Calorimeter Detectors: Longevity issues, new requirements and resulting upgrades

Calorimetry Preparatory Group

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outline

- brief survey of technologies used by present calorimeters of LHC experiments
- focus on specific challenges calorimeter detectors of the four experiments will face during Phase2 of LHC
  - discuss ability of present calorimeters to withstand very high radiation and particle fluxes
  - describe what are the mitigation options and upgrades considered for specific detectors
  - highlight critical R&D programs required by each of the options
- summary/concluding remarks

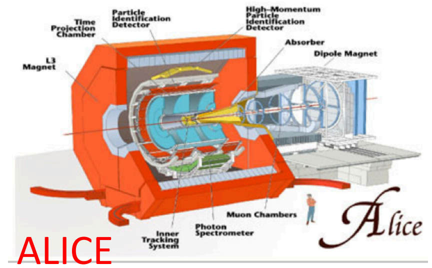
Technologies used in LHC calorimeters

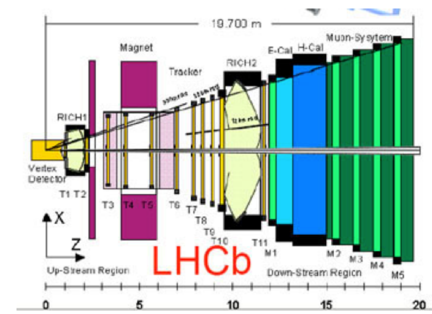
Lead Tungstate homogenous calorimeters
- CMS ECAL, ALICE PHOS

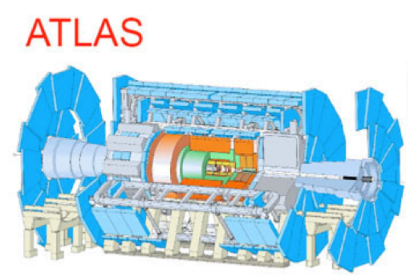
Liquid Argon sampling calorimeters
- ATLAS EM Barrel and Endcaps, HAD Endcaps and Forward

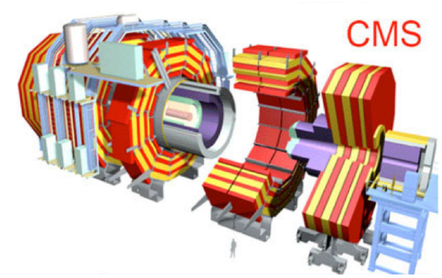
Scintillator/WLS fiber sampling calorimeters
- Megatiles: CMS HCAL Barrel and Endcap
- TileCal: ATLAS Hadron Barrel, LHCb HCAL
- Shashlik: ALICE EMCal/Dcal, LHCb ECAL

Quartz Fiber/Steel sampling calorimeter
- CMS HCAL Forward



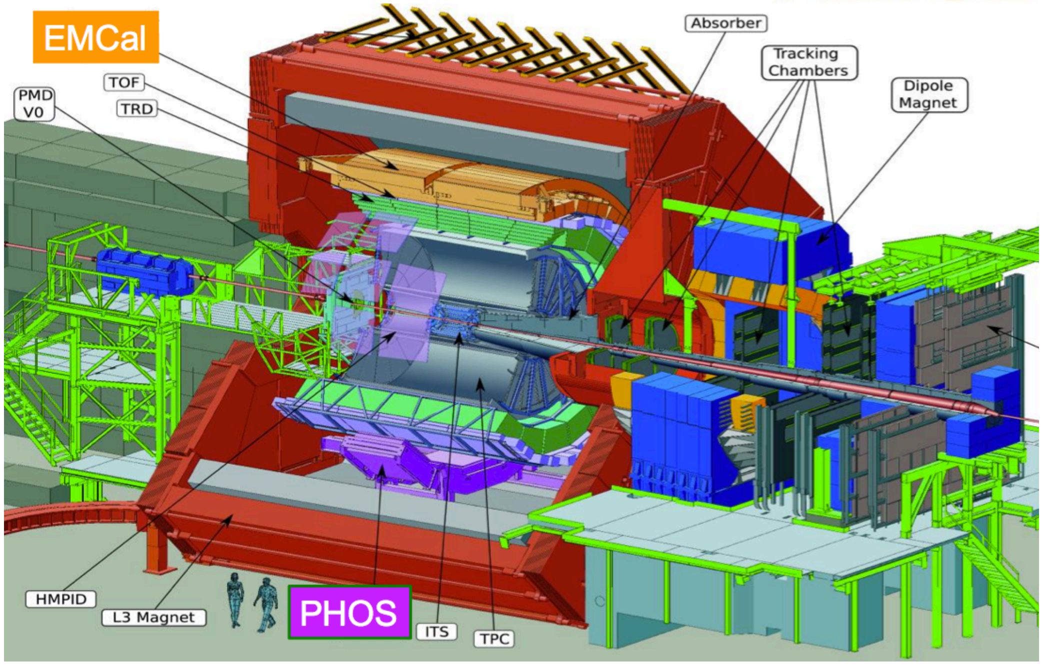






ALICE calorimeter system

ALICE goal after LS2:
Collect up to 10 nb^{-1} of Pb-Pb collisions, with Inst. Lumi up to 6 *10^{27} cm^{-2}/s



ALICE calorimeter system

Upgrades during LS1:

EMCal:

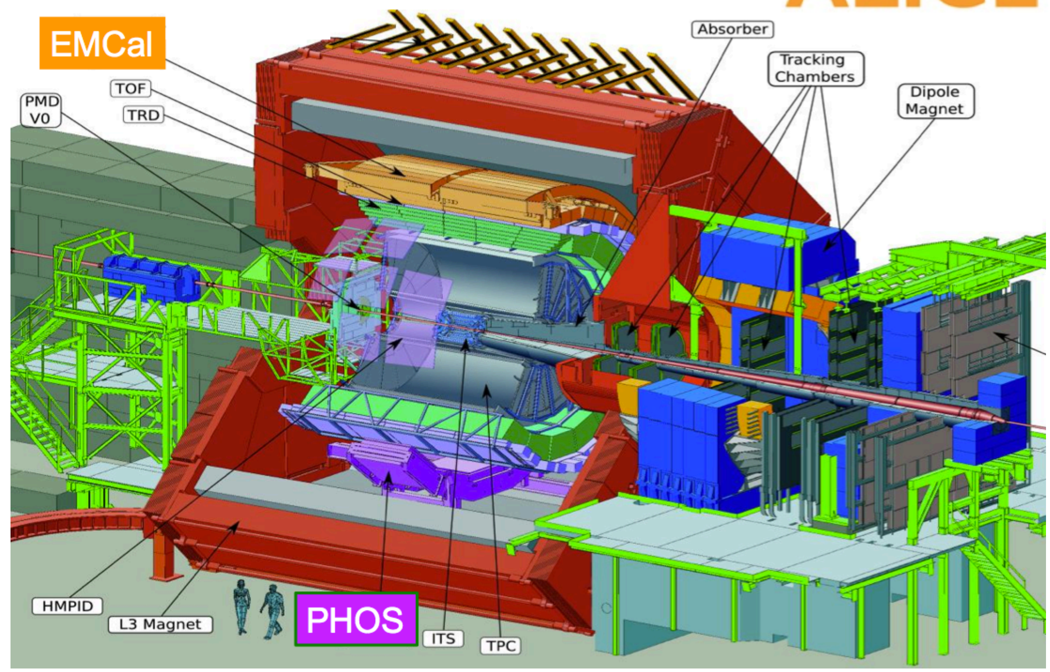
Pb/Scin (Shashlik), $0.12 < |\eta| < 0.7$

- Increase of ϕ coverage by adding Dijet Calorimeter (Dcal)
- number of towers from 12.3k to 17.7k

Photon Spectrometer (PHOS):

$PbWO_4$ crystals, $|\eta| < 0.12$

- Increase of ϕ coverage by installation of 4^{th} module
- Number of towers from 10.8k to 14.3k



Longevity of calorimeters:

Calorimeters located in ALICE central barrel ($|\eta|<0.7$, r~4.5m):

- expected doses ~1Gy (~ 0.1 krad)

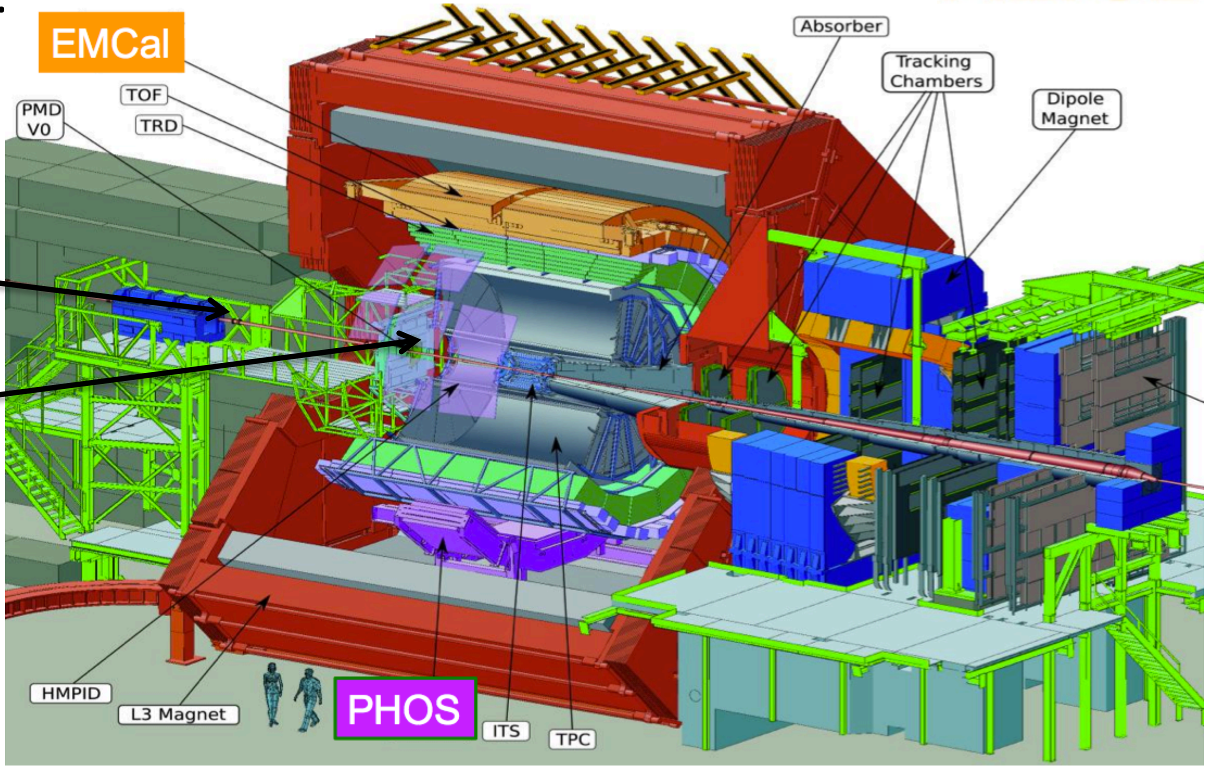
No issues related to integrated radiation dose are expected for ALICE calorimeters

ALICE FoCal

ALICE considers installation of additional calorimeter in the forward pseudorapidity region after LS2.

Two positions are being considered for FoCal:

- Preferred option:
  At z = 7-8m
  $3.3 < \eta < 5.3$
- Alternative option:
  $2.5 < \eta < 4.5$



Main features of FoCal:

- 21-24 layers with tungsten absorber (3.5 mm, ~ $1X_0$/sampling) and Si-sensors, dia ~ 1.2m
- Sensors: 2-3 very high-granularity (~mm^2) layers + ~20 lower-granularity (~1 cm^2) layers
- Small Molière radius (~1cm) to separate γ's from π^0 decays

Active R&D ongoing

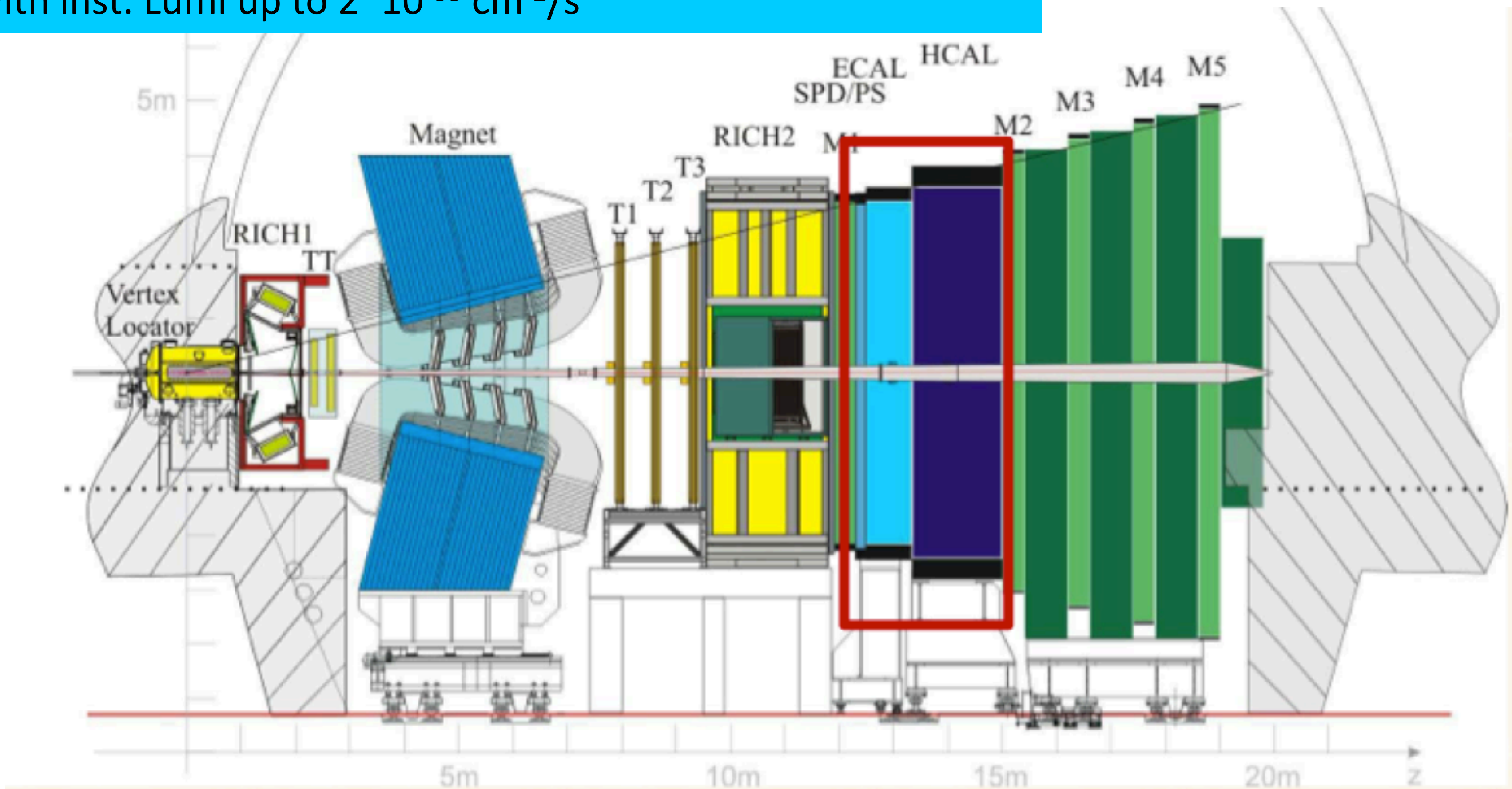
beam tests of prototype module performed, results very promising (http://arxiv.org/abs/1308.2585)

No significant radiation-related damage to calorimeters is expected during Phase2 operations of LHC.

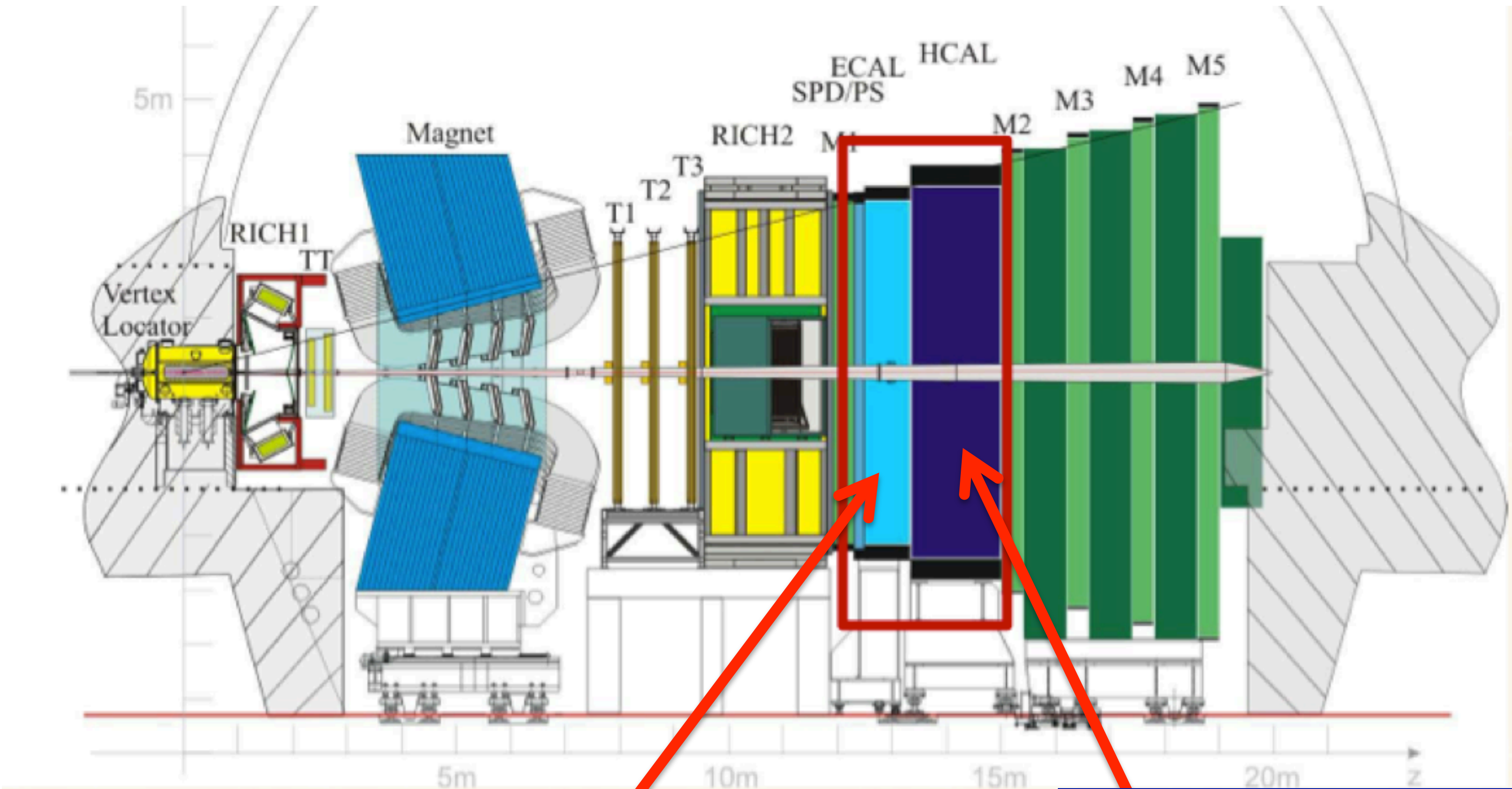
ALICE considers installation of additional calorimeter in the forward pseudorapidity region after LS2.

LHCb calorimeter system

LHCb goal after LS2 upgrades:
Collect up to 7.5 fb^{-1} of pp collisions per year (50 fb^{-1} total), with inst. Lumi up to $2*10^{33}$ cm^{-2}/s



LHCb calorimeter system



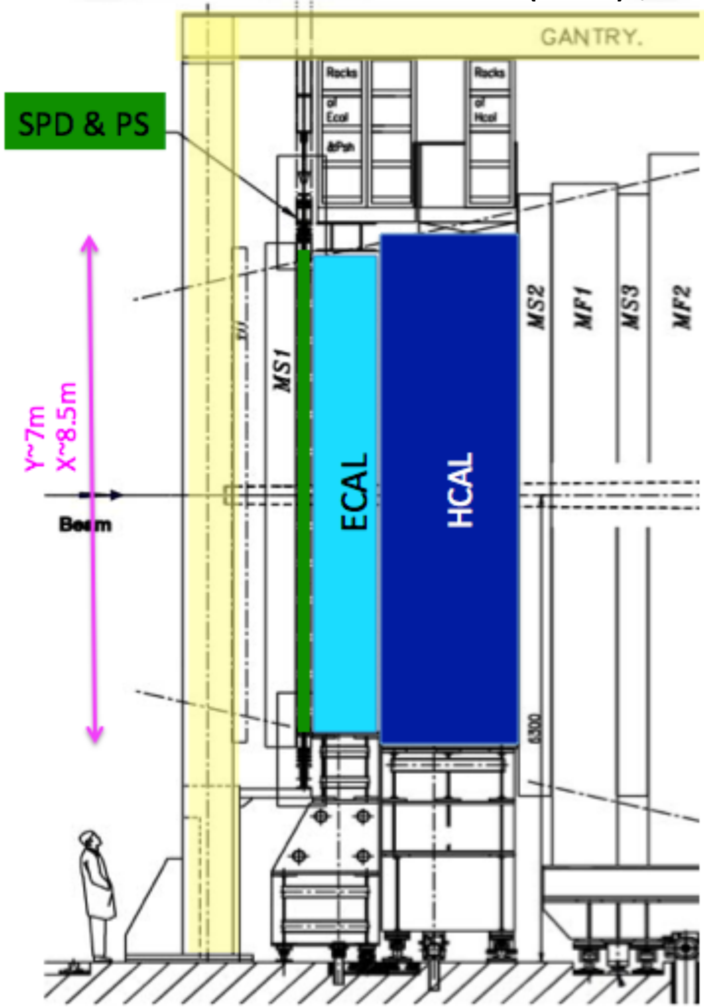
Electromagnetic calorimeter (with Preshower)

Hadronic calorimeter

LHCb calorimeter system

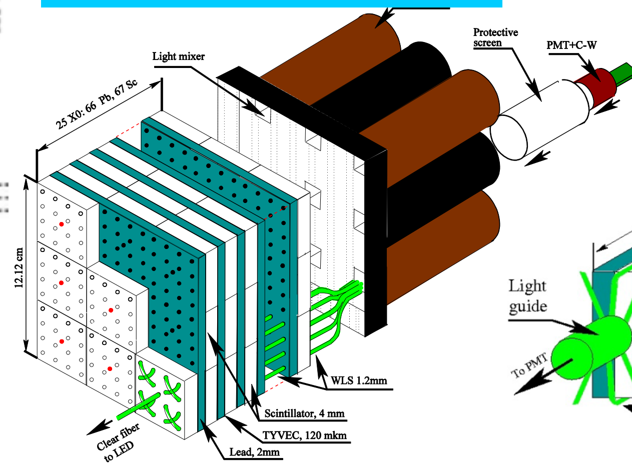
LHCb calorimeters are based on scintillator/WLS technique with light readout using PMT:

Scintillator Pad Detector (SPD) ,Preshower (PS), ECAL and HCAL

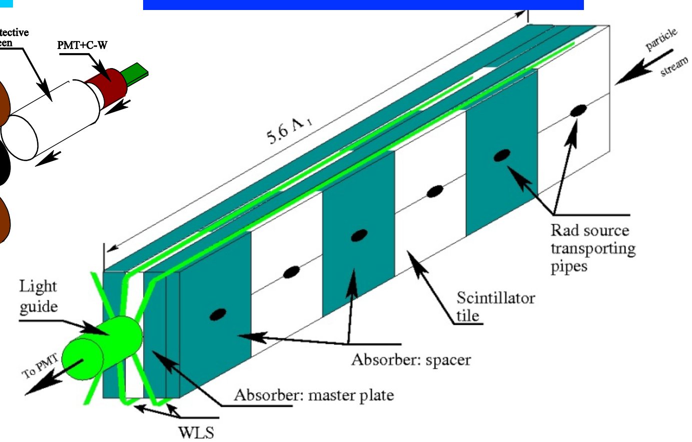


- **ECAL**: Pb/scint. Shashlik, 25 X_0 , 6016 cells,
- **SPD&PS**: Pb/scint sandwich, cells matching ECAL
- **HCAL:** Fe/scint. TileCal, 5 longitudinal depths , 1488 cells

ECAL Shashlik Module



HCAL TileCal Module

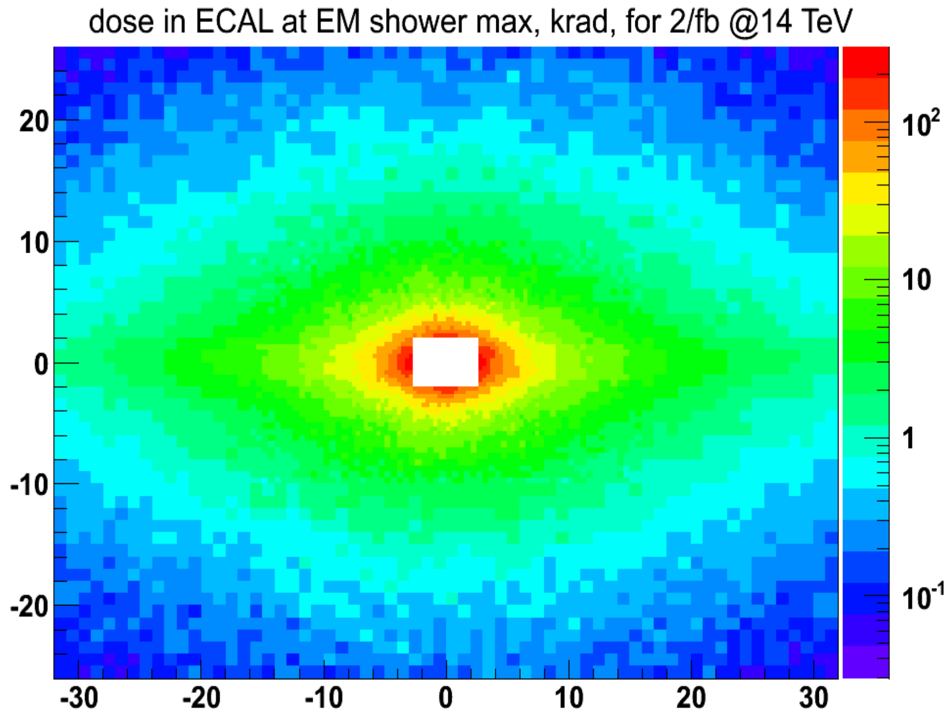


Calorimeter system provides:

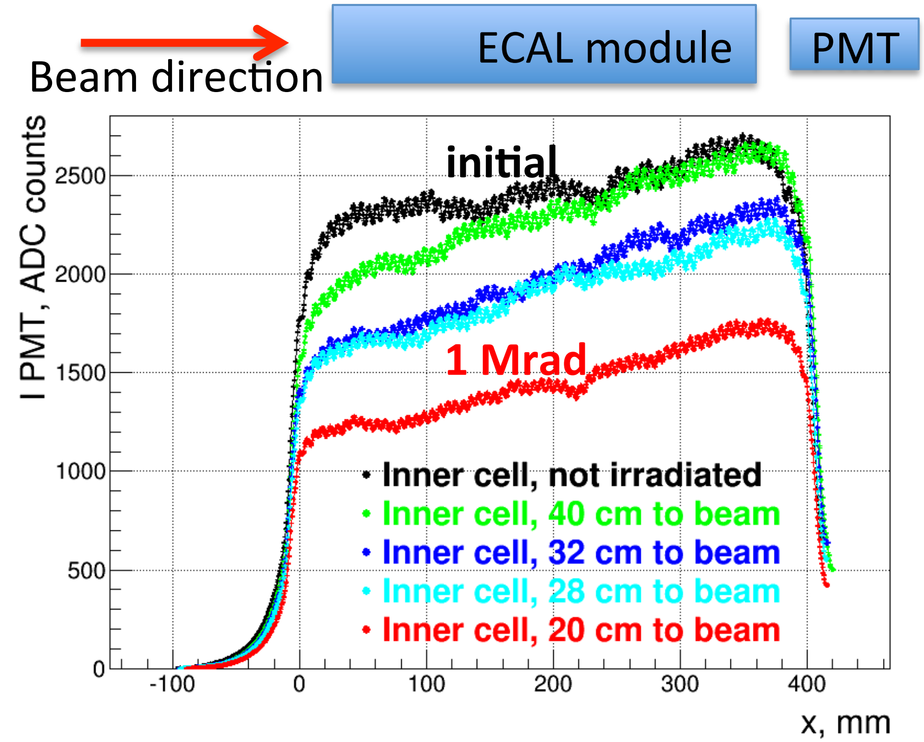
- **L0 trigger** on high p_T $e^{\pm}$, π^0, γ, hadron
- precise **energy measurement** of $e^{\pm}$ and γ
- **particle identification:** $e^{\pm}$/γ/hadron; contributes to Muon ID

Longevity of LHCb ECAL

Simulation of Radiation Doses in ECAL:
~6 Mrad is expected for 50 fb^{-1} in Shower Max region, ECAL cells closest to the beam pipe



Measurement of Signal Degradation:
~ x2 reduction in the light output is seen for inner most cells after ~1 Mrad (red vs black)

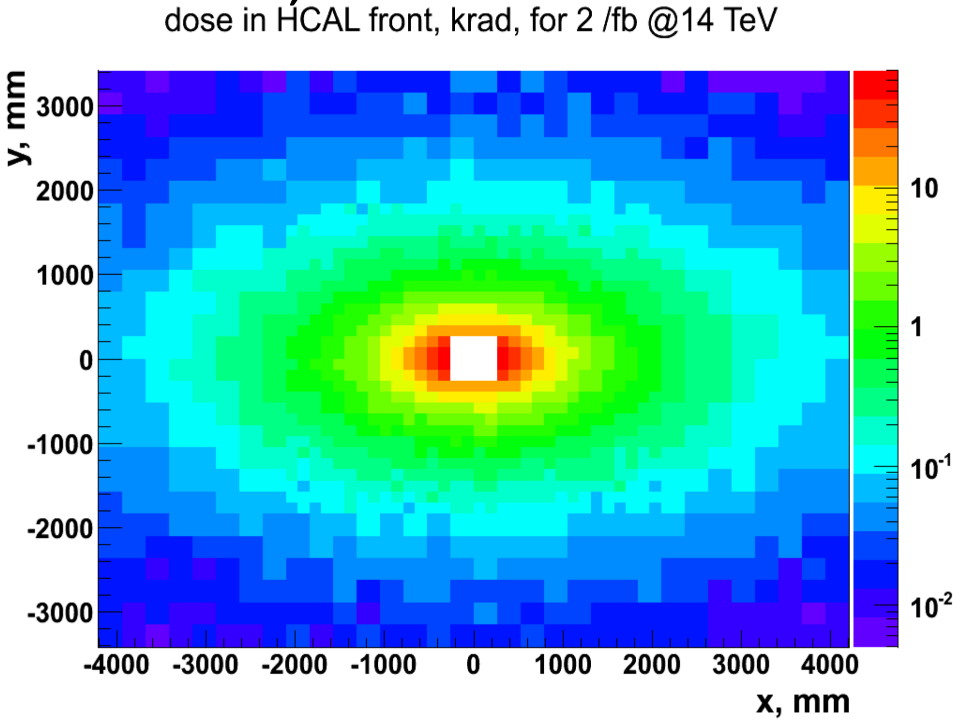


Reduction by x5 in light output is **acceptable** from resolution point of view.
-> The performance of ECAL central modules is expected to remain satisfactory till LS3.

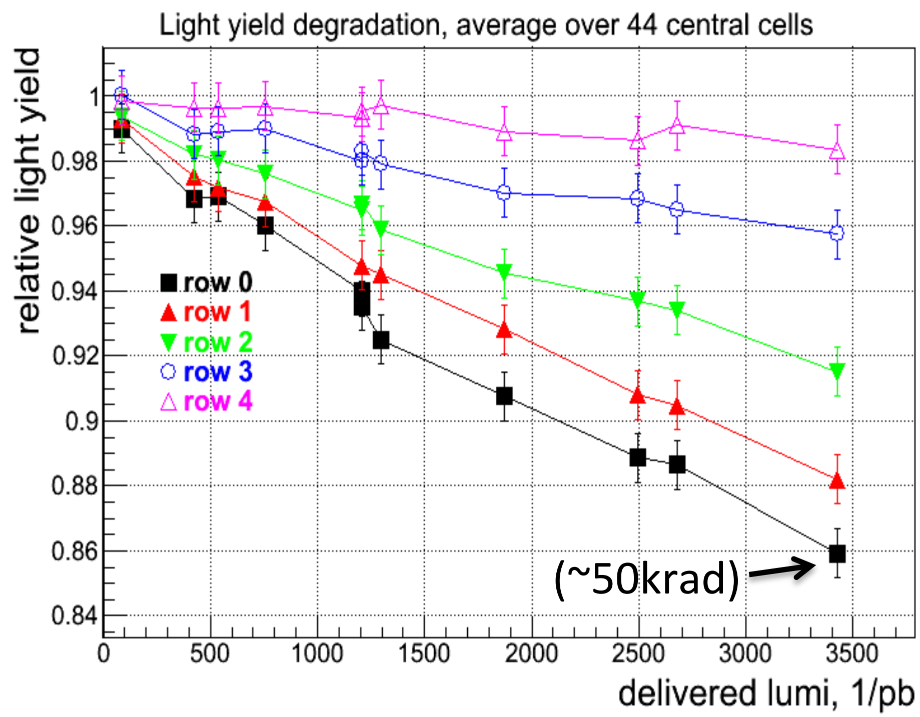
-> LHCb plans replacement of ECAL central modules (48 out of ~ 6000) during LS3.

Longevity of LHCb HCAL

Simulation of Radiation Doses in HCAL: ~1 Mrad for 50 fb^{-1} is expected for the up-stream front, central cells of HCAL



Observed Signal Loss for HCAL central cells: ~15%/ 3.4 fb^{-1} (2011+2012)



Up to LS2 (8-10 fb^{-1}), signal degradation in HCAL central cells will be compensated by re-calibration.
After the trigger upgrade (in LS2), the HCAL will not be used to provide the L0 trigger for high-p_T hadrons.
For other (non-trigger) applications, the loss of central cells will not be critical.

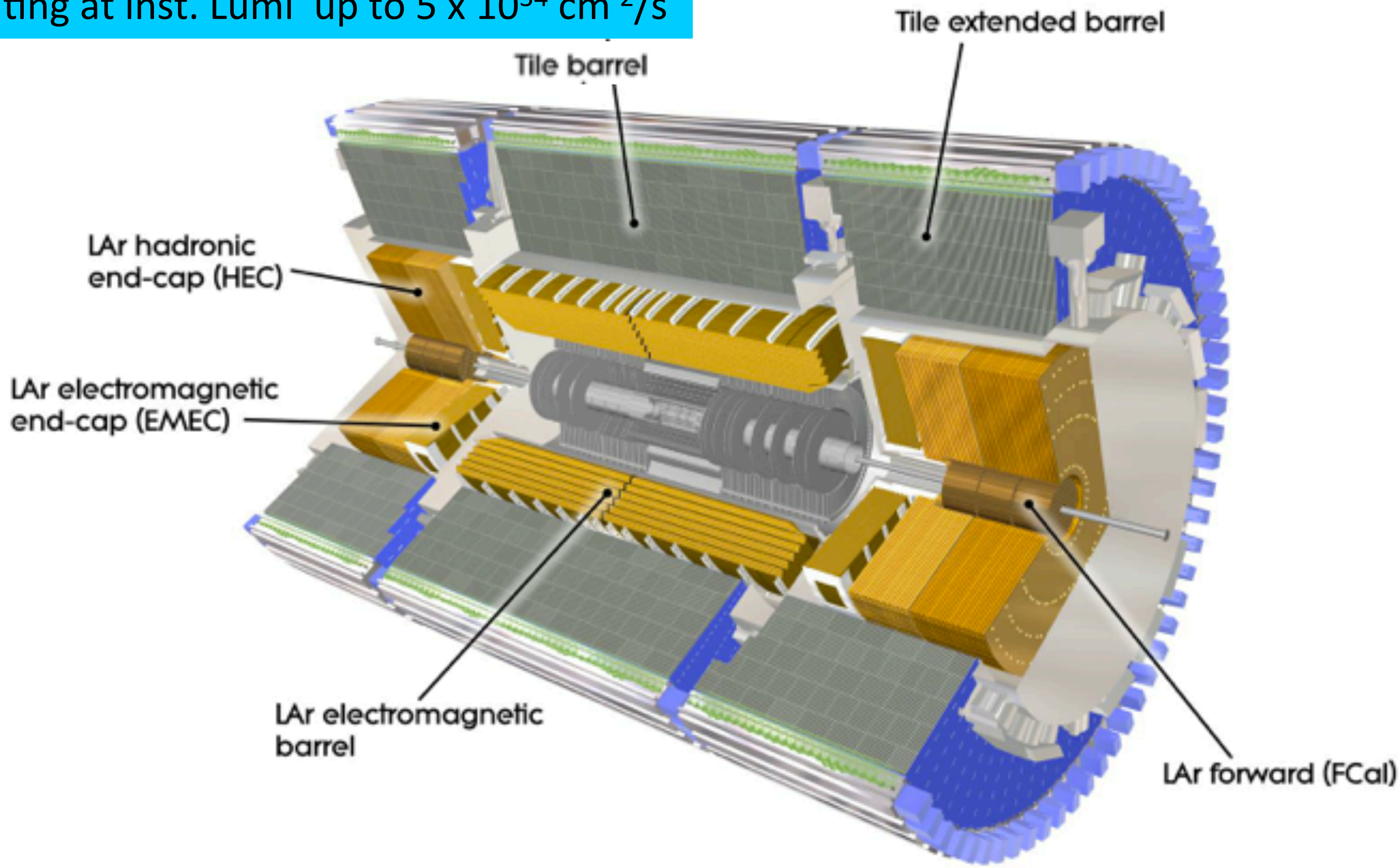
LHCb HCAL modules will not be replaced for Phase2

ECAL modules closest to the beam will suffer significant radiation damage. ECAL requires substituting modules closest to the beam during LS3, spare modules for replacement exist.

HCAL modules closest to the beam will also suffer significant radiation damage, but they will not be replaced. The loss is acceptable, as after LS2 upgrades, LHCb will switch to 40 MHz readout and high p_T hadron trigger will be based on tracker information.

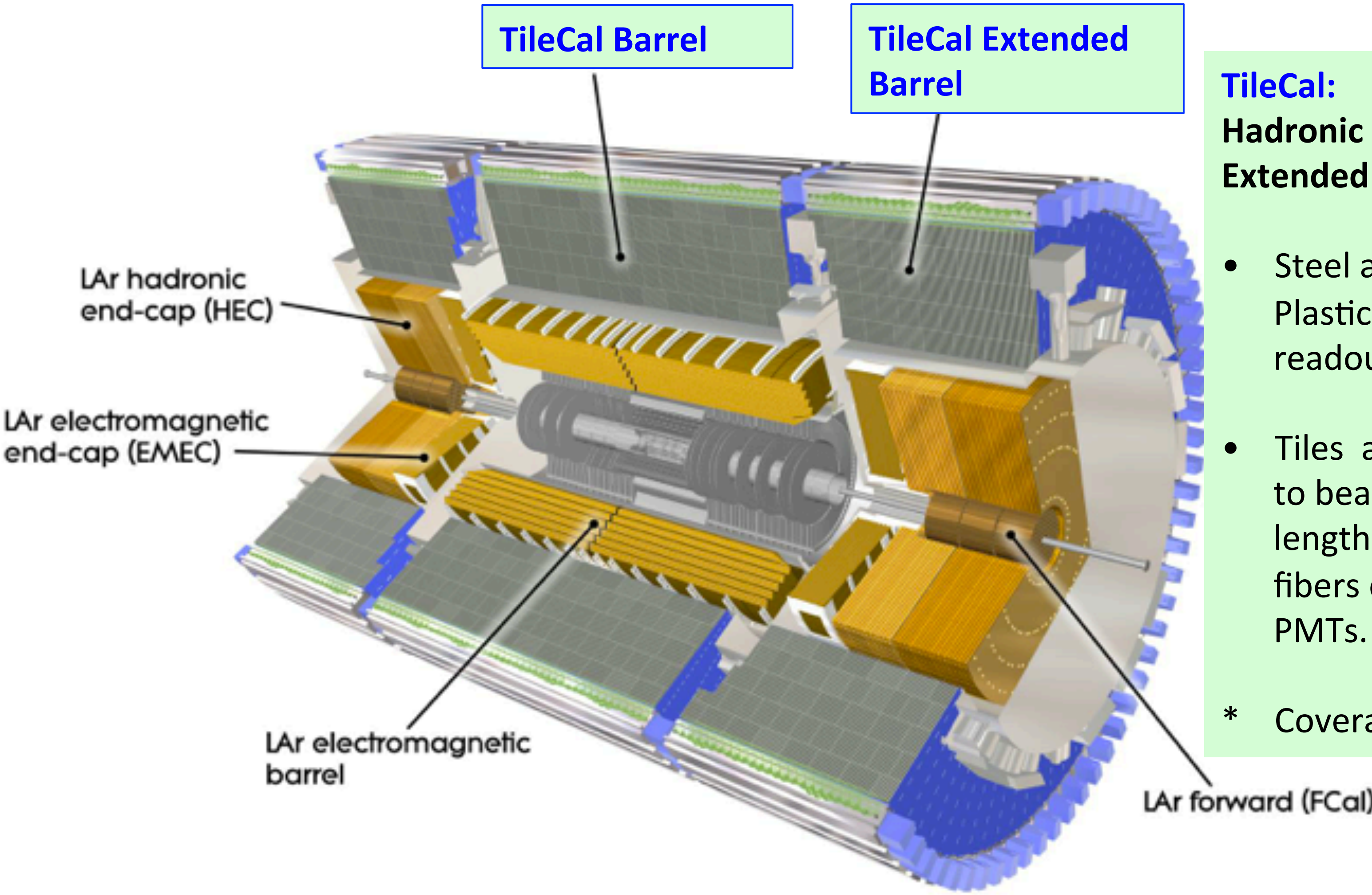
ATLAS calorimeter system

ATLAS goal after LS3:
Collect up to 3000 fb^{-1} over 10 years,
operating at inst. Lumi up to $5 \times 10^{34}\ cm^{-2}/s$



ATLAS calorimeter system

ATLAS EXPERIMENT
http://atlas.ch

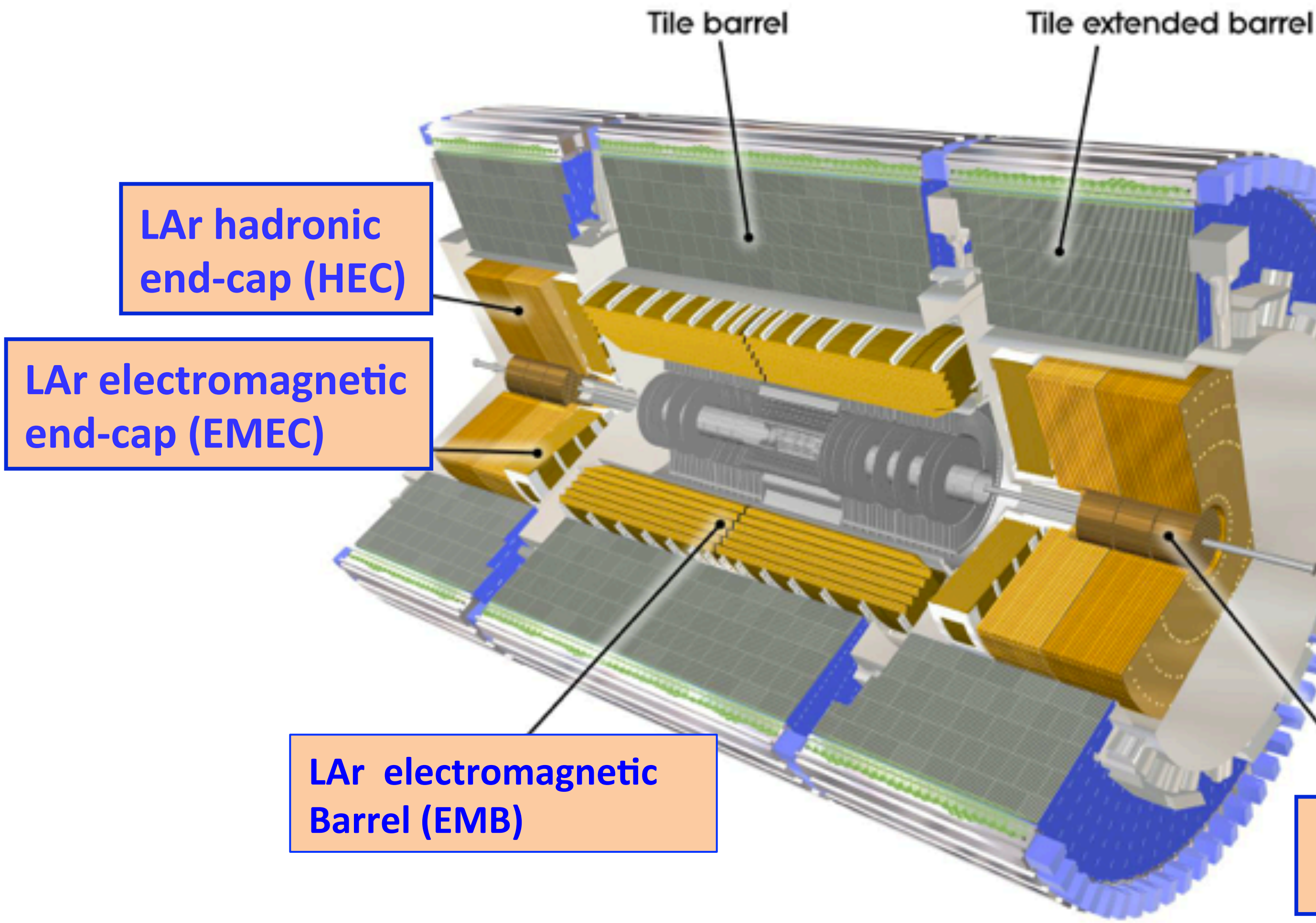


TileCal:
Hadronic Barrel and Extended Barrel

- Steel absorber with Plastic scintillator readout.
- Tiles are perpendicular to beam axis with wave-length shiftig (WLS) fibers carrying light to PMTs.

* Coverage: $|\eta|<1.7$

ATLAS calorimeter system



Liquid Argon:

EM barrel and end-cap
* Lead absorber
* Accordion geometry
* Barrel: $|\eta| < 1.475$
* End-cap: $1.375 < |\eta| < 3.2$

Hadronic end-cap
* Copper absorber
* Parallel plate electrodes
* Coverage: $1.5 < |\eta| < 3.2$

Forward Calorimeter
* tubes and rods in copper or tungsten matrix
* Coverage: $3.1 < |\eta| < 4.9$

Expected performance of ATLAS LAr and TileCal calorimeters

Longevity of ATLAS TileCal

- Maximum integrated dose for HL-LHC in TileCal will be between 0.2- 0.3 Mrad.
- Expected signal loss ~ 30% (for 3000 fb^{-1}).
- The expected signal degradation in TileCal can be corrected in the reconstruction.

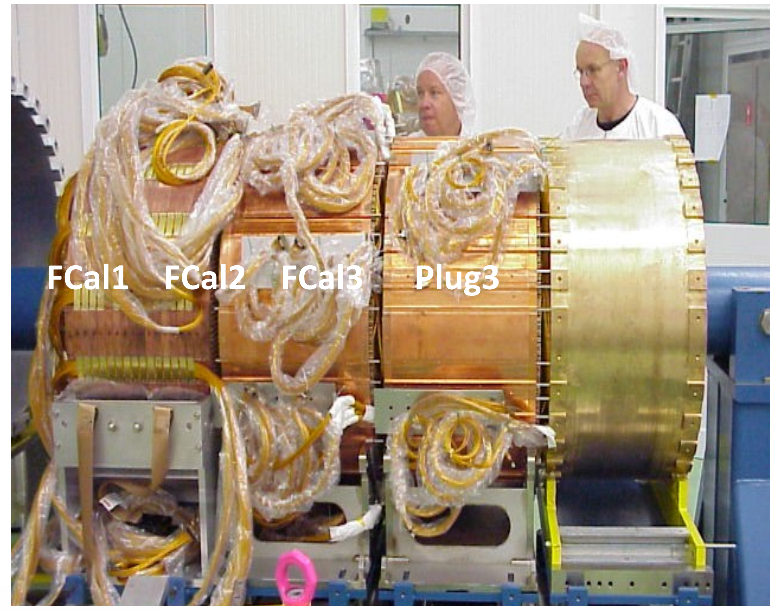
Longevity of ATLAS LAr

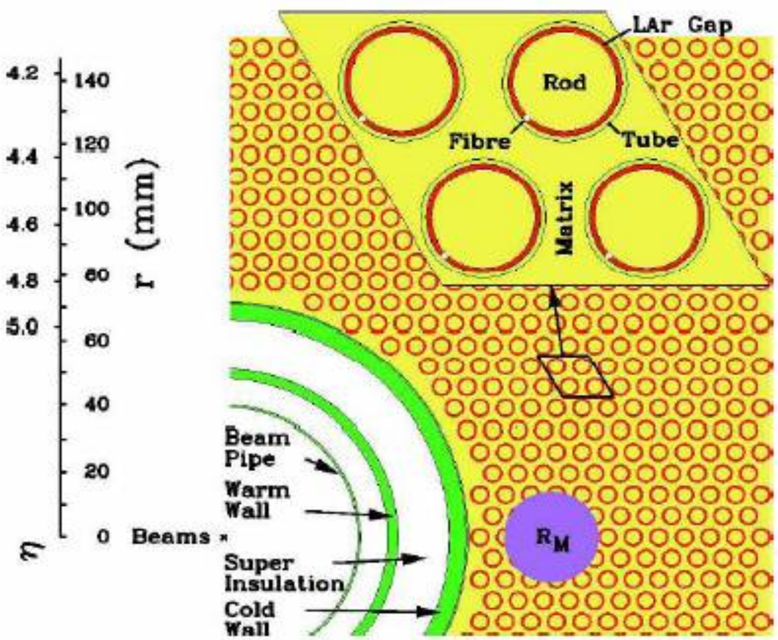
- Liquid Argon calorimeters are intrinsically radiation tolerant.
- Integrated dose in LAr expected during Phase2 will not pose operational problems.
- The challenge for operations of LAr calorimeters is high instantaneous luminosity leading to high flux of particles crossing LAr gaps.
- The issue is especially important in the forward region ($3 < |\eta| < 5$) where flux of particles during Phase2 operations can reach beyond $5 * 10^5$ kHz/cm^2 .

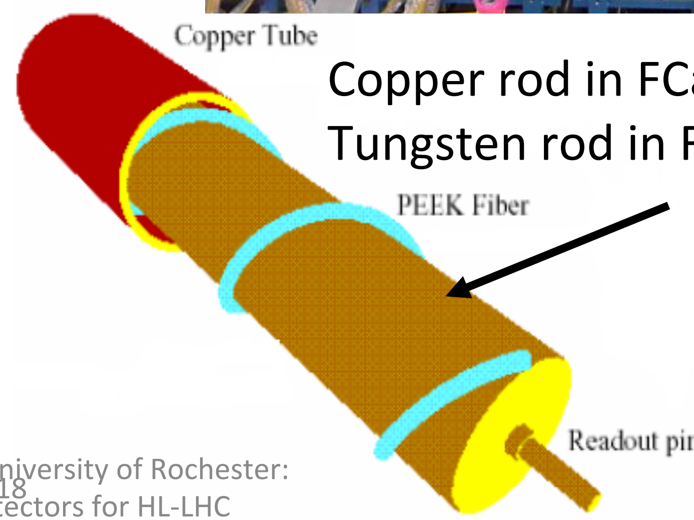
Barrel TileCal can operate through entire Phase2 of LHC program.
Barrel and Endcap LAr calorimeters will maintain their performance throughout Phase2 of LHC

ATLAS Forward Calorimeter

- **3 modules in each end-cap, 3.1<|η|<4.9**
  - FCal 1: electromagnetic, LAr-Cu, $28X_0$
  - FCal2/3: hadronic, LAr-W, 2x3.7λ
- **LAr gaps : 0.25, 0.375, 0.5 mm for FCal1, 2 & 3**
  - Narrow gaps were chosen to minimize sensitivity to high flux of particles in forward region.
  - No significant performance degradation expected during Phase1 of LHC.







Copper rod in FCal1 or Tungsten rod in FCal2/3

Limitations of present FCal at high instantaneous luminosities

In present FCal, there are three mechanisms that could lead to performance degradation at high instantaneous luminosities:

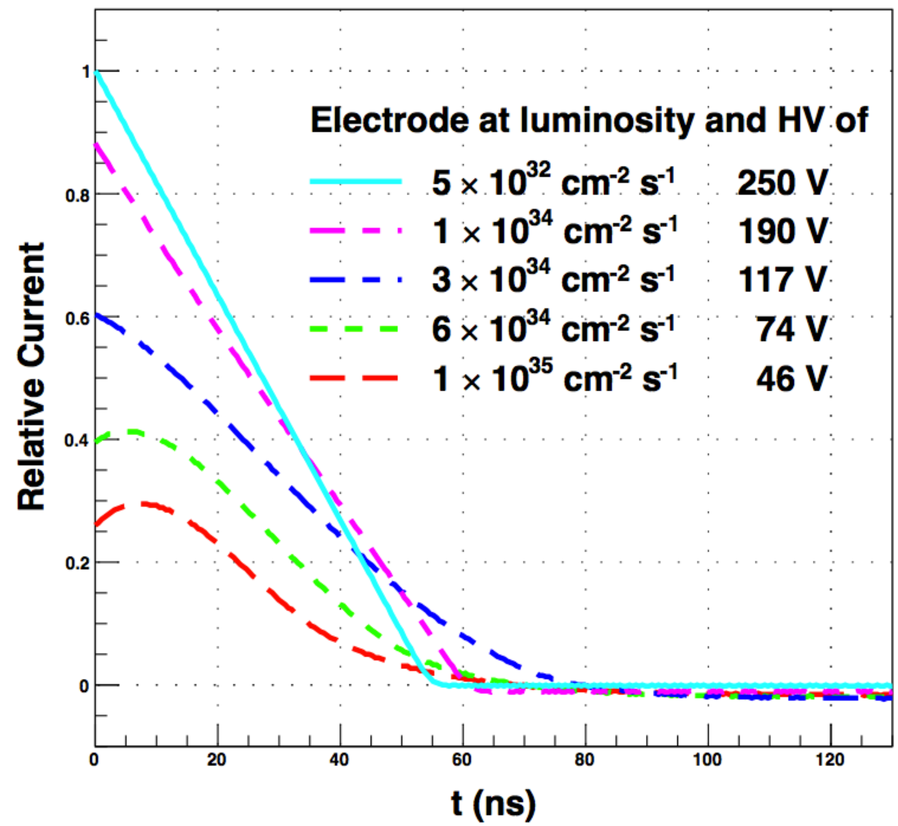
* **Space charge effect:** buildup of Ar^+ ions could lead to field distortion and in effect to signal distortion
* **Large currents** drawn through protection resistors (1 MΩ) could lead to HV drop and to a stronger signal degradation
* energy depositions producing excessive heat could lead to **bubble formation in LAr**.

These effects would degrade the response of the FCal1 in the high |η| region:

Performance implications:

- Missing E_T resolution, tails
- Forward jet tagging

ATLAS Simulation, FCal1 at η=4.7



FCal mitigation options

Additional studies are underway to quantify the expected level of degradation in FCal during Phase2 operations. Three options are considered:

0. If expected degradation of signal is limited, apply corrections, but **DO NOT replace FCal**
   – It also needs to be proven that the LAr in the FCal under high instantaneous luminosity conditions will not form bubbles

1. **Replace FCal modules** with new ones (sFCal):
   – Implement smaller LAr gaps, 100 μm, instead of 269 μm in present FCal1, (see next slide), lower value of protection resistors to 100kΩ , introduce cooling loops
   – As installation of sFCal would require opening the endcap cryostat cold volume , this option would be pursued only if there is a need to open the cold volume, in particular to replace HEC cold electronics (under investigation)

2. **Install additional calorimeter**, miniFCal, in front of current modules to absorb part of the increased flux
   – Various technologies under investigation

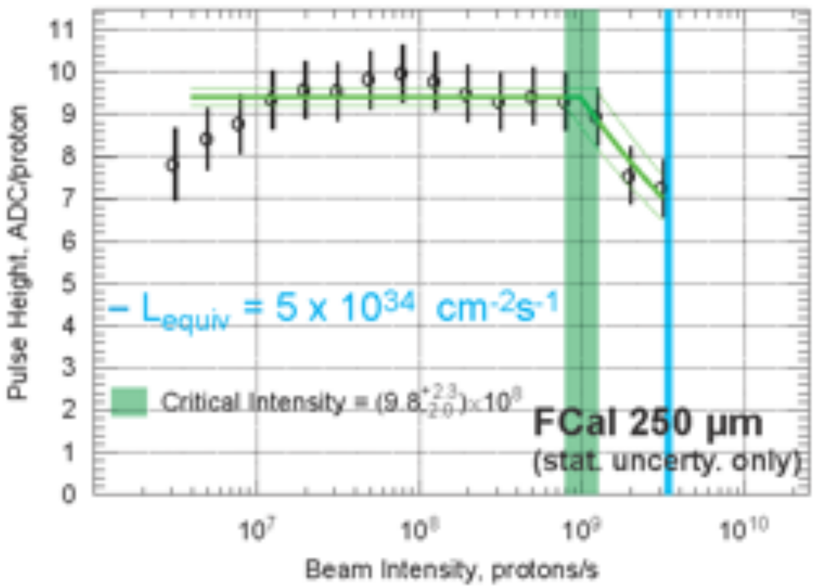
sFCal Option

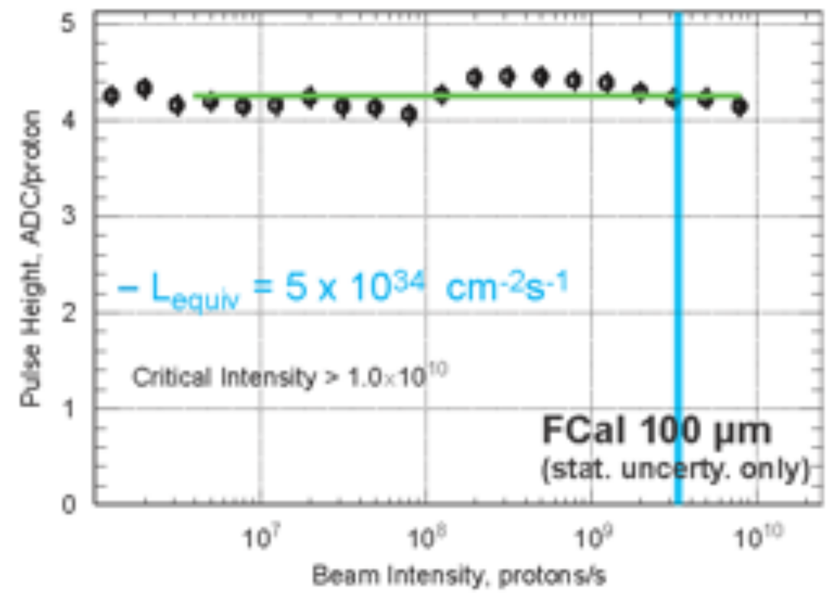
NIM A 669 (2012) 47

HiLum testbeam (Protvino):

* The current FCal will see degraded pulse shapes already at $1.5*10^{34}$ cm^{-2}/s

- The sFCal is in the safe regime for all HL-LHC luminosities





Green band== critical intensity == intensity at which pulse height degrades (stat. errors only)

Blue line = beam intensity equivalent to inst. Lumi= $5*10^{34}$ cm^{-2}/s

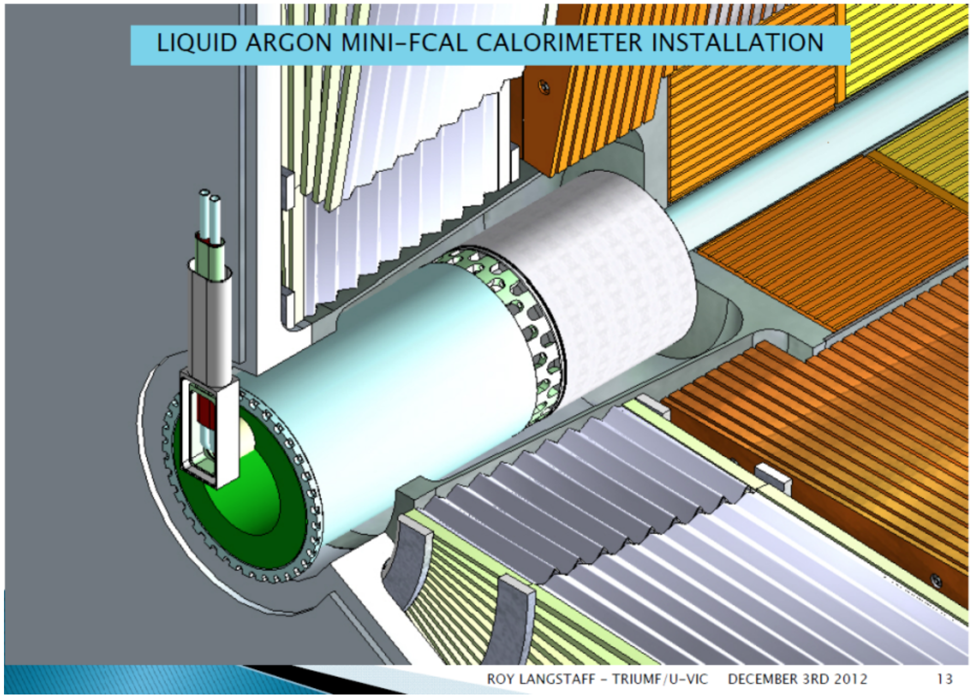
New measurements and simulation are underway to reduce systematic uncertainties on the critical intensity and to extract FCal pulse shapes.

This information will be used in HL-LHC performance simulation of FCal (MET, jets,..)

MiniFCal Option

MiniFCal sampling calorimeter would be installed in front of current FCal to absorb part of the increased flux

- Basic concept: 12 copper absorber disks reducing energy deposit in FCal1 by 45%
- Challenges for active detector area: neutron fluence up to ~5 x 10^{17} n/cm^2
- 3 technologies have been considered :
  - Diamond sensors → studied in detail but not favored any more
  - High-pressure Xe → basic R&D required
  - **LAr → well known technology**
    - engineering issues to be resolved (LAr supply line)
    - impact of moderator geometry on neutron background
    - simulation of detector geometry and energy response needed



Currently LAr technology is favored among the MiniFCal options, but more studies required

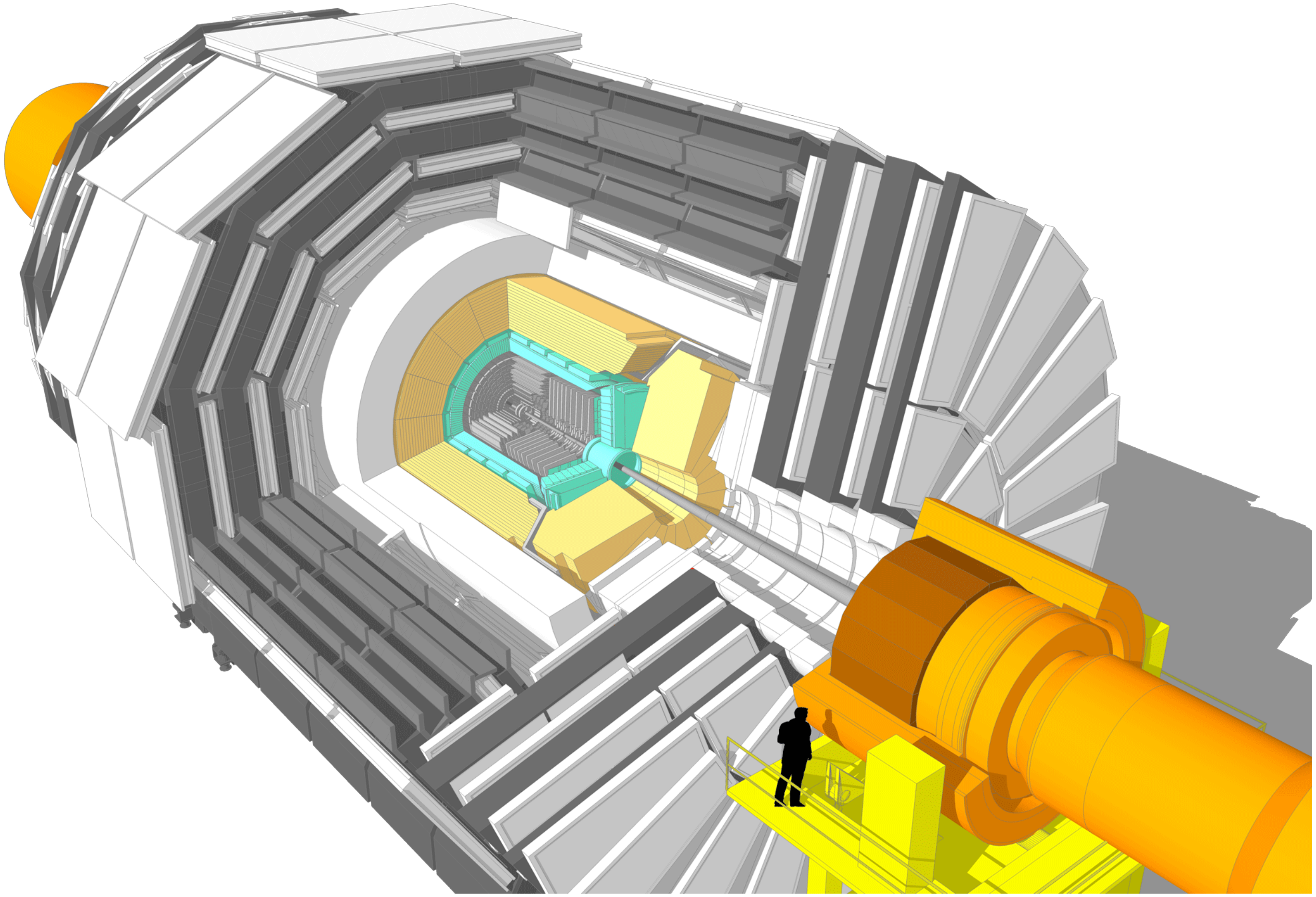
Barrel TileCal will suffer only moderate damage and can operate through entire Phase2 of LHC program.

Barrel and Endcap LAr calorimeters are intrinsically radiation tolerant and will maintain their performance throughout Phase2 of LHC.

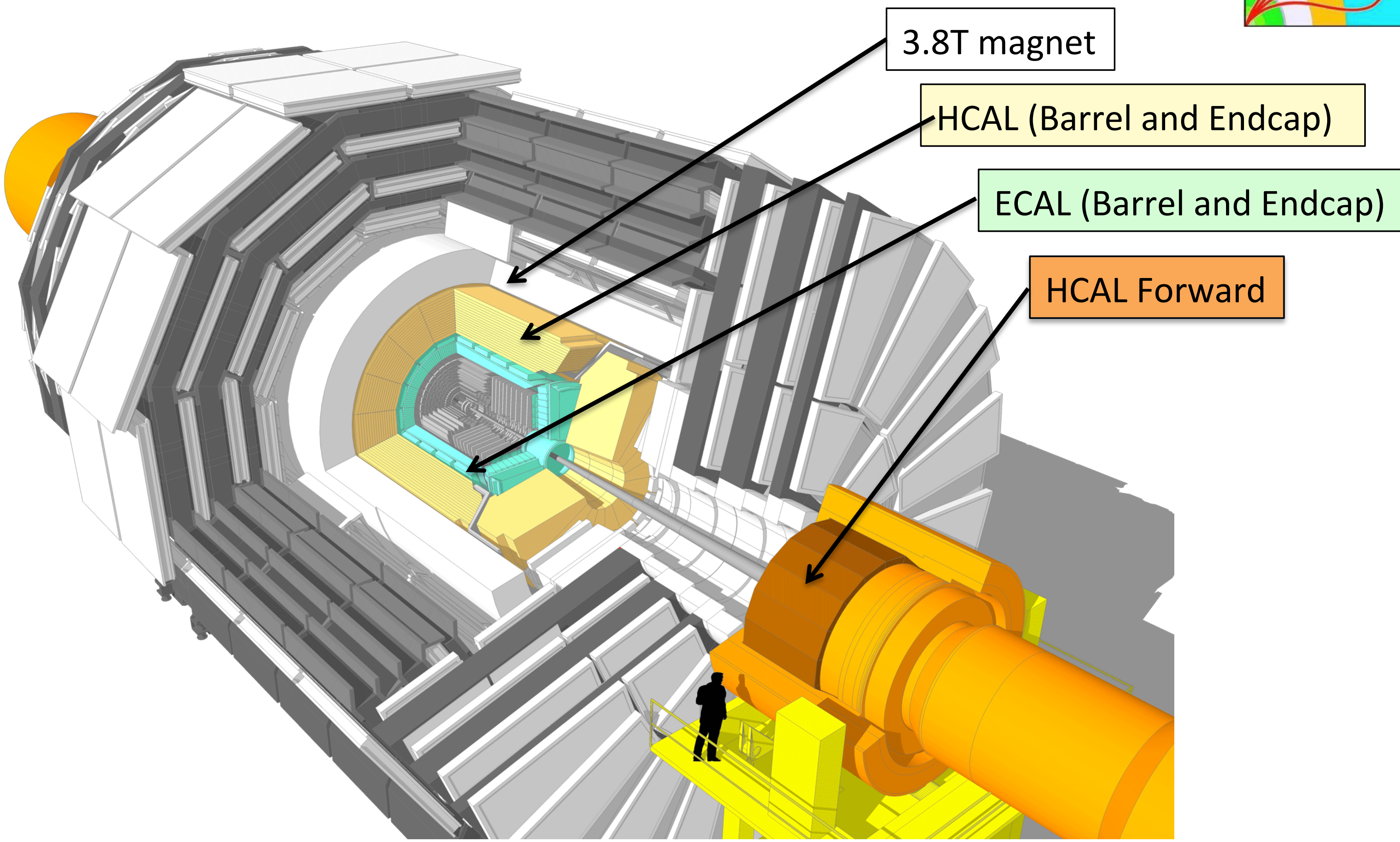
The FCal may partially suffer due to the high instantaneous rates, and may need to be replaced during LS3 or a new detector may need to be installed in front of it.

CMS calorimeter system

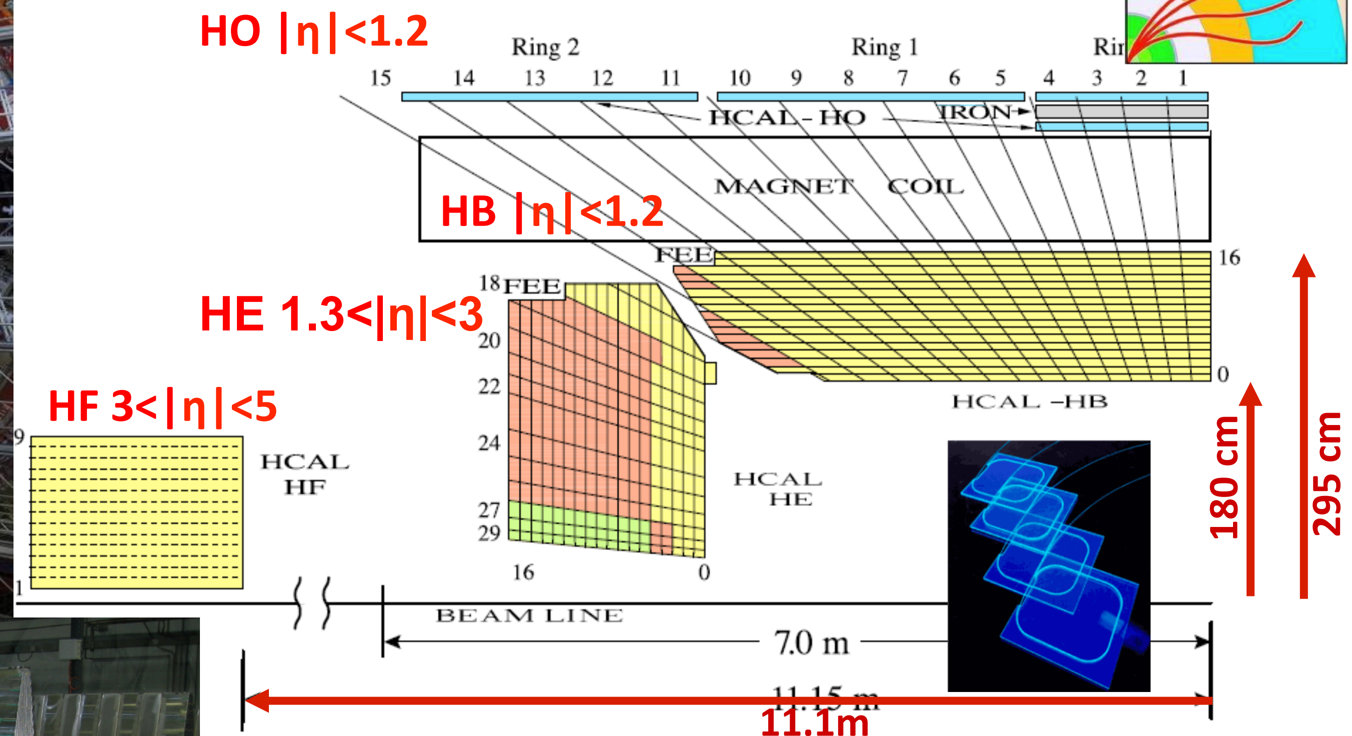
CMS goal after LS3:
Collect up to 3000 fb^{-1} over 10 years,
Operating at inst. Lumi up to 5×10^{34} cm^{-2}/s



CMS calorimeter system



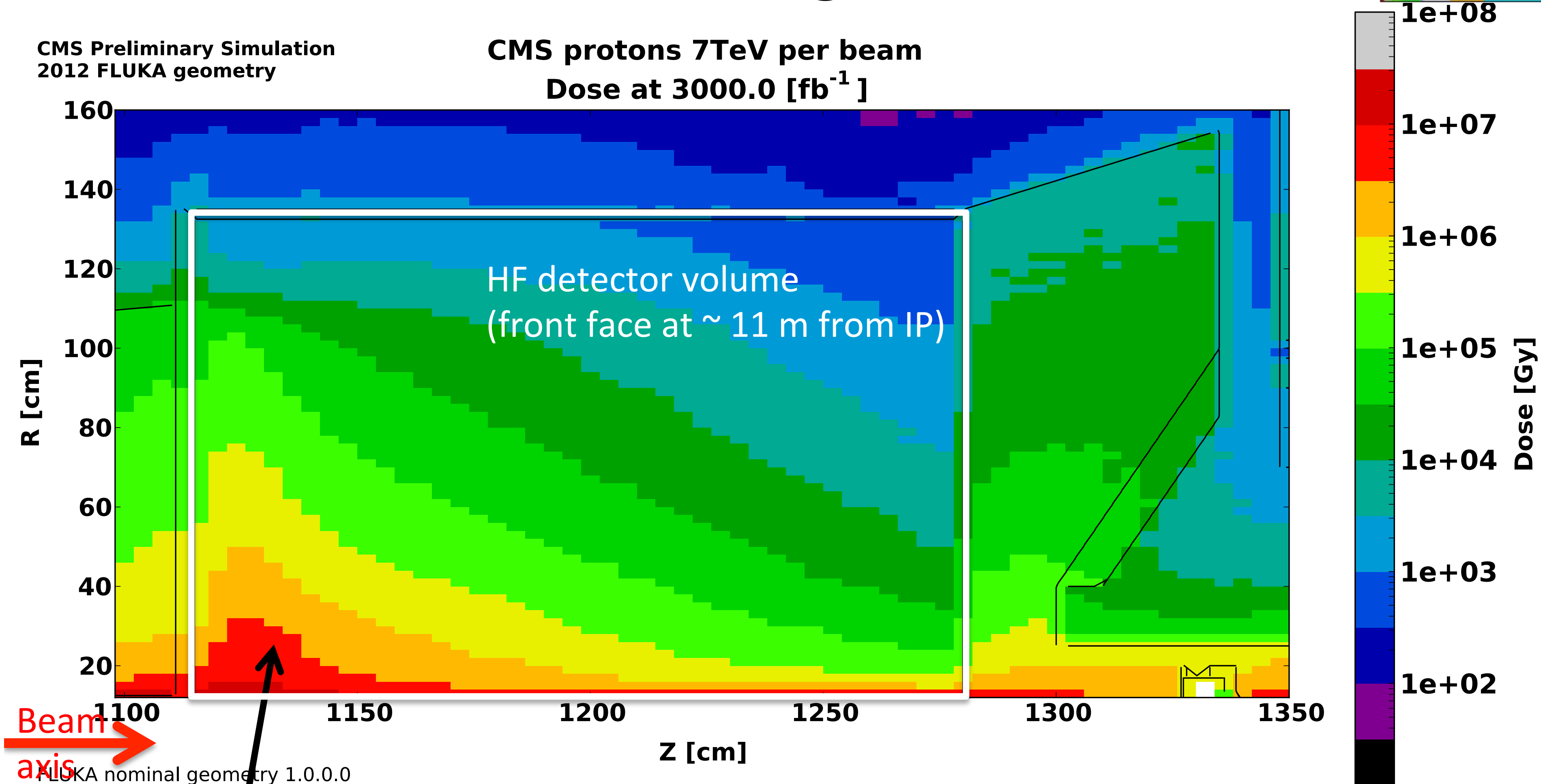
CMS HCAL



Hadron Barrel (HB) and Endcap (HE) calorimeters are sampling brass/scintillator tiles calorimeters. HB and HE cover |η|<3 range.

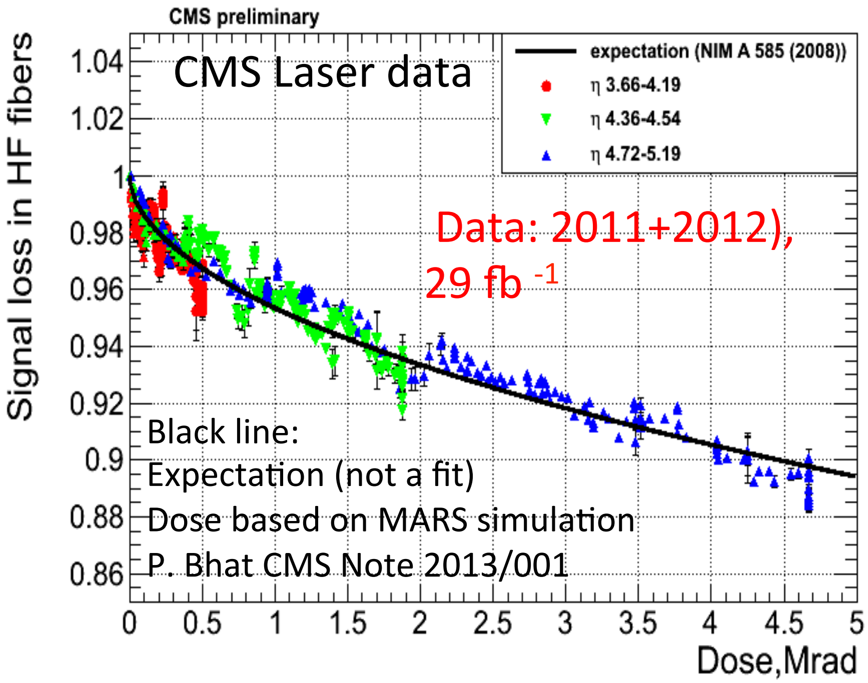
Hadron Forward (HF) calorimeter is made of steel absorber and quartz fibers emitting Cherenkov light. HF covers 3< |η| <5 range.

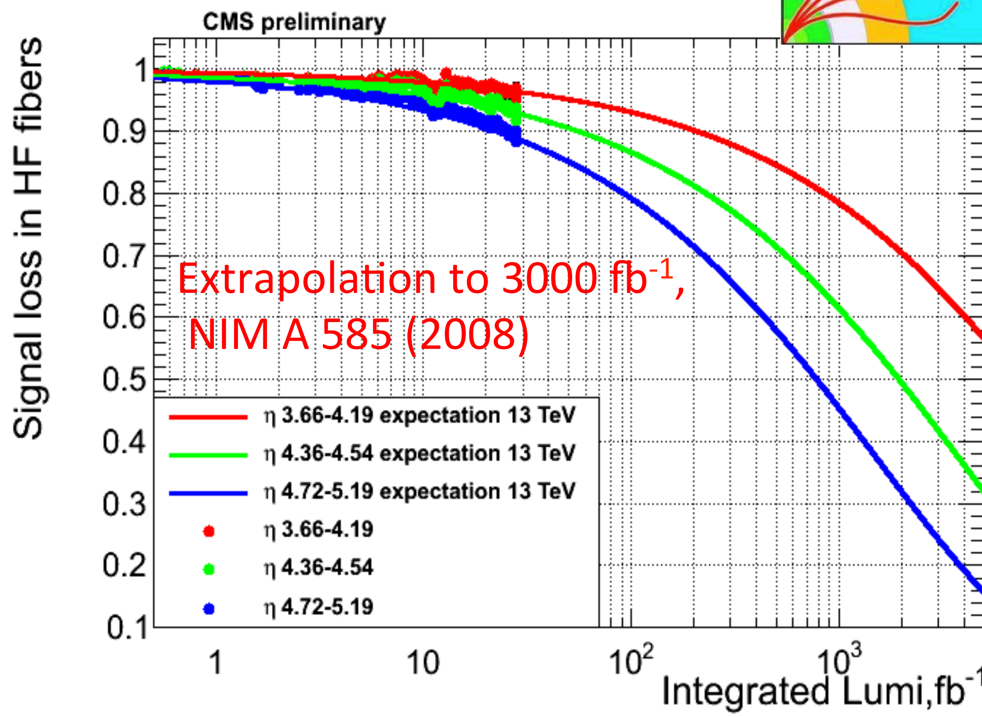
Radiation Environment: Simulated Dose map for CMS Hadron Forward region



HF front face/inner ring:
$0.5*10^7$ Gy (500 Mrad)

Radiation Damage to HF





Signal loss in HF due to radiation induced reduction of transparency of quartz fibers. Data are shown here as a function of Dose for three different eta ranges for exposure during 2011+2012 run (combined 29 fb^{-1}).

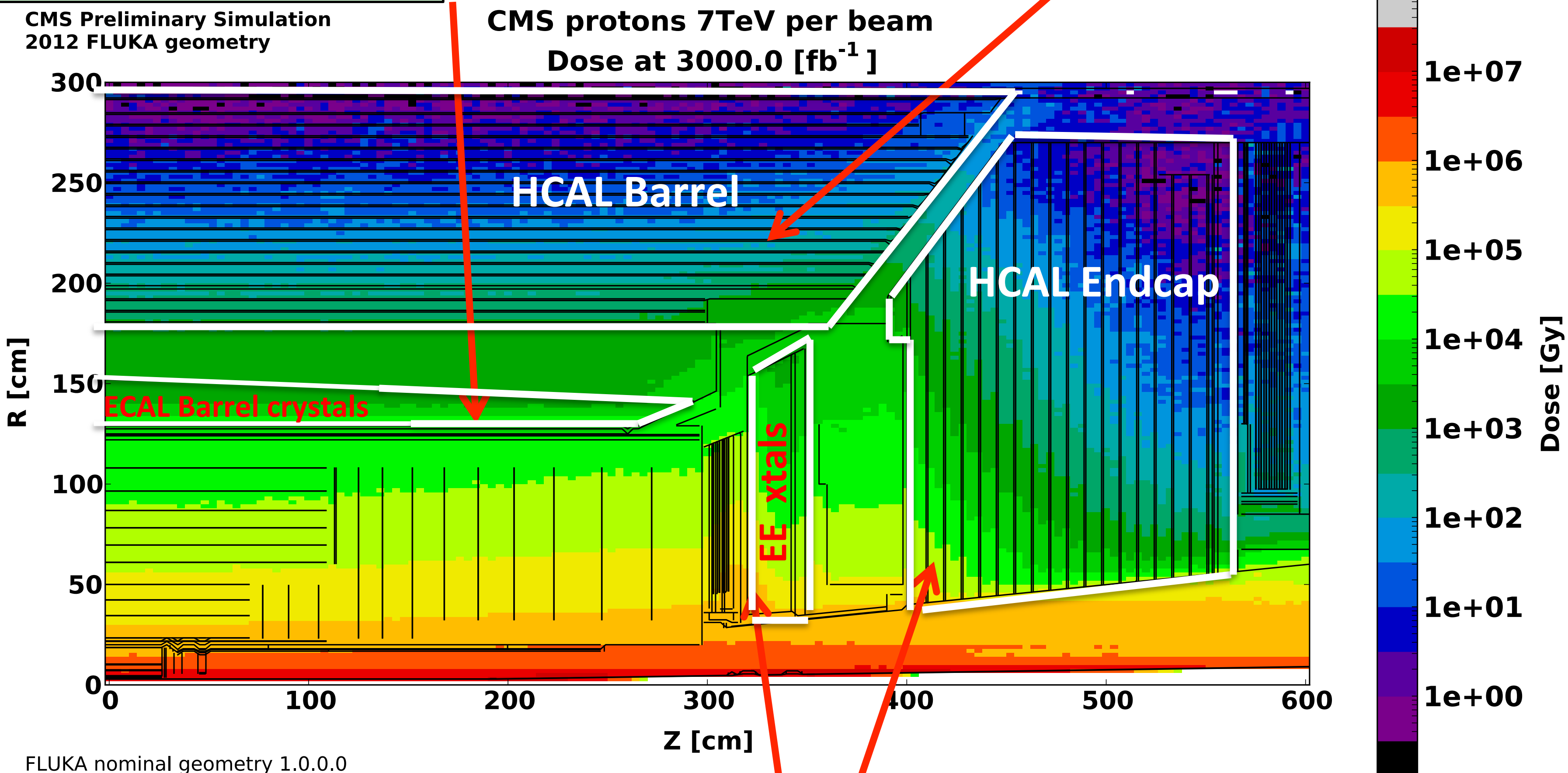
Expected loss of signal for up to 3000 fb^{-1}:
In the highest eta region, signal reduction by factor x3-x4 is expected and can be compensated by re-calibration.
HF will survive 3000 fb^{-1}, at least up to $\eta < 4.5$.

No upgrade of HCAL Forward is planned for LS3

Radiation Environment: Simulated Dose map for CMS Barrel and Endcap regions

ECAL Barrel
below 10^4Gy (1 Mrad)

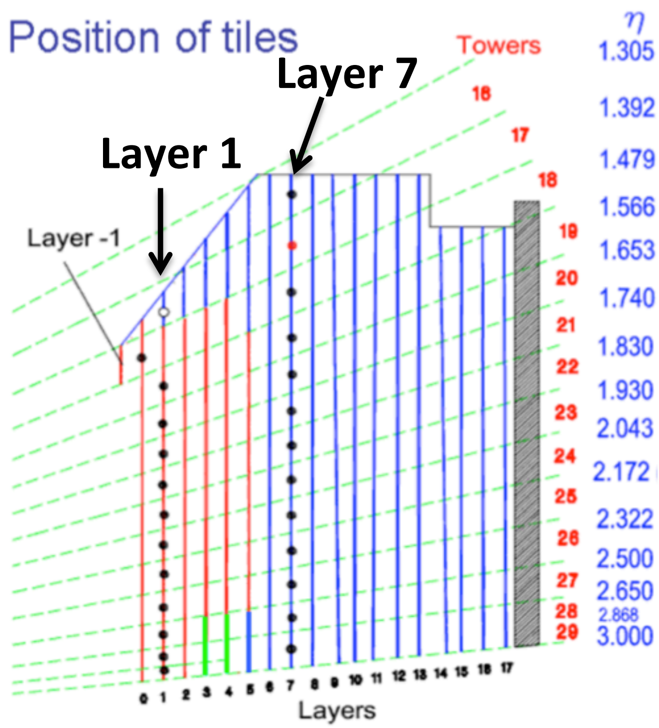
HCAL Barrel
below 10^3Gy (0.1 Mrad)

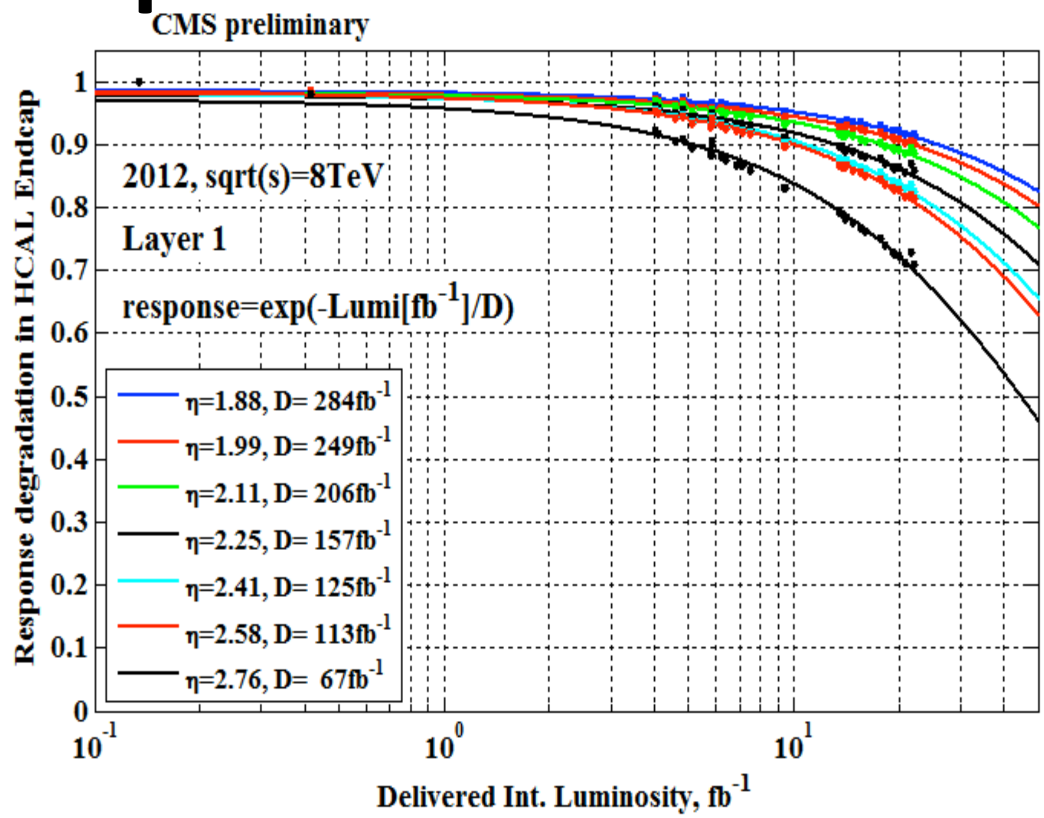


ECAL Endcap
At eta=2.6: $3*10^5$Gy (30 Mrad), $2*10^{14}$ h/cm^2

HCAL Endcap
up to 10^5Gy (10 Mrad)

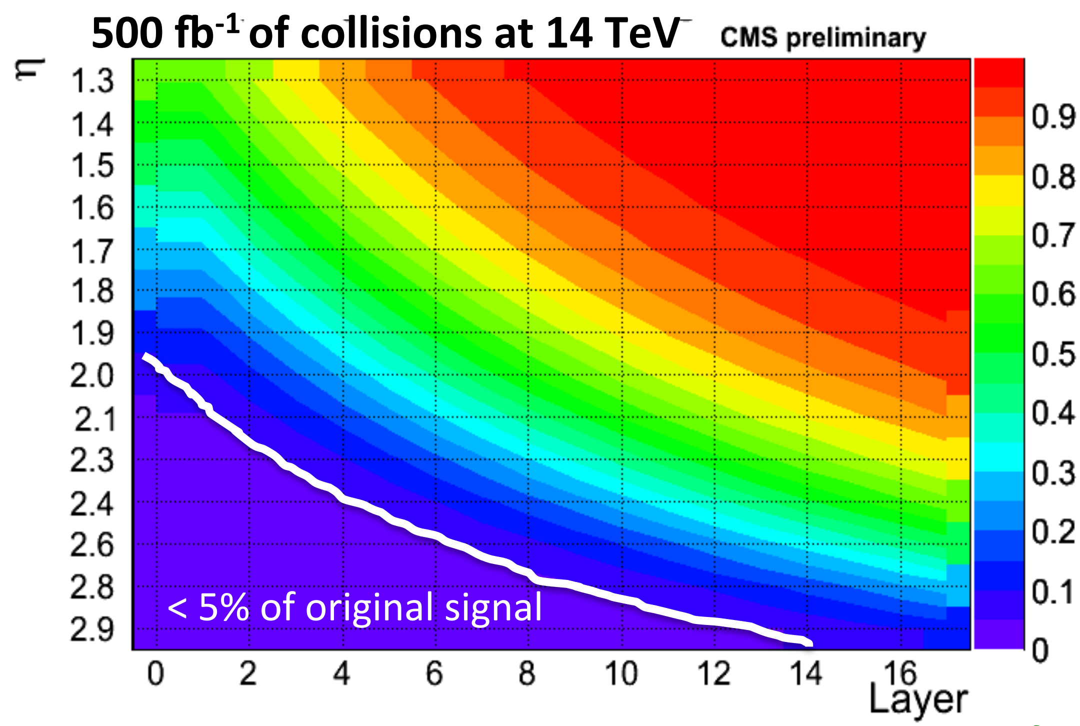
Observed Radiation damage: CMS Hadron Endcap: 22 fb^{-1}

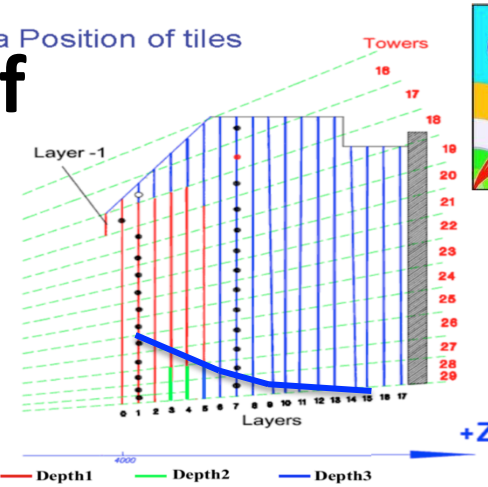




Degradation of signal in CMS HCAL Endcap as a function of integrated luminosity (2012 data).
Different colors correspond to different η rings of the HE.
Degradation of signal is shown for the 1st sampling layer (Layer 1) of HE.
After ~ 22 fb^{-1}, at highest η region (η ~ 3), we observe signal reduction of ~ 30%.
Data are well described using single exponent parameterization.

Extrapolated Signal Degradation of CMS Hadron Endcap





- ❑ Extrapolated degradation based on exponential parameterizations of observed damage as a function of sampling depth (layer) and η
- ❑ At 500 fb^{-1}, in the high η region, signal drops to 5% or less of the original value.

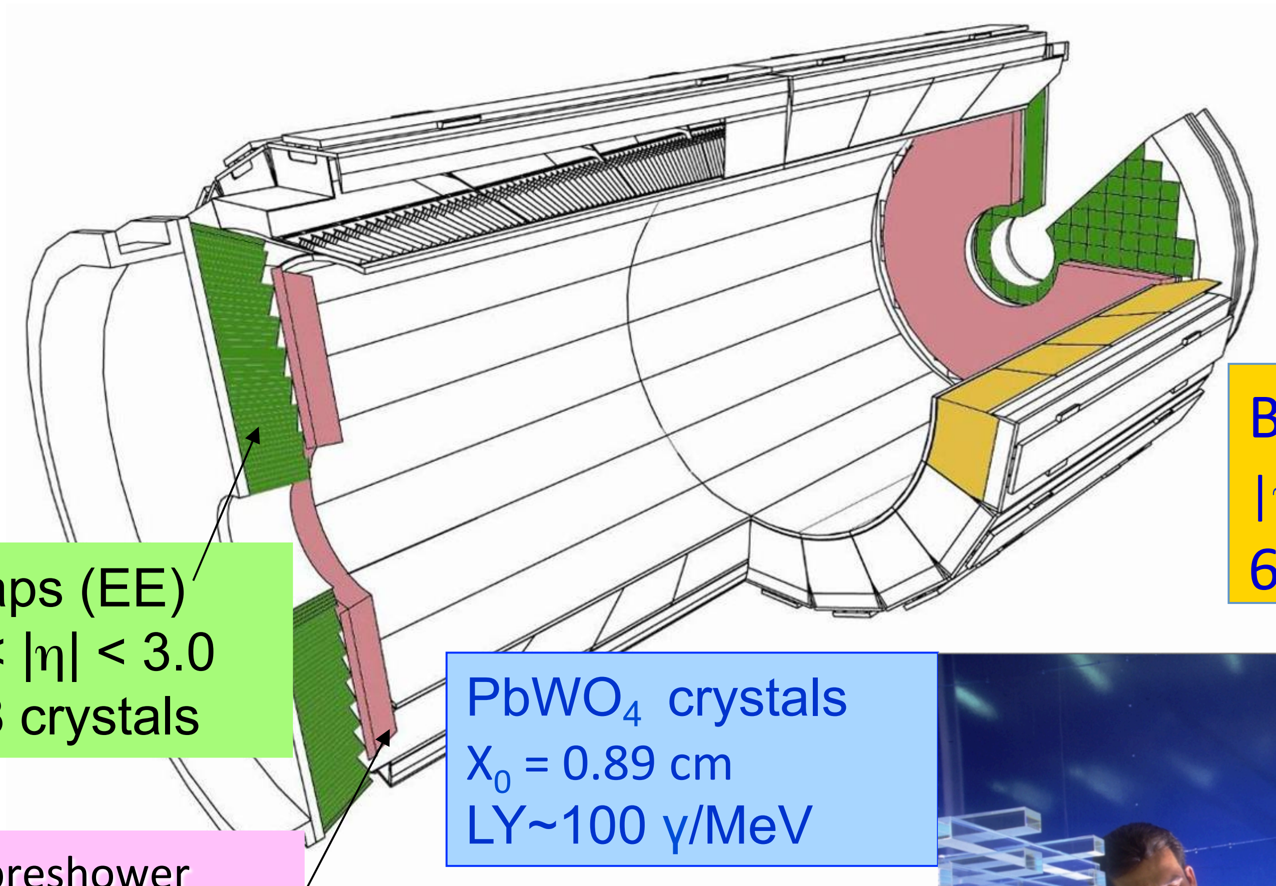
CMS will upgrade Front End Electronics of HE (and HB) in LS2.

This upgrade will ensure performance of HE up to LS3:

- ✓ **Photon Detection Efficiency (PDE) of SiPMs will be x3 higher than in present photodetectors.**
- ✓ **Depth segmentation will allow for re-weighing of radiation damage degradation.**

CMS HCAL Endcap calorimeter will be replaced during LS3

CMS ECAL

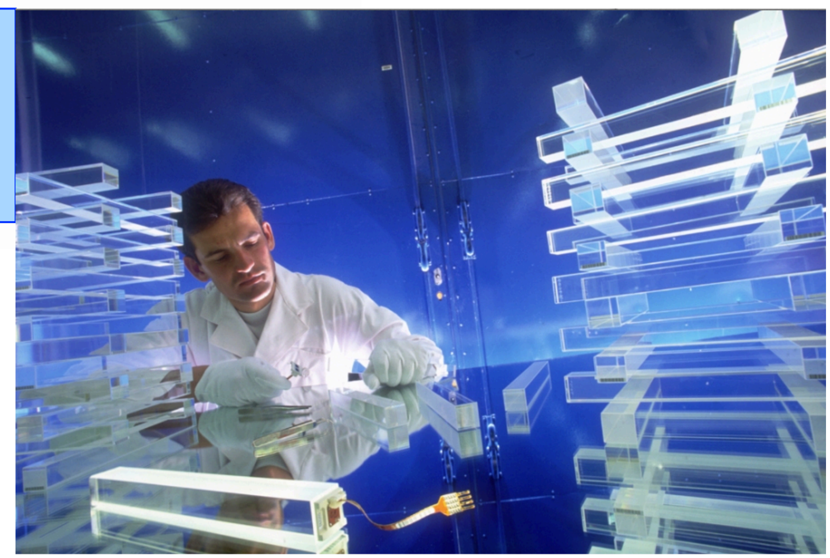


Endcaps (EE)
1.48 < $|\eta|$ < 3.0
14648 crystals

Pb/Si preshower
1.65 < $|\eta|$ < 2.6

Barrel (EB)
$|\eta|$ < 1.48
61200 crystals

$PbWO_4$ crystals
X_0 = 0.89 cm
LY~100 γ/MeV

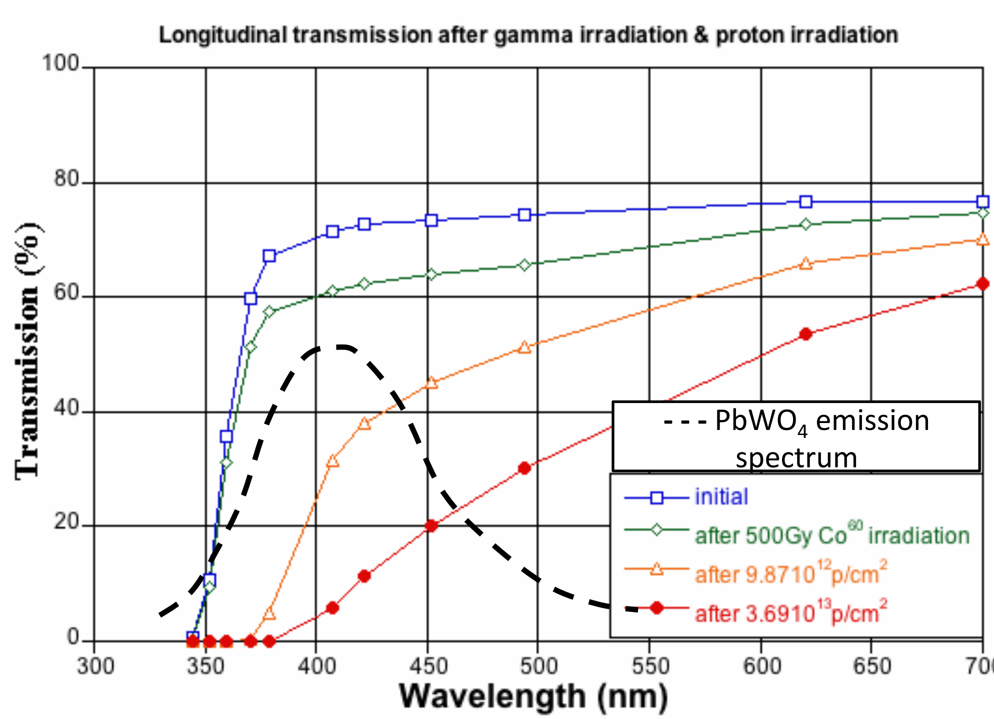


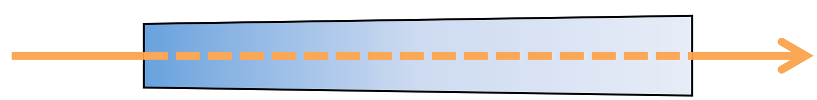
Radiation damage to crystals

Crystals are subject to two types of irradiation:

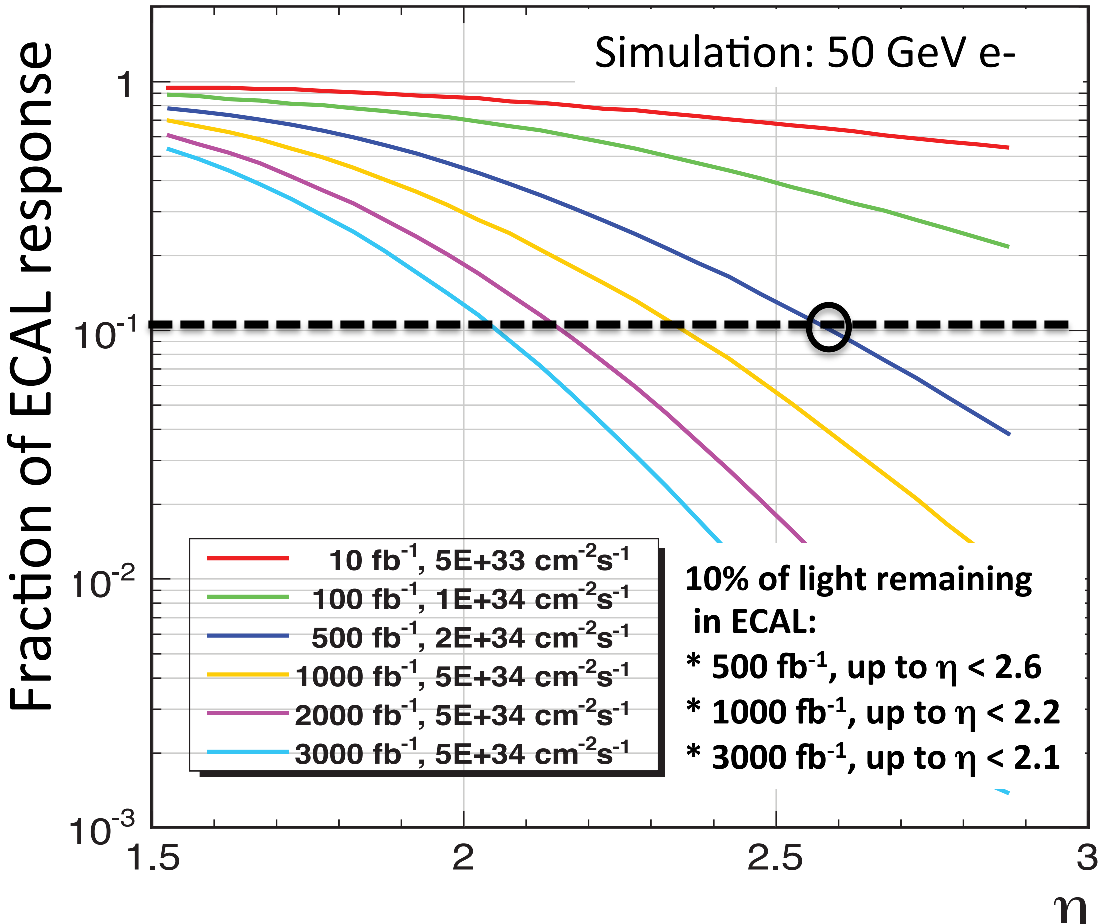
1. Gamma irradiation causes damage which is **spontaneously recovered** at room temperature.
* Recovery has been observed in 2011 and 2012 during long shutdowns, technical stops etc.
* Loss of transmission caused by γ irradiation for few fb^{-1} (at η = 2.6): **green line** vs. **blue line**

2. Hadron damage creates defects which cause light transmission loss. The damage is **permanent and cumulative** at room temperature.
* Loss of caused by proton irradiation:
  -> 150 fb^{-1} (at η = 2.6): **orange line** vs. **blue line**
  -> 600 fb^{-1} (at η = 2.6): **red line** vs. **blue line**
* Hadron damage **causes band-end shift** at low wave lengths of the $PbWO_4$ emission spectrum.





ECAL Endcaps response degradation



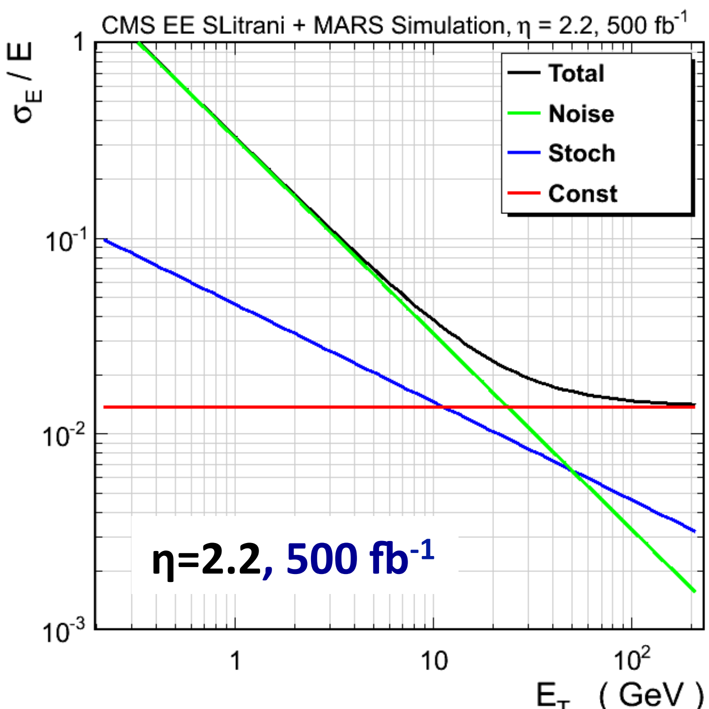
At 500 fb^{-1}, $|\eta| < 2.6$ regions of EE would have **correction factors of x10** or smaller to adjust for the light loss.

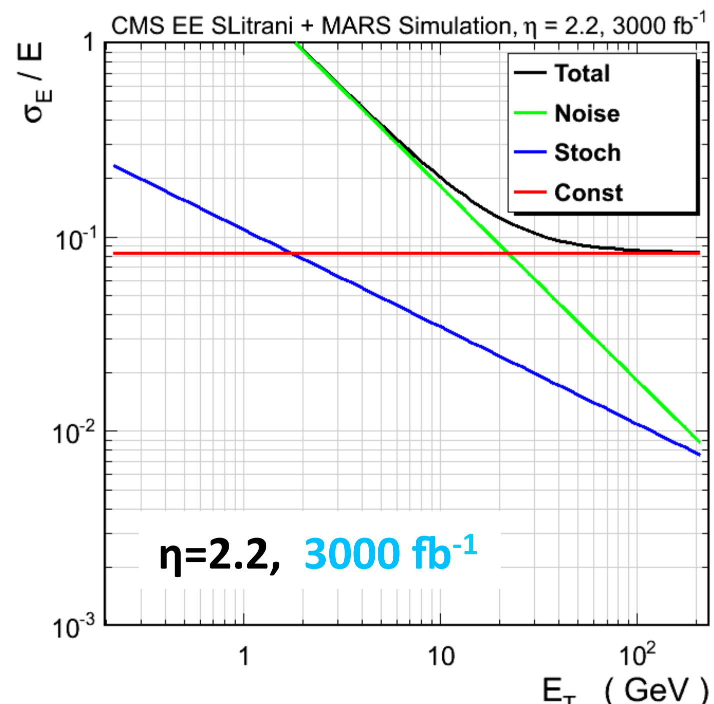
However, **at 3000 fb^{-1}**, significant regions of EE would have correction factors of x100 or larger to adjust for the light loss.

We would also suffer **loss of trigger efficiency.** Effective Noise from 3x3 cluster (trigger unit in ECAL) in high η region would reach 36 GeV.

Performance for e/γ ($|\eta| < 2.5$) is acceptable up to 500 fb^{-1}.
Progressive deterioration of energy resolution and trigger efficiency, with strong η dependance.

ECAL Endcap: evolution of energy resolution





Reduction of light output causes worsening of **stochastic term**, amplification of the **noise**, light collection non-uniformity (impact on the **constant term**).

At η **=2.2** resolution would degrade from **~2% (500 fb^{-1})** to **~10% (3000 fb^{-1})**.

Because of technical and electronics constraints, partial replacement of Endcap crystals is not possible.

CMS ECAL Endcap calorimeter will be replaced during LS3

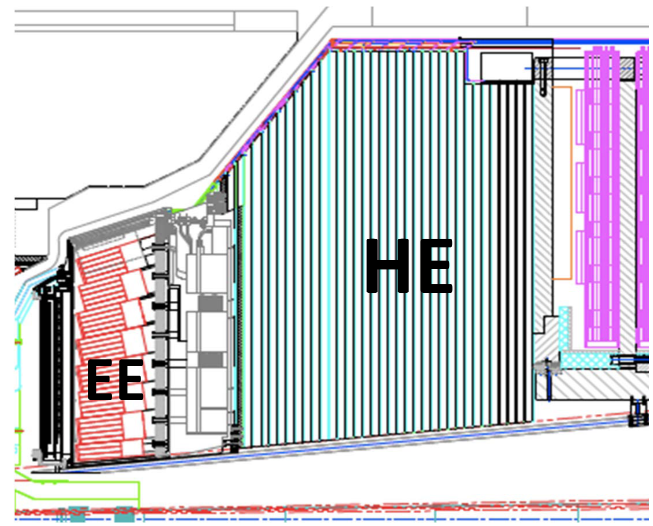
Two scenarios considered for the CMS Endcap Calorimeter upgrade:

Scenario 1:

- Maintain present tower geometry
- Develop radiation tolerant solutions for ECAL and HCAL Endcap calorimeters

Scenario 2:

- Alternative concept with potential for improved performance and/or lower cost to develop an integrated Endcap calorimeter



Significant R&D is required to demonstrate viability of the options. Also need to demonstrate engineering/system level feasibility.

Under consideration

- Replacement of Endcap calorimeters allows the consideration of **extended calorimetry coverage up to $|\eta| = 4$** for uniform measurement in the region important for VBF Jets, potentially increased e/γ acceptance, as well as opportunity for increased muon coverage in calorimeter shadow.
- **Increased granularity and segmentation** may help to separate out pile-up activity from primary event physics objects.
- **High precision (10-20 pico-seconds) timing** may help in pile-up mitigation for neutral particles.

Scenario 1 option: standalone Endcap ECAL

Option considered:

- Sampling calorimeter with rad-tolerant inorganic scintillator (LYSO, YSO, Cerium Fluoride) and lead or tungsten as absorber.
- Shown here in Shashlik configuration, with light readout via wavelength shifting fibers (WLS) in quartz capillaries
- Light path is short in scintillator and WLS resulting in reduced sensitivity to radiation (see slide in the back-up)
- **Ongoing R&D**: rad-tolerant crystal scintillators, WLS capillary fibers and photo-detectors (eq GaInP);

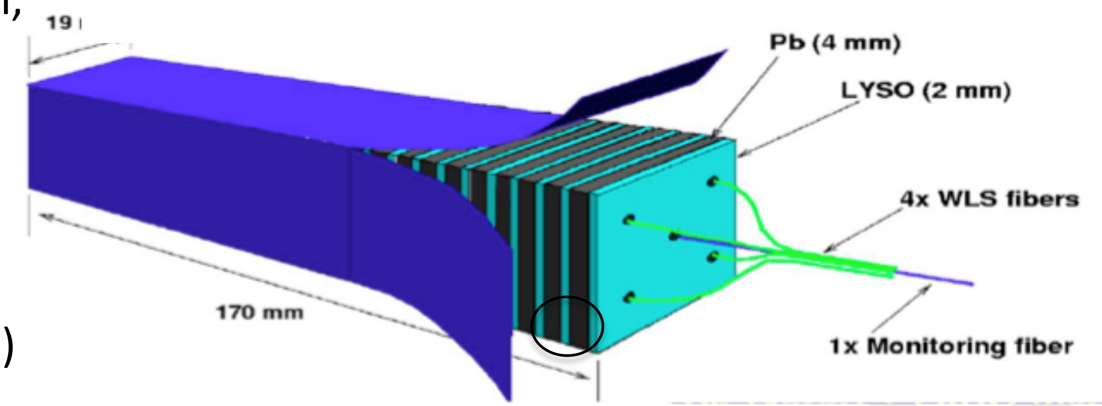
Example of ECAL Sampling calorimeter

~ 30k towers

Pb(4mm) + LYSO (2mm)

Target e/gamma resolution: 10%/√E +1%

Light collection: WLS quartz capillaries



Scenario 1 option: replacement of HE active readout

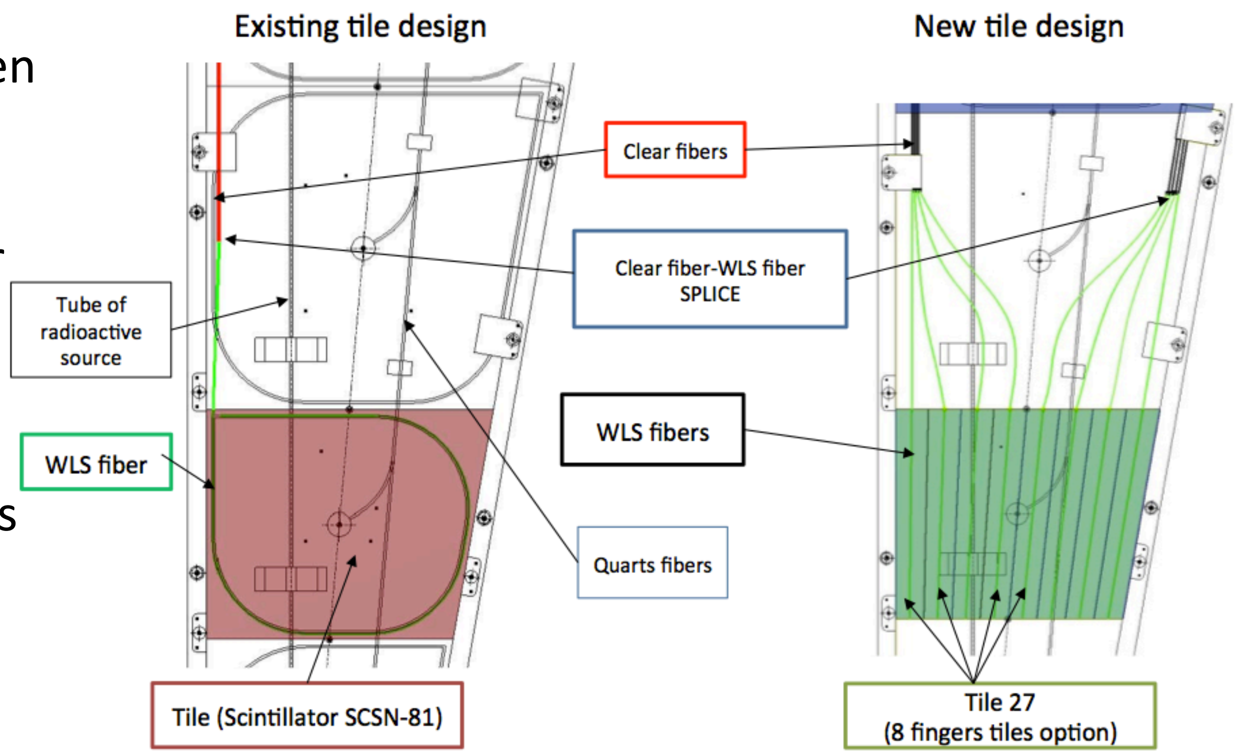
Option considered:

- Change of layout of wave-length shifting (WLS) fiber within scintillator to shorten light path length

Ongoing R&D:

- Replacement of scintillator material with radiation tolerant version (yellow emitting 3HF)
- Replacement of WLS fibers with quartz capillaries

Modification to the layout of a WLS fiber inside scintillator tile



Ideas for Scenario 2: Dual Readout Calorimeter

- **Dual Readout Calorimeter**: simultaneous measurement of the Cherenkov and scintillation signal in the calorimeter in order to correct for intrinsic fluctuations in the hadronic and e.m. component (γ, π^0, η) of the hadronic showers (RD52 Collaboration)

Ongoing R&D for Dual Readout Calorimeter option:

- **Quartz fibers:**

-> to be used as Cherenkov light radiator

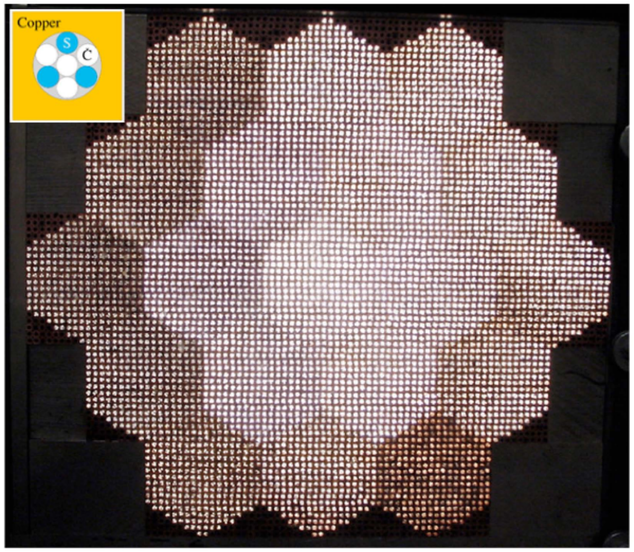
-> doped Quartz fibers for scintillation signal

- **Crystal fibers:**

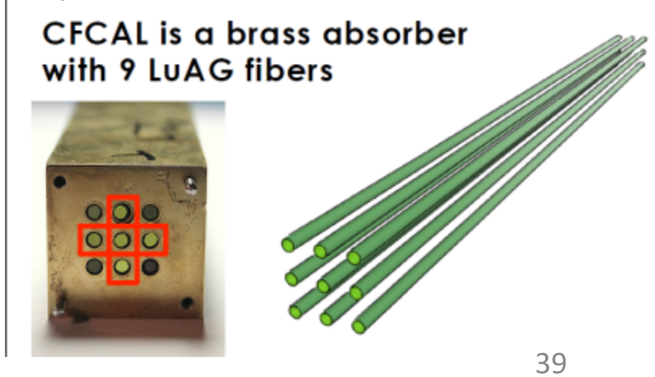
-> undoped LuAG for Cherenkov light detection

-> doped inorganic crystal fibers, e.g. LuAG for scintillation light detection

The original DREAM calorimeter

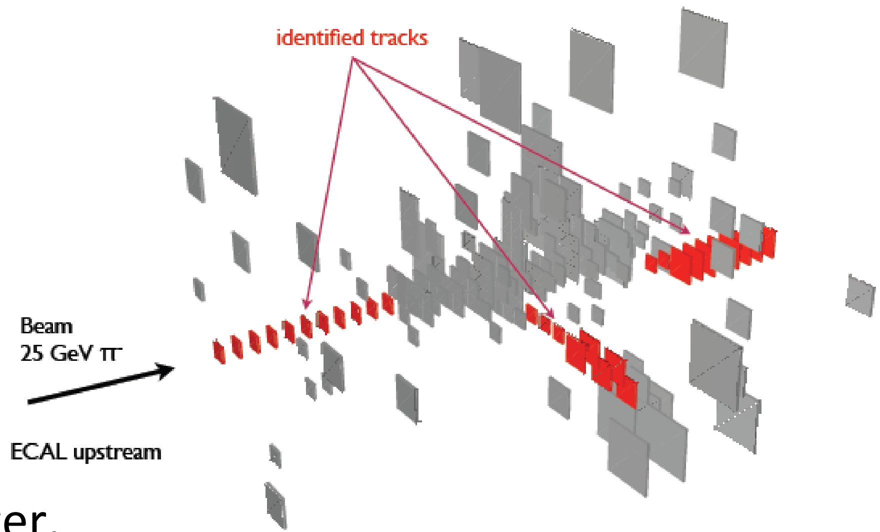


Crystal Fiber Calorimeter (CFCAL)



Ideas for Scenario 2: High granularity Particle Flow (PFCAL)/Imaging Calorimeter

- **High Granularity Particle Flow (PFCAL)/ Imaging Calorimeter** based on studies for CALICE, using GEM technology
- **Key feature:** high segmentation both transverse and longitudinal to measure shower topology
- **Challenges**: high number of channels, compact and inexpensive electronics, trigger, cooling, linearity, high rate capabilities of gas detectors.



CMS ECAL and HCAL Barrel, as well as HCAL Forward will sustain 3000 fb^{-1}.

Major upgrades are necessary for the CMS Endcap calorimeters:
Both EM and HAD compartments in CMS Endcap region will suffer major radiation damage beyond 500 fb^{-1} and therefore require replacement during LS3.

Significant R&D effort is required to demonstrate viability of the considered replacement options for CMS Endcap detectors, as well as to demonstrate their engineering and system level feasibility.

Concluding remarks

- Well-performing calorimeters in the full rapidity range are essential for successful physics program of High Luminosity LHC.
- The HL-LHC poses severe requirements on calorimeter detectors, especially in the endcap regions, in terms of instantaneous flux of particles and radiation doses.
  - We have described specific areas where present detectors may not be able cope with HL-LHC conditions.
  - In some cases, decisions have already been made to upgrade certain detectors for Phase2 of LHC.
  - For other detectors, we still need to complete physics performance studies in order to reach conclusive decision.
- We have to continue intensive R&D program focusing on the technologies for upgrade of calorimeter detectors for HL-LHC in order to meet the time scale needed for making decisions.

Summary table

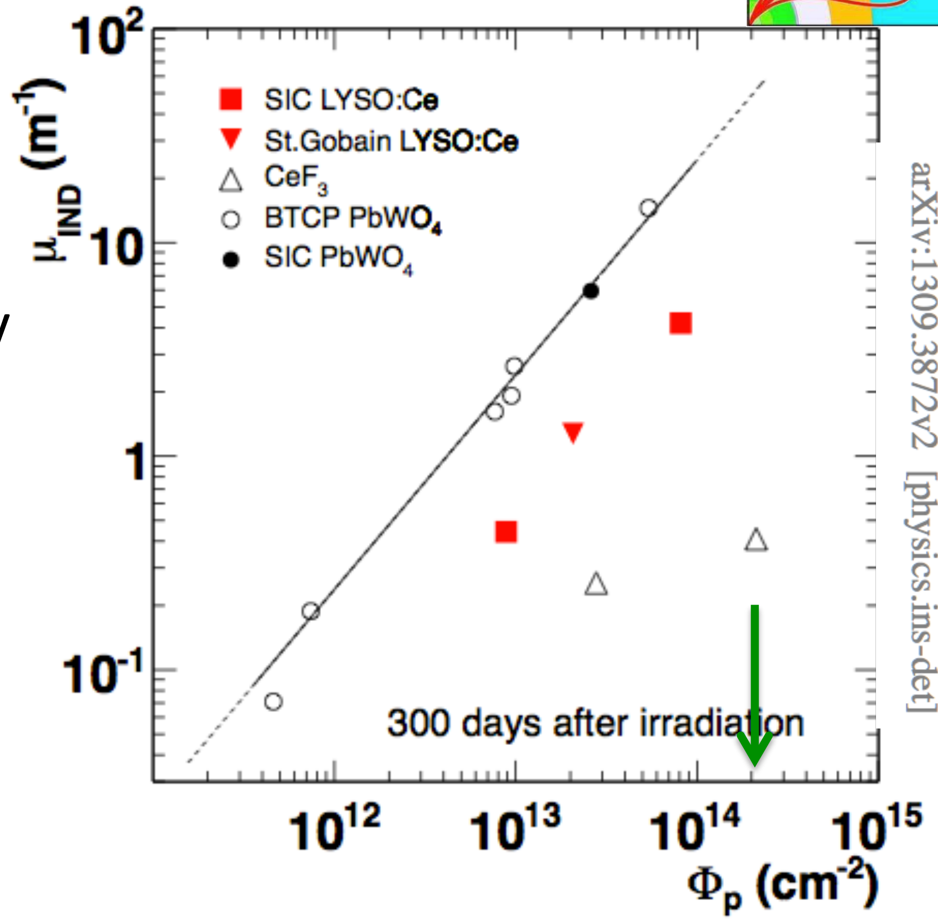
Experi -ment	detector	technology	Critical condition	maximal value for Phase2 of LHC	Expected degradation, considered mitigation
ALICE	PHOS	PbWO4	Hadron fluence	$< 10^{9}$ h/cm ^{2}	OK
ALICE	EMCal/Dcal	Pb/Scint Shashlik	Radiation Dose	~ 0.1 kRad	OK
LHCb	ECAL	Pb/Scint Shashlik	Radiation Dose	~ 6 Mrad	will replace central cells during LS3 (spares exist)
LHCb	HCAL	TileCal	Radiation Dose	~ 1 Mrad	Not critical, accept the loss
ATLAS	ECAL Barrel	LAr	Inst. luminosity	OK up to 10^{35} cm $^{-2}$/s	OK
ATLAS	ECAL Endcap	LAr	Inst. luminosity	OK up to $5*10^{34}$ cm $^{-2}$/s	OK, re-calibrate if required
ATLAS	HCAL Endcap	LAr	Inst. luminosity	OK up to $8*10^{34}$ cm $^{-2}$/s	OK
ATLAS	HCAL Barrel	TileCal	Radiation Dose	~ 0.3 Mrad	Re-calibrate
ATLAS	Forward	LAr	Inst. luminosity	Possible degradation above $2*10^{34}$ cm $^{-2}$/s	May have to replace or add new detector during LS3
CMS	ECAL Barrel	PbWO4	Hadron fluence	$2*10^{12}$ h/cm ^{2}	Re-calibrate
CMS	HCAL Barrel	Brass/Scint	Radiation Dose	~ 0.1 Mrad	Re-calibrate
CMS	ECAL Endcap	PbWO4	Hadron fluence	~ $2*10^{14}$ h/cm ^{2}	Will be replaced during LS3
CMS	HCAL Endcap	Brass/Scint	Radiation Dose	~ 10 Mrad	Will be replaced during LS3
CMS	Forward	Steel/Quartz fibers	Radiation Dose	~ 500 Mrad	Re-calibrate

Back-up slides

R&D on crystal scintillators

R&D program is ongoing

- Key points are:
  - radiation hardness, especially for hadron damage
    - attenuation length
    - Scintillation mechanism
    - Activation/fluorescence
  - Light emission spectrum matching to WLS fibers or to rad-hard photo-detectors
  - Cost and production capability



Flux of ~ $2*10^{14}$ h/cm^2 expected for 3000 fb^{-1} for Endcap ECAL (η= 2.6)

R&D on new fibers

R&D program is ongoing

Quartz fibers:

- Cerenkov radiator in Dual Readout Calorimeter
- Doped Quartz fibers for scintillation signal in Dual Readout Calorimeter
- Wave Length Shifting (WLS) capillaries

Crystal fibers:

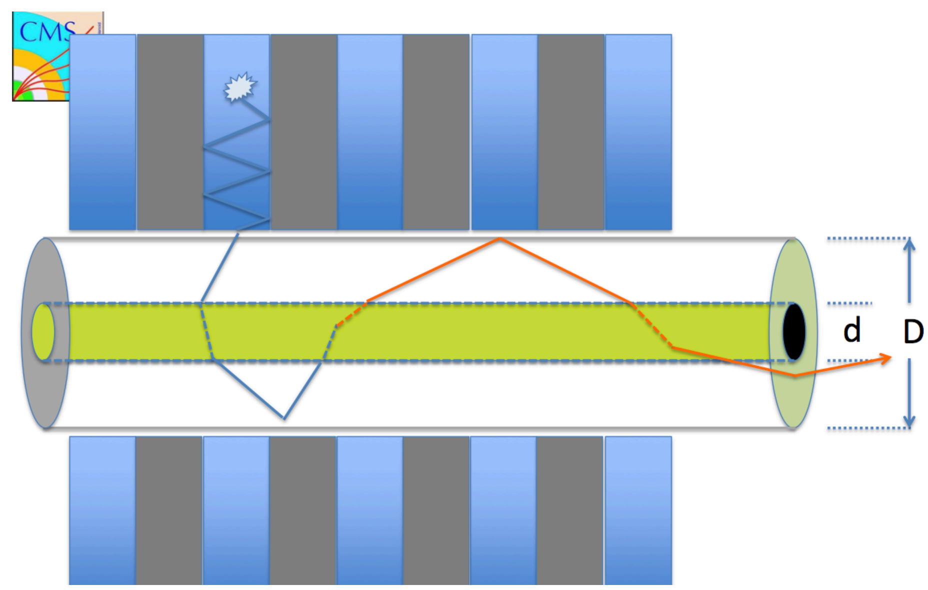
- doped inorganic crystal fibers, e.g. LuAG for scintillation light detection
- Undoped LuAG for Cerenkov light detection

Concept WLS capillary:

- Quartz fiber provides rad hard media for light propagation
- Core material is source of shifted light, not a light guide
- The core does not need to be rad-hard

Potential Applications:

-Endcap ECAL (Shashlik)
-Endcap HCAL (active readout replacement)
-scintillation light in Dual Readout Calorimeter



R&D on Precision timing

Up to 5×10^{34} $cm^{-2}s^{-1}$ instantaneous luminosity

- $\sigma_{z,lum} \sim 4.5$ cm r.m.s. $(d\langle m\rangle/dz)_{max}$ up to 1.4→ 1.8 event/mm

Precision timing capability could improve CMS event reconstruction in the HL-LHC environment

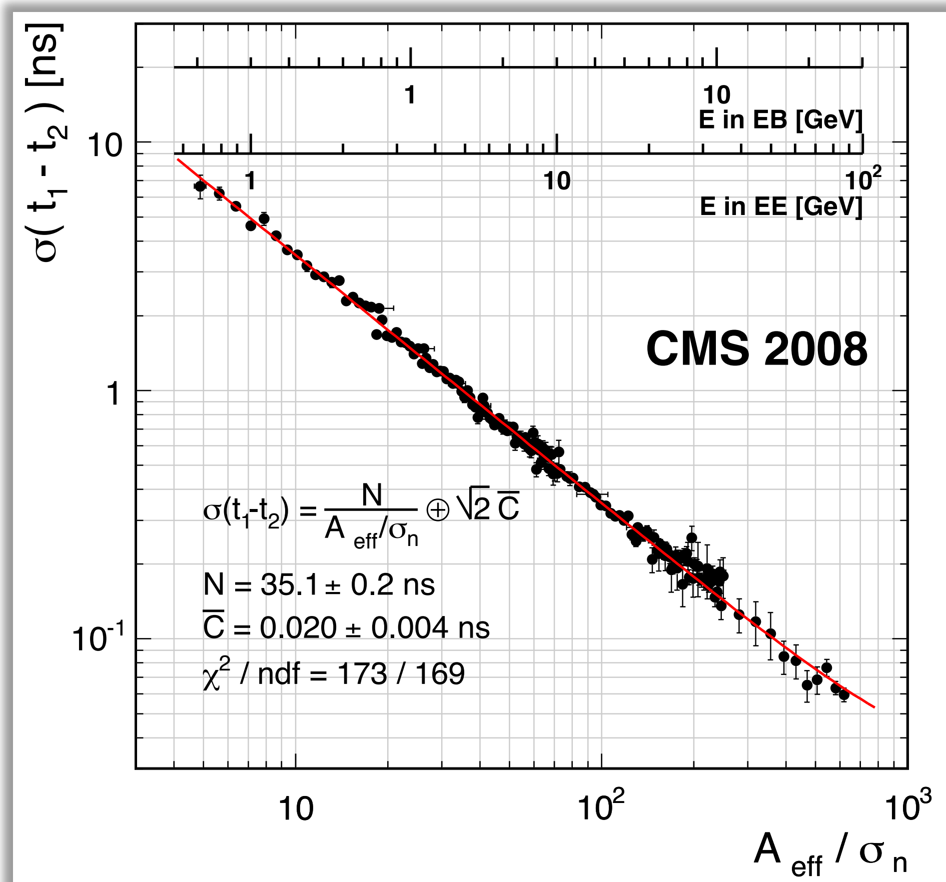
- Even with extended coverage in rapidity of trackers, neutral particles need to be identified

Preliminary studies have shown that ~10ps device would be able to significantly reduce PU contamination

- Remove PU hits, identify PV vertex, remove PU jets
- Improve object ID and energy resolution

~100ps precision already achieved with the current CMS ECAL with collision data

- Survey technology and develop a system for O(10)psec precision in HL-LHC environment



Test beam resolution: 80 ps ~20 GeV