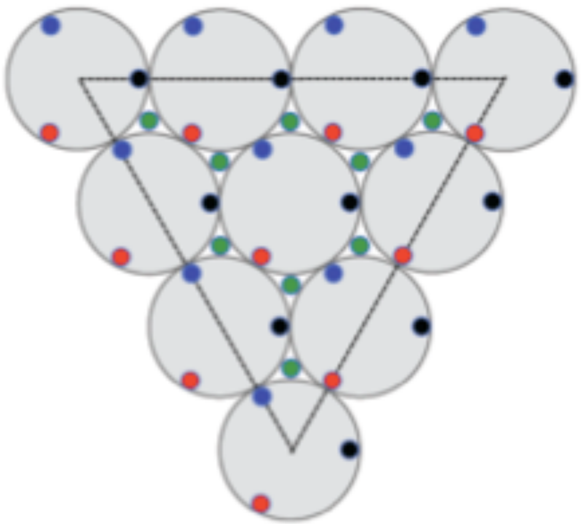
# Forward calorimeters: Integrated ECAL and HCAL

- Alternative approach:

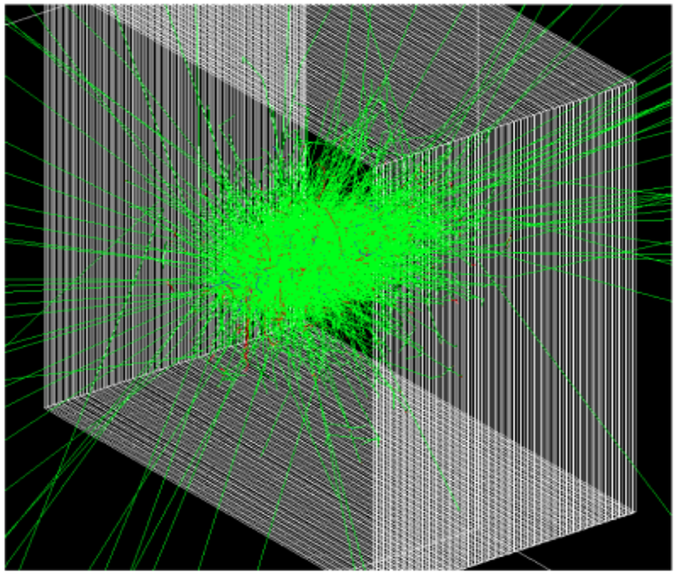
  Integrate ECAL and HCAL with potential for improved performance and/or lower cost.

  Two concepts under consideration:

  - Dual fiber read-out: scintillation & Cerenkov (DROC) - based on studies for DREAM - using doped/crystal fibers - allows e/h correction for improved resolutions
  - High Granularity Particle Flow Calorimeter (PFCAL) - based on studies for CALICE - using GEM/Micromegas technology - high segmentation both transverse and longitudinal to measure shower topology



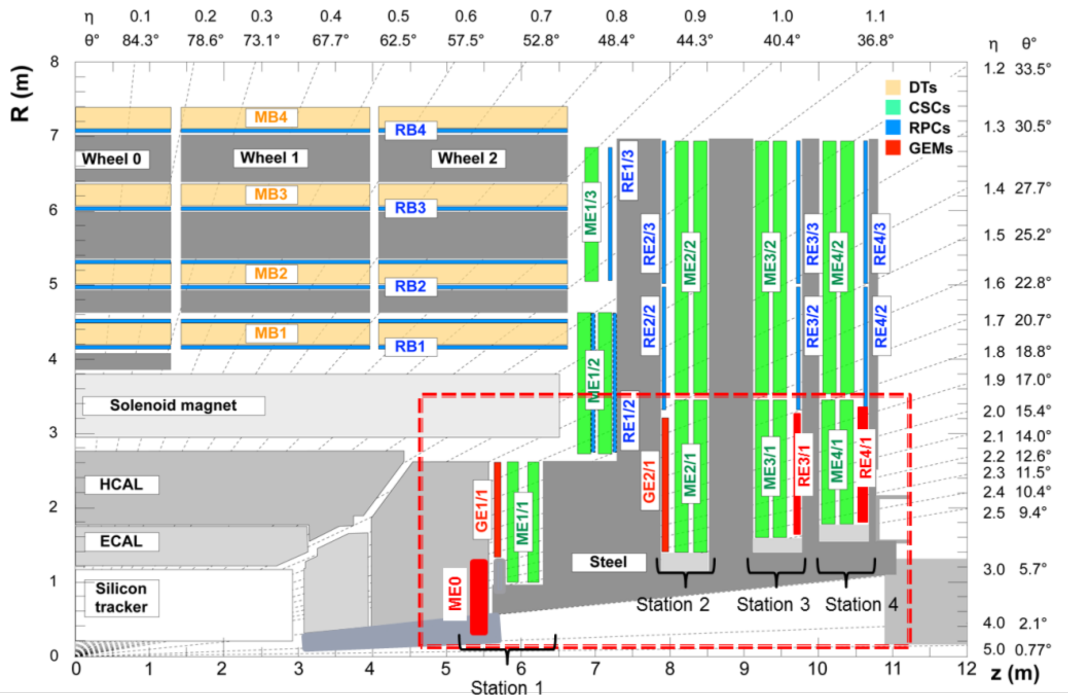
Dream Concept



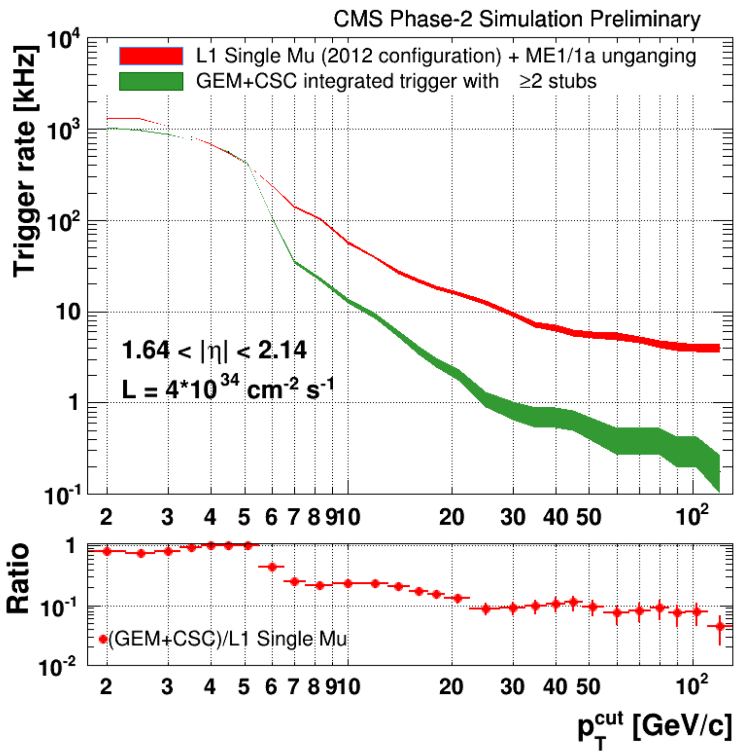
PFCal Concept

# Muon systems

- Improve offline and trigger performance - provide redundancy
  - Complete muon stations at 1.6 < |η| < 2.4 - GEM in 2 first stations (Pt resolution) & Glass-RPC in 2 last stations (timing resolution to reduce background)
  - Considering increase of the muon coverage to 2.2 < |η| < 4.0 with GEM tagging station (ME0) coupled with extended pixel
- R&D activities: GEM/Glass-RPCs




Example of single μ trigger rate reduction with GEM1/1 station



# Trigger/DAQ systems

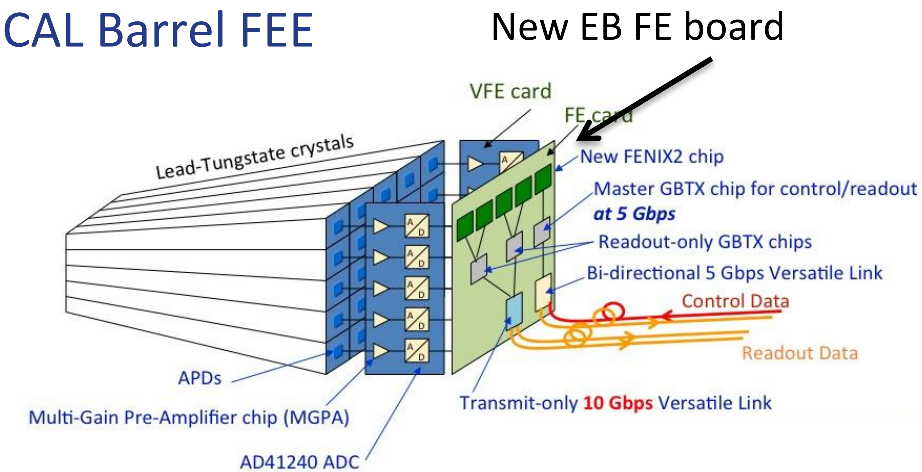
- New L1-trigger will build on the Phase 1 architecture, adding tracking (from outer tracker) into all trigger objects, with increased granularity (EB at crystal level), and will be able to operate up to 1 MHz
  - Match leptons with high momentum resolution tracks
  - Provide isolation of e, $\gamma$, $\mu$ or $\tau$ candidate
  - Provide track vertex association to reduce pileup effect in multiple object triggers, e.g. in lepton plus jet triggers (investigating pixel implementation in trigger)

Preliminary studies of L1-trigger rate reduction with track-trigger

| Trigger, Threshold | Algorithm | Rate reduction | Full eff. at the plateau | Comments |
|---|---|---|---|---|
| Single Muon, 20 GeV | Improved Pt, via track matching | ~ 13 (central region) | ~ 90 % | Tracker isolation may help further. |
| Single Electron, 20 GeV | Match with cluster | > 6 (current granularity) >10 (crystal granularity) ( \| η \| < 1 ) | 90 % | Tracker isolation can bring an additional factor of up to 2. |
| Single Tau, 40 GeV | CaloTau – track matching + tracker isolation | O(5) | O(50 %) (for 3-prong decays) | Work in progress to improve efficiency |
| Single Photon, 20 GeV | Tracker isolation | 40 % | 90 % | Probably hard to do much better. |
| Multi-jets, HT | Require that jets come from the same vertex | | | Performances depend a lot on the trigger & threshold. |

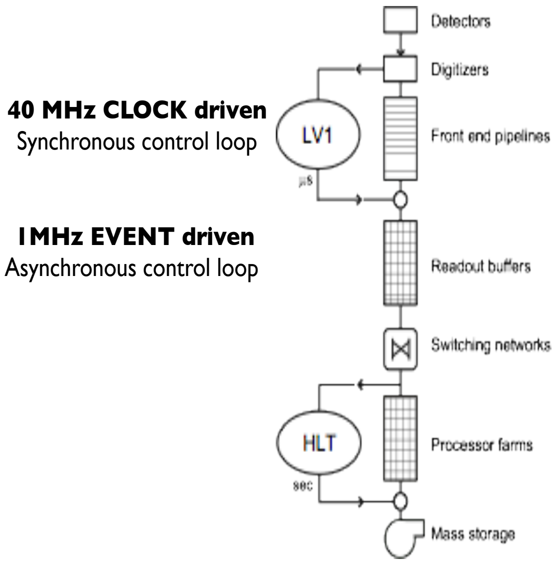
# Trigger/DAQ systems

- New L1 trigger requires replacement of ECAL Barrel FEE
  - Allow 10 µs latency (limited by CSC RO)
  - Allow L1 rate up to 1 MHz to maintain trigger menu for objects or regions where the track trigger is less efficient
  - Provide crystal granularity (track match)
  - Improved APD spike rejection




Note: this upgrade must happen concurrently to the tracker replacement in LS3

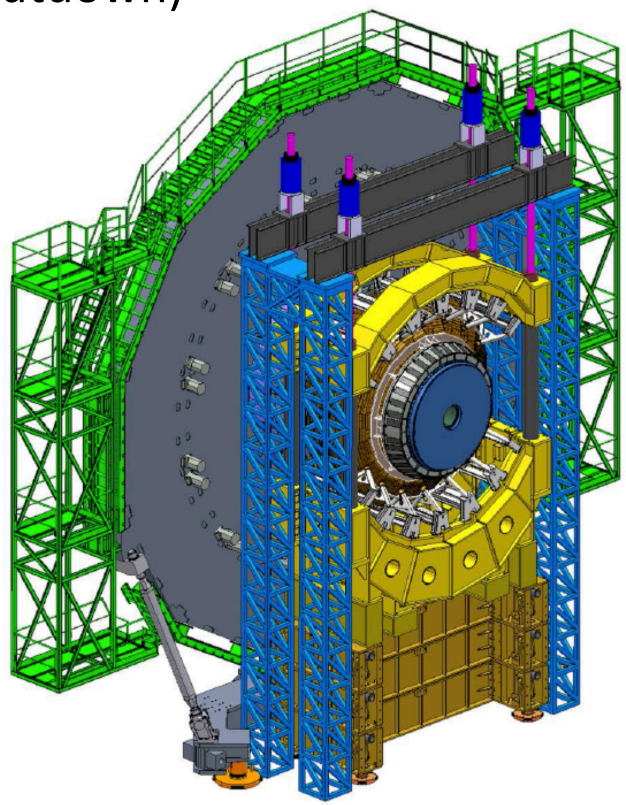
- The DAQ and HLT will be upgraded for up to 1 MHz into HLT and 10 kHz out to maintain ~ to current rejection factor




- "Moore's Law" (CPUs, networks, storage) over 10 years suggests that "normal technology improvements" will handle this, including offline

# Infrastructure and common systems

- Changes to the accelerator (new low-$\beta$ quads, new TAS…) will require major changes to the shielding and the forward region
- Radiation protection will require personnel shielding, special handling
- New cranes, platforms and rail systems to facilitate the work in LS3
  (likely very cost effective in limiting length of shutdown)
- Infrastructure will need upgrades (itself and for the detector upgrades): rack system, cooling… DCS, DSS…
- Specific items for longevity: solenoid power/controls…
- New YB0 services
- The sequence of work during LS3 is being developed, ~ 30 months seems possible with proper parallelism of work and sufficient and trained manpower



Tooling concept for removal of endcap calorimeters

# Concluding remarks

The scope of the CMS Phase 2 upgrade is becoming well developed. It will meet high PU and radiation challenges, supporting a broad and rich physics program at the HL-LHC

The longevity of detectors has been thoroughly studied clearly showing that the tracker and calorimeter end-caps need replacement during LS3

We are proceeding to develop cost effective conceptual designs based on simulation studies and to target specific R&Ds - this will be documented in a Technical Proposal in 2014

R&D support in the 3-4 coming years is critical to develop the technical solutions for the upgrades, and to optimize their cost