Detector Radiation Hardness: CMS HCAL Lessons

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Overview

Introduction to the CMS Hadronic Calorimeter

Observation of a larger than expected signal loss in the Hadronic EndCap Calorimeter

Speculation and investigation

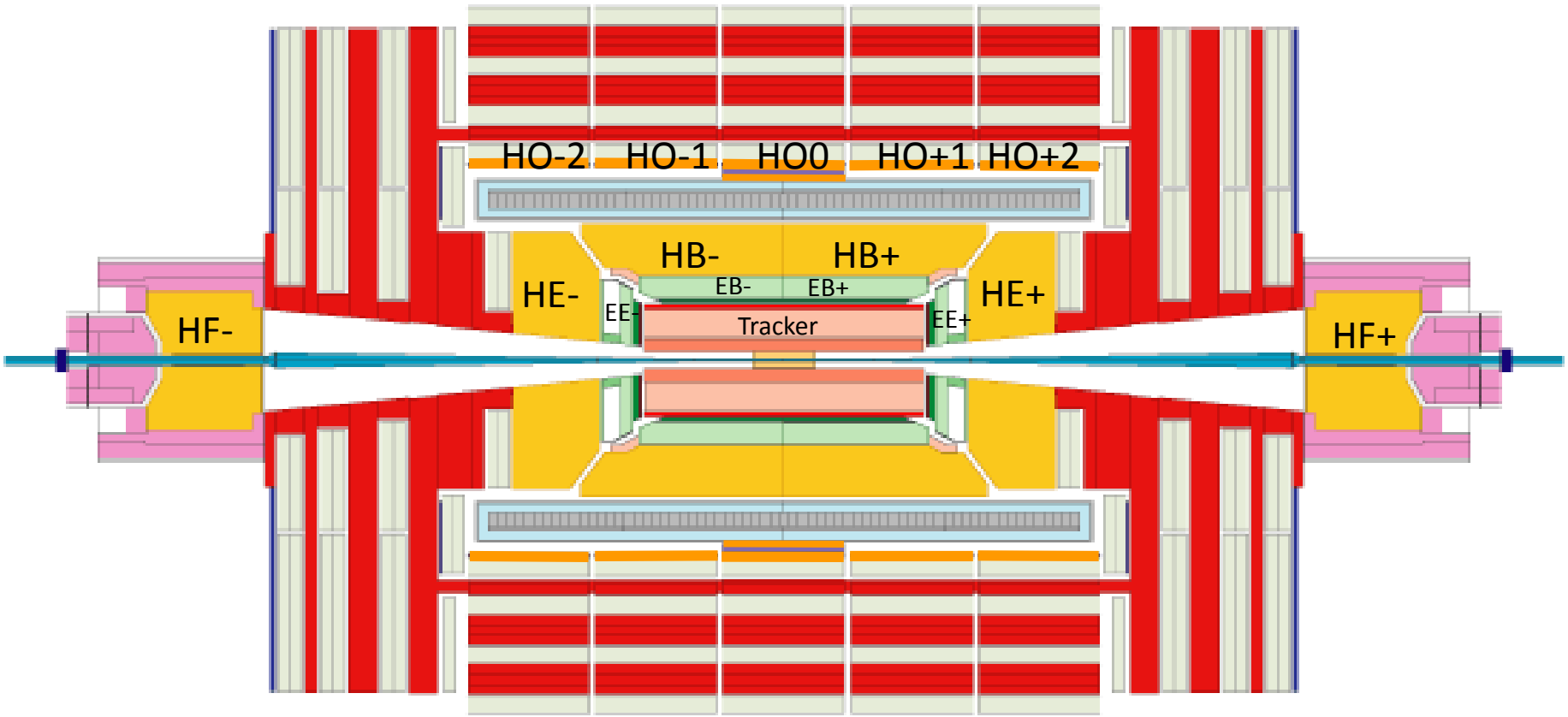
Understanding the components of the problem
- Damage to the scintillator
  - Dose rate dependence
- Damage to photodetectors
  - HPDs, then SiPMs (increasing dark current)

Modeling the damage and predictions for future runs

Impact on decisions for HCAL upgrades
- Accelerated HPD->SiPM replacement, NO scint replacement, HL-LHC lessons

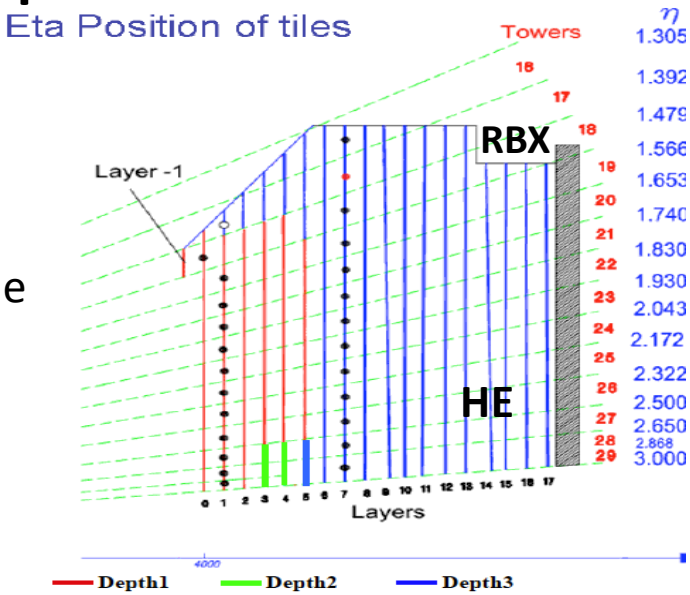
CMS Calorimeter

CMS Calorimeter (ECAL+HCAL) - Very hermetic (>10λ in all η, no projective gap)



HB	**Brass Abosber (5cm) + Scintillator Tile (3.7mm)**	**Photo Detector (HPD)**	**|η|**	**0.000 ~ 1.393**
HE	**Brass Absober (8cm) + Scintillator Tils (3.7mm)**	**Photo Detector (HPD)**	**|η|**	**1.305 ~ 3.000**
HO	Scitillator Tile (10mm) outside of solenoid	Photo Detector (HPD)	|η|	0.000 ~ 1.305
HF	Iron Absober + Quaartz Fibers	Photo Detector (PMT)	|η|	2.853 ~ 5.191

HCAL and Dan

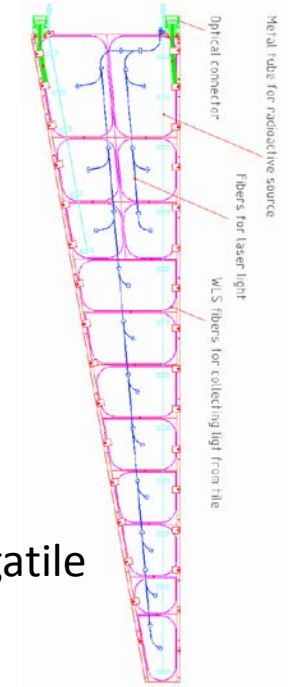


HCAL is a scintillator+brass sampling calorimeter

- Scintillator tiles are arranged into 20° megatiles
- Light from tiles is collected by WLS sigma fibers and transported to photo-detector readout box (RBX) on the outer edge

Dan was the first HCAL Project Manager

- Design and R&D
  - Design objective: HE survives until LS3 (up to 500 fb^{-1}), HB until end of CMS
  - Many radiation damage tests were performed, esp. in the 1990's
  - Design allowed for replacement of megatiles, should it be necessary
  - Radiation issues are more severe in HE (our focus)
- Construction and operations
  - Including monitoring and calibration systems:
    - laser in HE layers 1 and 7
    - sourcing tubes in all tiles



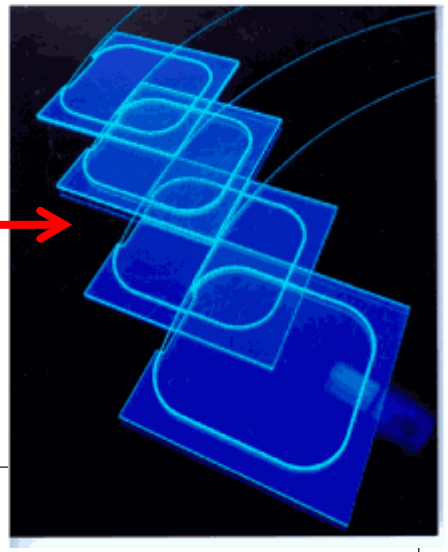
Megatile

Barrel (HB) and Endcap (HE) Calorimeters

Similar technology used for HB and HE calorimeters

Light readout via an optical fiber doped with wavelength shifter acting as light guide

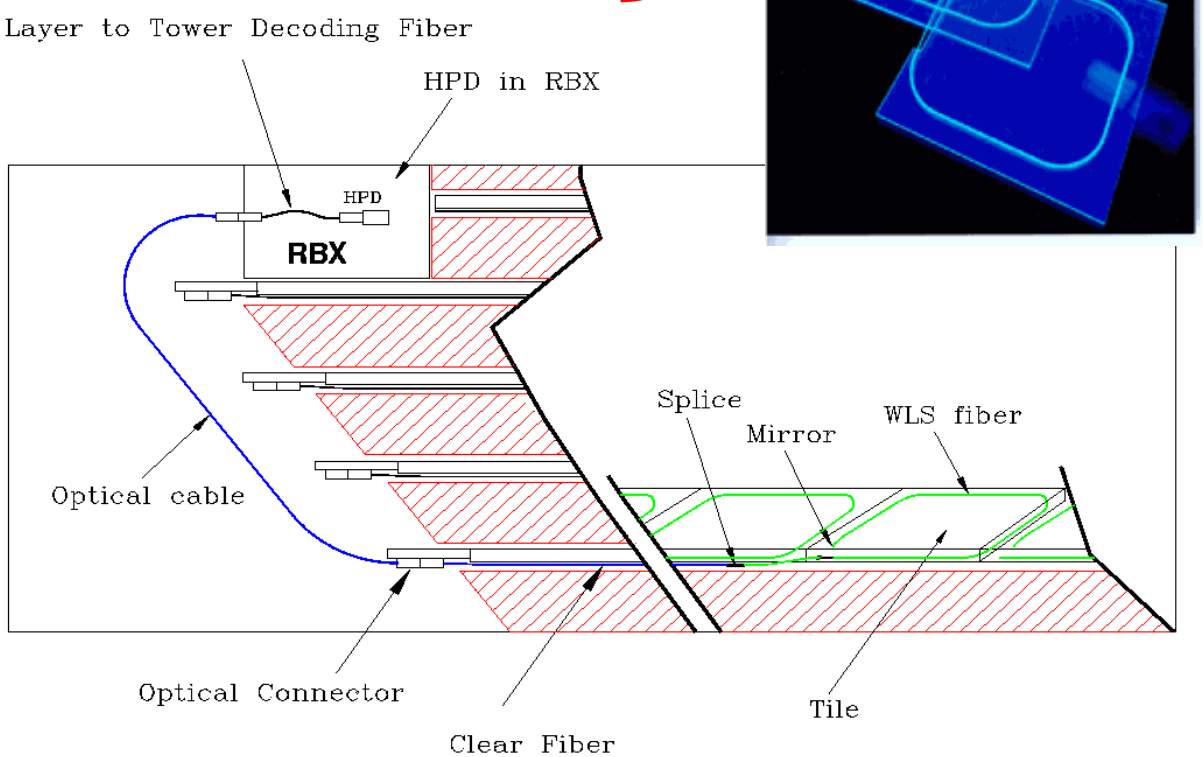
Fiber is placed in a groove in the scintillator, absorbs scintillator light, re-emits it



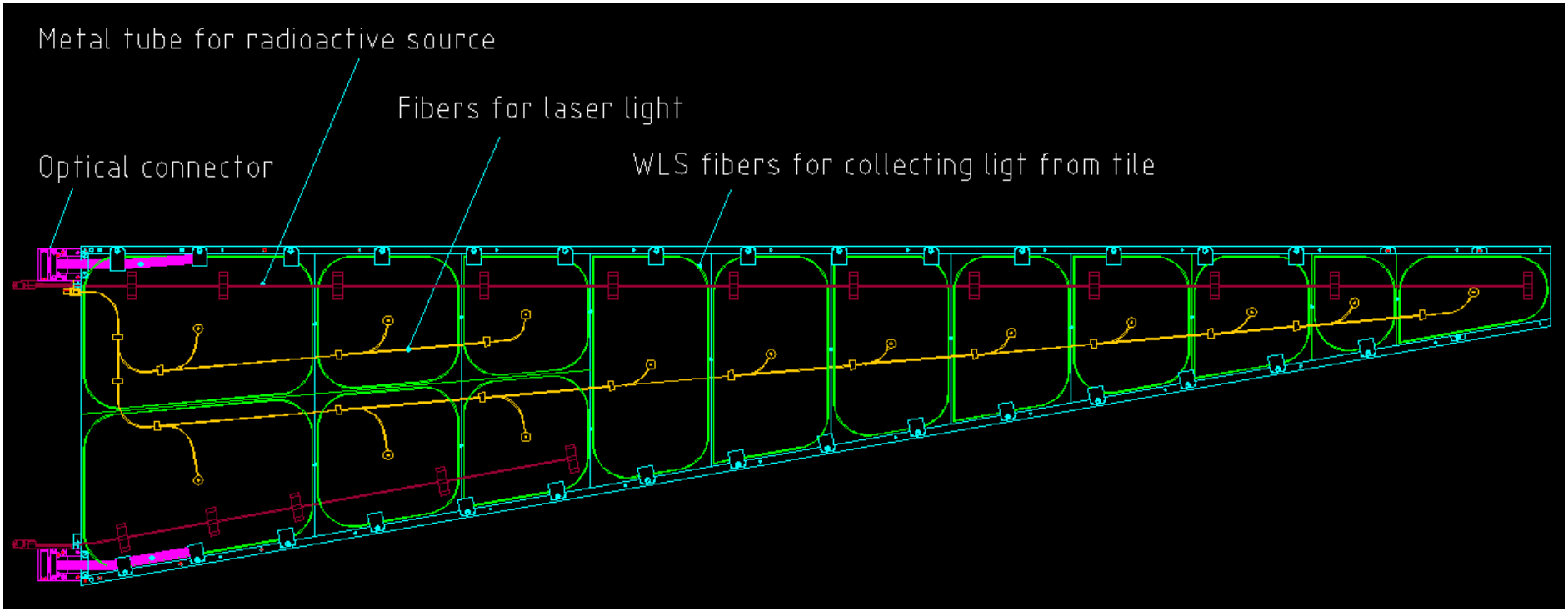
Passive layers of brass to induce showering

About 5% of the light is captured in the fiber

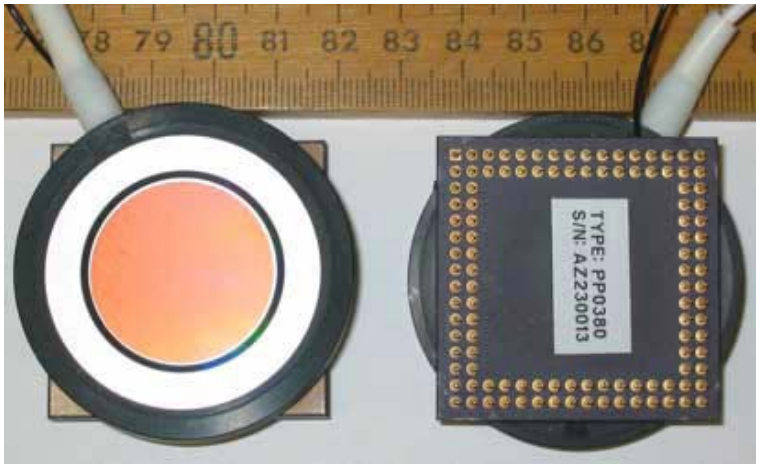
Fibers sent to a Hybrid PhotoDiode (HDP) with 19 or 73 channels/device

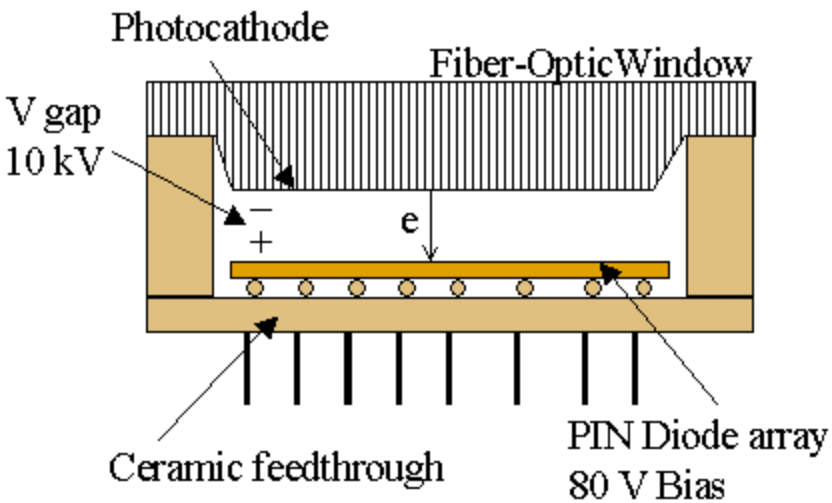


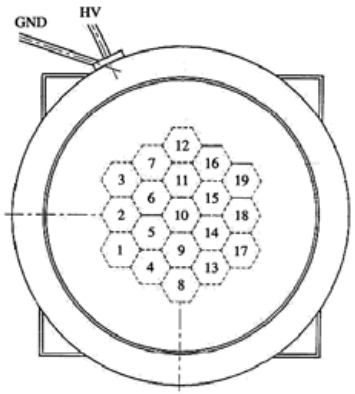
Megatile


Metal tube for radioactive source
Fibers for laser light
Optical connector
WLS fibers for collecting ligt from tile

Hybrid Photo Diode (HPD)







Hybrid Photo Diode photon transducer (HB, HE, HO)

19 or 73 channels/device
(one channel used for calibration)

Optical Decoder Unit
Directs light collected from the calorimeter scintillator to the HPD channel

Larger than Expected Signal Loss (2012)

Light from the laser signal injected into tiles indicated a much faster deterioration of response than expected, esp. at large eta

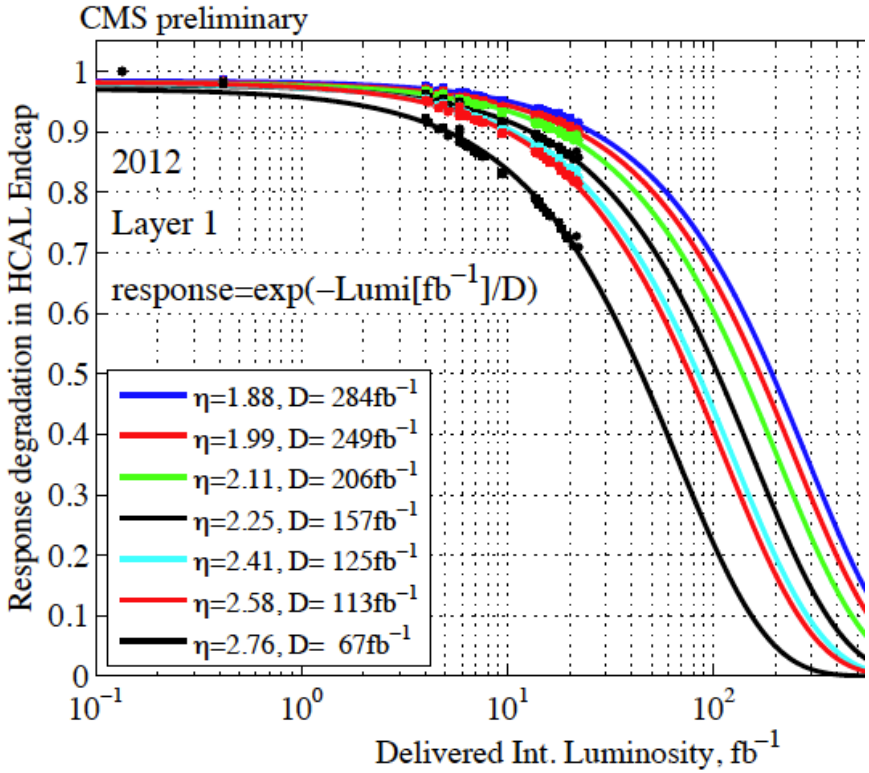
Light = L_0 * exp(-lumi / D[fb^{-1}]) = L_0 * exp(-dose / D[Mrad])

Concerned that the high-eta tiles of HE would be dead by a few 100 fb^{-1} if the trend continued

Accelerated replacement of HPD photodetectors with SiPMs was advocated to gain x2.5 in PDE

Replacement of several layers of megatiles in HE was seriously considered for LS2, and in HB for LS3

This would pose technical risks to ECAL, at the cost of multi M$



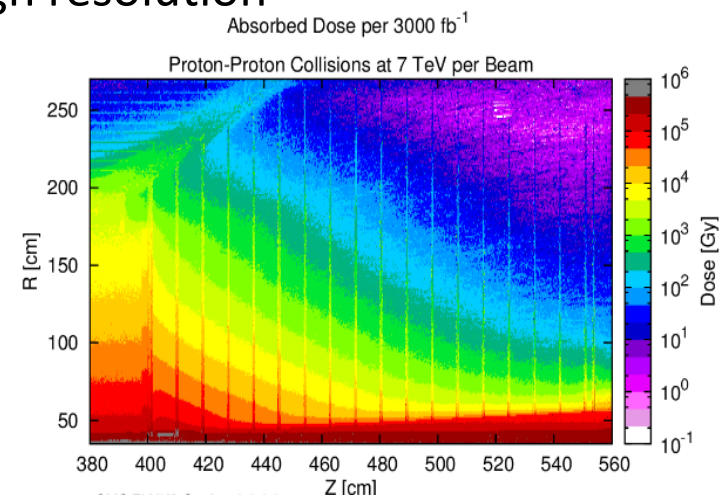
Scrutinize Everything

A decision on the megatile replacement was needed fast

Dan was skeptical. It contradicted earlier raddam studies and his physics intuition

Intense studies began in 2016 using new data after LS1
We established the HCAL RadDam Studies Working Group

Verified CMS material structures and radiation levels
Worked with BRIL to recalculate Fluka maps with high resolution
(corresponding to tile thickness)



With info from LHC experts, established future
dose and doserate profiles
Cross-checked laser results with other tools
Radioactive scans
Inclusive energy-deposit vs luminosity
MIP signal vs luminosity
Parameterized radiation damage and implemented in CMS simulations
Calculated physics benchmarks (eg. jet resolutions) for various raddam scenarios

Dose Rate Effect

One early suspect was dose rate dependence of radiation damage

All radiation damage studies were at high rates

There was some information available suggesting at low rates the damage can be larger

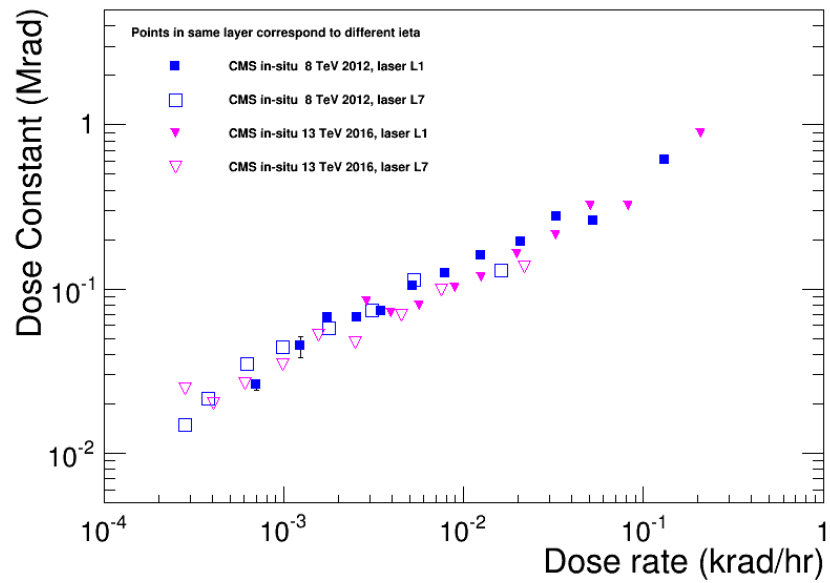
Laser measurements in HE indicated that dose constant strongly depends on dose rate

Universal behavior showing D's vs dose rate

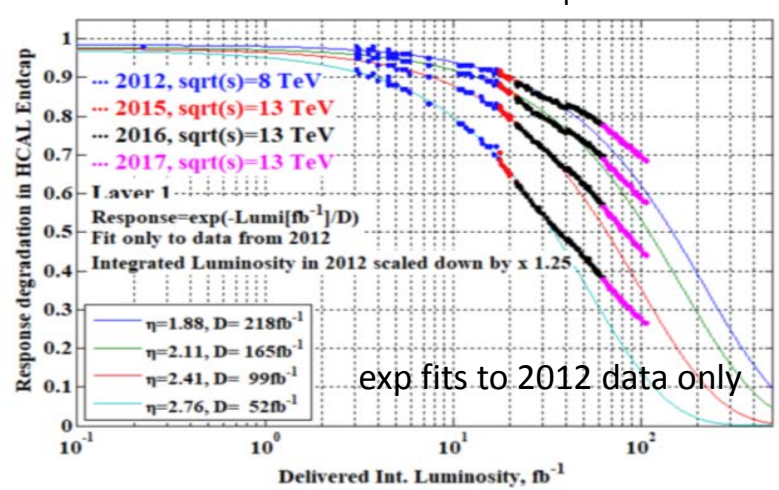
Possible explanation the slowing-down of signal deterioration at higher LHC lumi rate

Which was not observed until late 2016

Doserate effect is important for estimating future damage, since LHC lumi rate increases over time



Data at the beginning of each run are normalized to data at the end of previous run

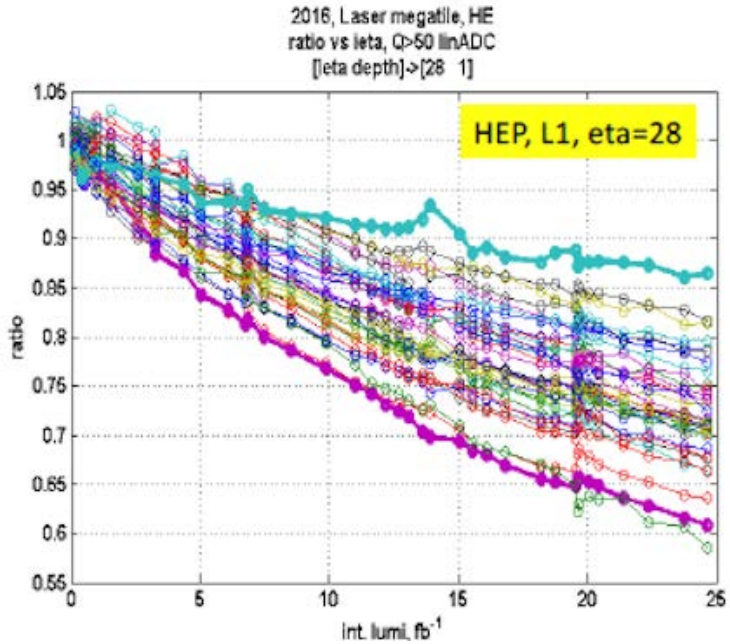


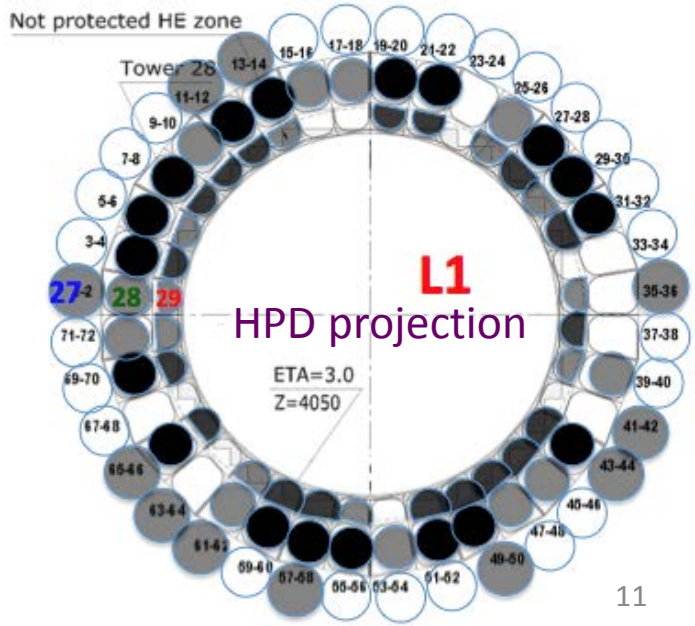
Raddam: Phi Dependence

Another surprise was the observation that the damage strongly depends on phi for a given eta

Known distribution of detector material could not explain it

Taken at face value, non-uniform "swiss-cheese" damage pattern would develop by LS3, with some towers becoming completely dead





HPD Damage

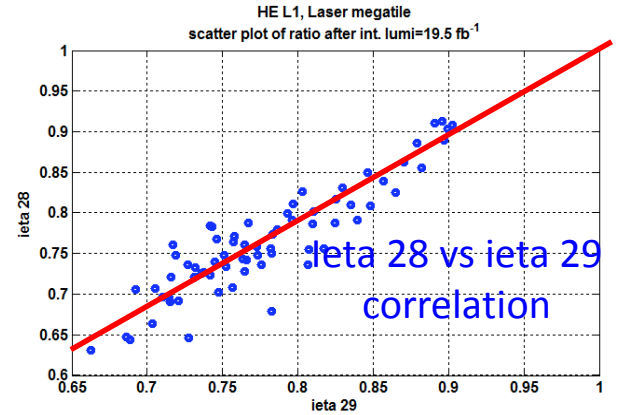
Observed that the damage between certain pairs of tiles was correlated

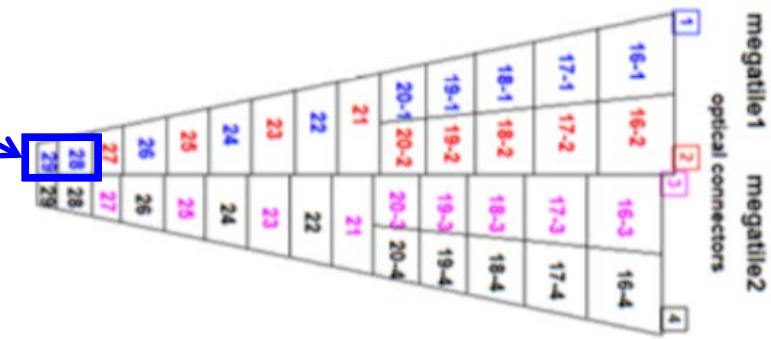
The correlated tiles were read out by the same HPD! (same color tiles)

In 2017, one wedge worth of HPDs was replased with SiPMs

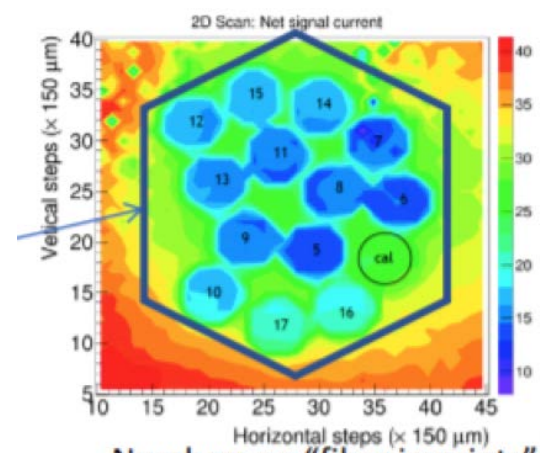
HPDs were found to be responsible for ~50% of total damage!

Surface scan of an HPD showed clear pattern of readout fibers within pixels – damage from the signal light!





zoom into a single HPD pixel

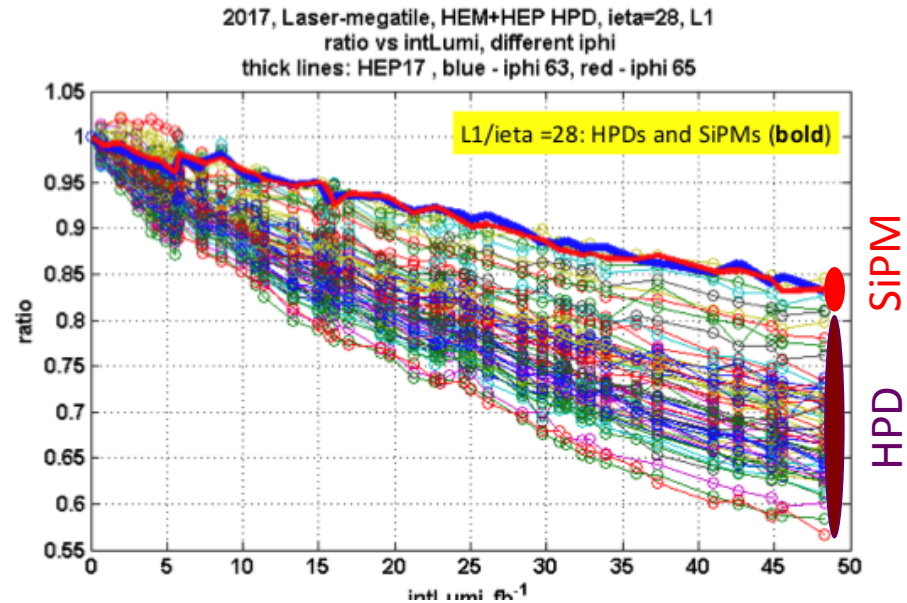


Numbers on "fiber imprints" indicate layer# of tile

Benefits of SiPMs (I)

Large part of signal deterioration caused by HPD damage was removed

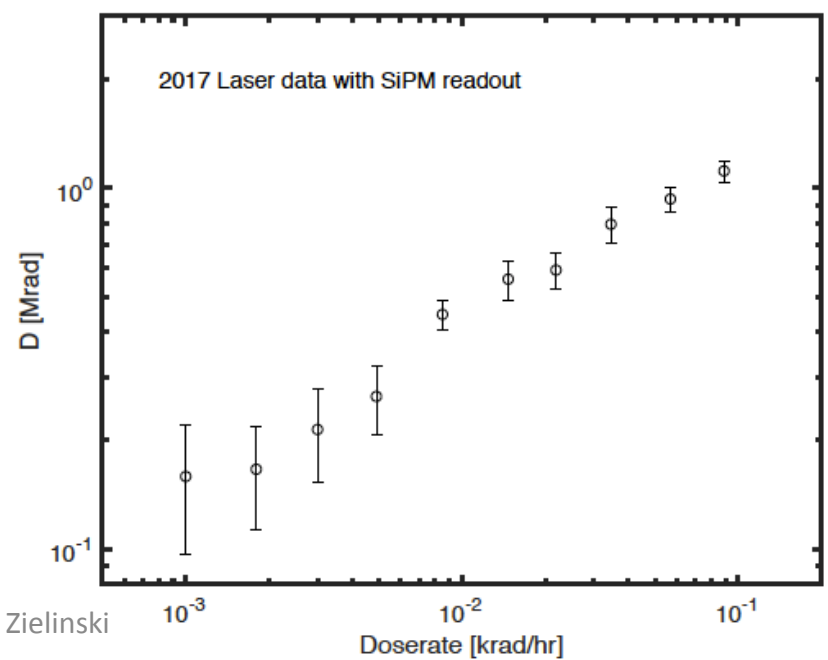
- When observed with SiPM readout, damage is consistent with upper edge of HPD spread (best HPD)
- With SiPMs, phi dependence is uniform except at largest etas (maybe due to material variation)



Higher PDE by factor ~2.5 relative to HPDs extends lifetime of HCAL

SiPMs facilitate

- *Determination of **scintillator** raddam*
- *Finer HE longitudinal segmentation*
- *More precise calibration*
- *Improved reconstruction algorithms*



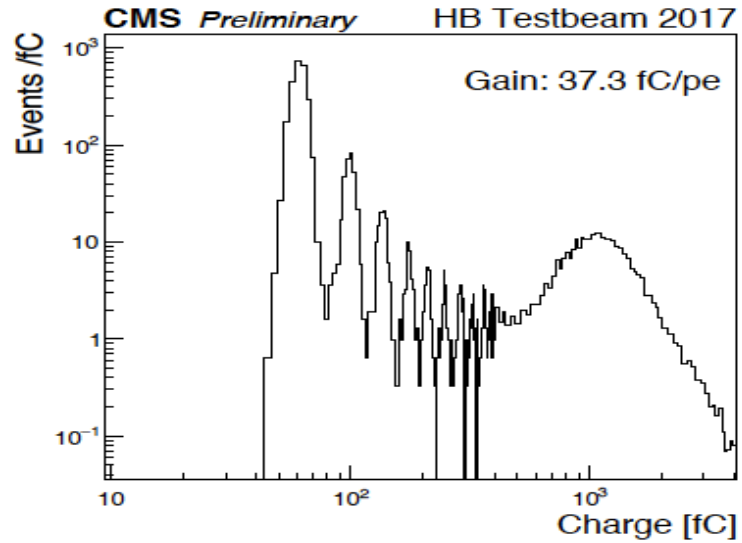
Benefits of SiPMs (II)

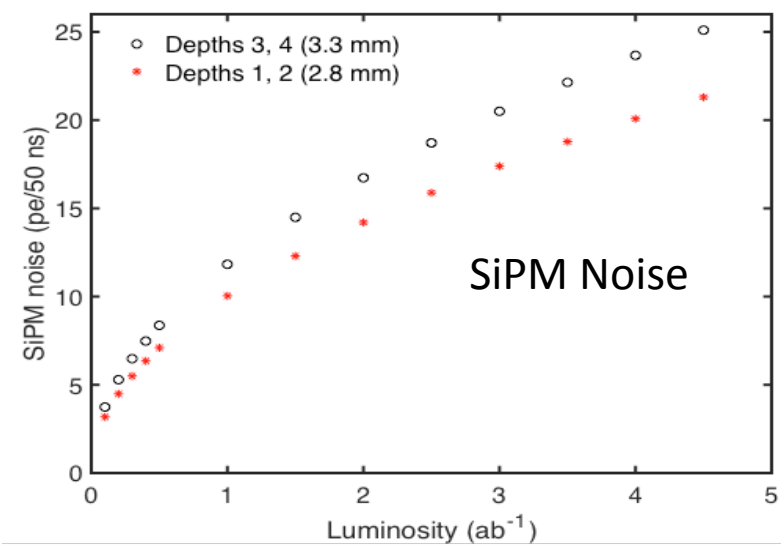
Significantly lower noise levels than HPDs

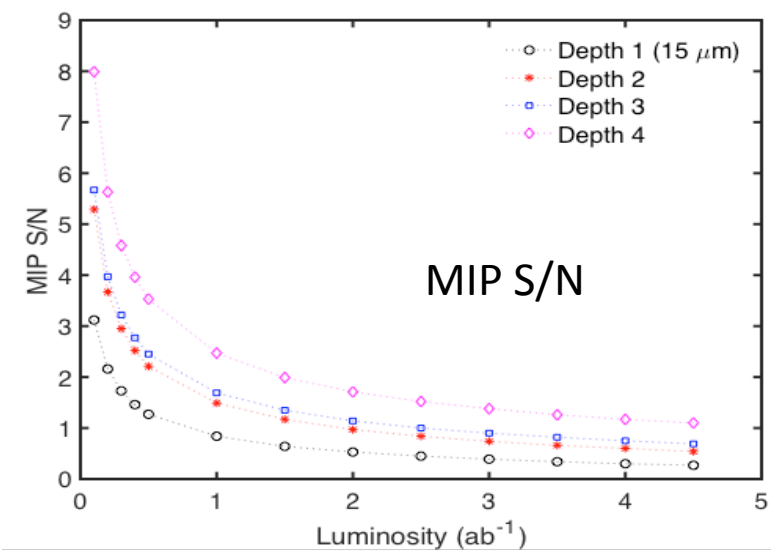
Allow the clear observation of MIP signals in HCAL, *useful for calibration and monitoring*

Although dark current increase with luminosity, HB will retain sensitivity to MIPs for much of HL-LHC period

SiPM noise vs dose behavior is important for HGCal design (Si-Scint boundary)







Techniques to Study Radiation Damage

Laser: light out vs time/lumi
- Fast, done every several days
- But… only in layers 1 and 7 in HE; need inter/extrapolations

Radioactive sourcing
- Slow and infrequent
- But… known energy deposit into every tile

Muon signals in real data
- known energy deposit
- measures groups of tiles (readout depths)
- low statistics

Inclusive energy deposit
- requires stable trigger and run conditions (eg. pileup)
- measures groups of tiles (depths)
- high statistic

Special irradiations R&D
- radioactive sources and CMS Castor Facility

All of the above techniques perform much better with SiPM readout

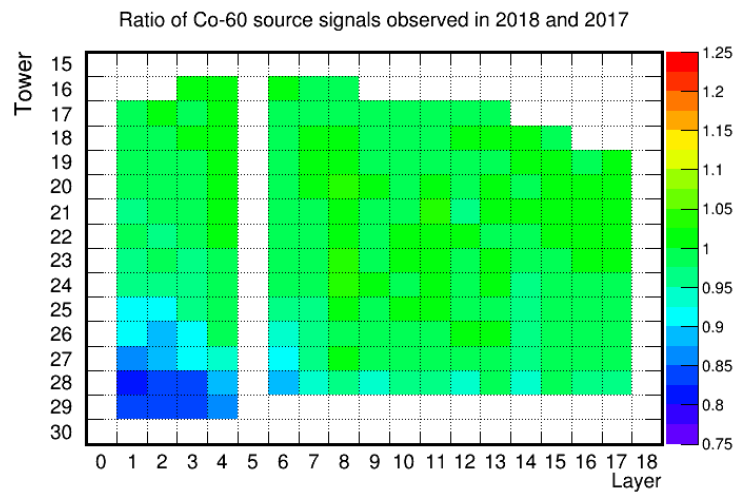
New Handles: Source Scans

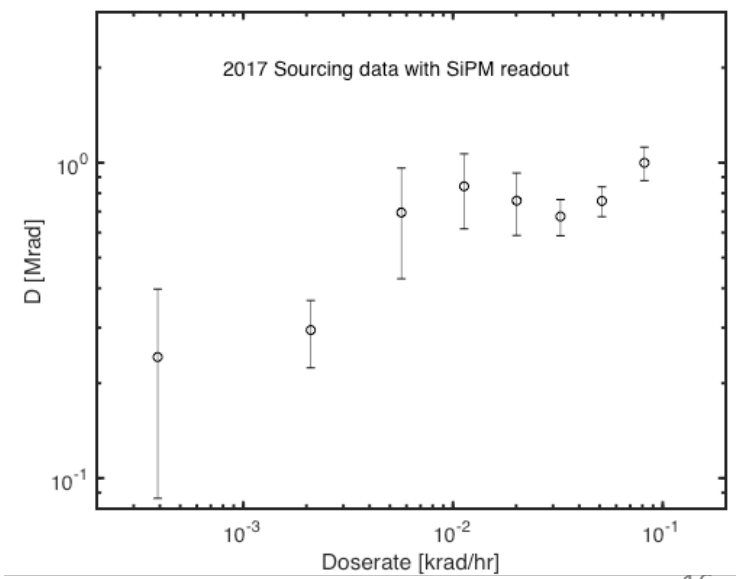
Movable radioactive source can be inserted into (almost) every calorimeter tile to deliver a known amount of energy
→The only method to test all tiles

All HE tiles were sourced before and after the 2017 run

The ratio of the two measurements provides a measurement of raddam in HE channels read out with SiPMs independently from the laser data

Sourcing and laser data are consistent and are both used in the fit for the doserate model parameters





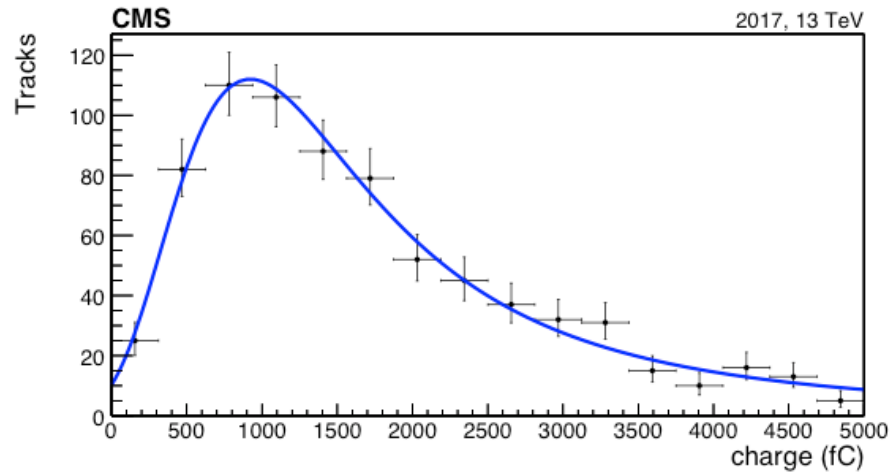
New Handles: Muons

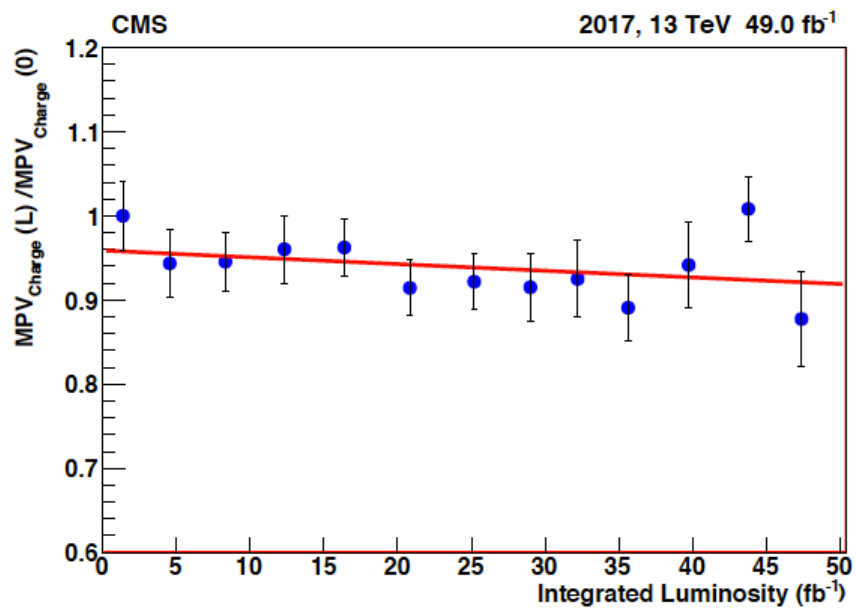
Muon candidates in data allow for the determination of the MPV peak position vs integrated luminosity

2017 SiPM data demonstrate the feasibility of this measurement, but do not have sensitivity competitive with other methods

2018 data will have much higher power since all of HE is now instrumented with SiPM readout

MIP calibration will be a primary calibration method for the HGC





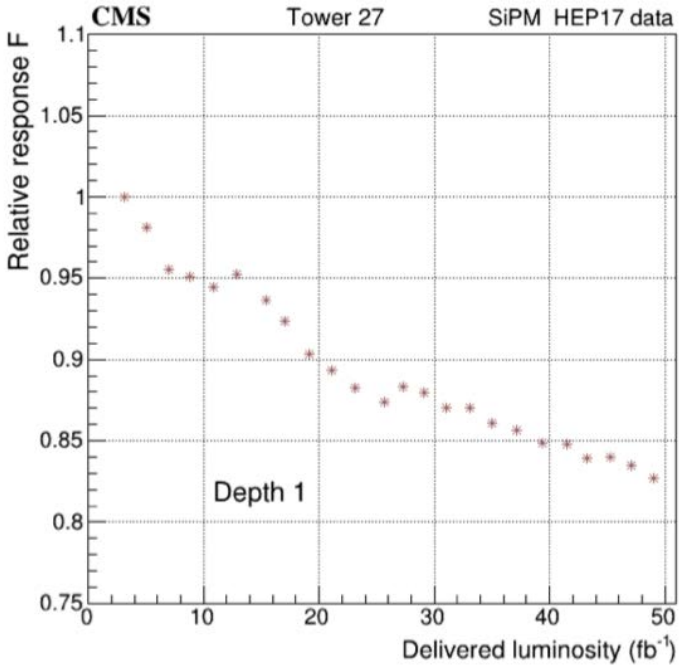
New Handles: In-situ Inclusive

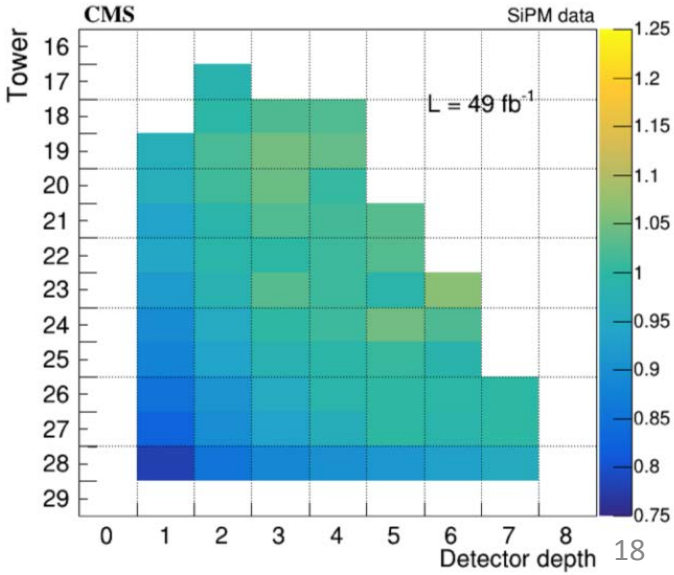
Another raddam sensitive quantity is the average energy deposit per a calorimeter SiPM readout channel

This approach provides the highest statistical precision so far, it is the only measurement of raddam in L0 which uses a different scintillator (BC408) than the rest of HCAL

Can measure dependence vs luminosity for different etas

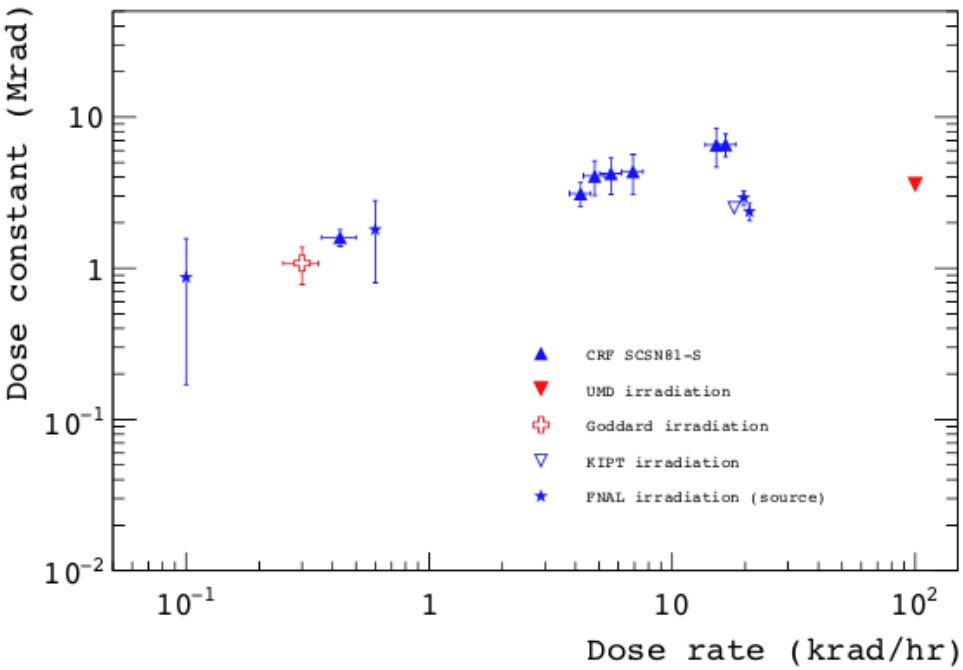
Requires a stable trigger
Pileup corrections are important





New handles: non-HCAL irradiations

Scintillator raddam at higher dose rates has been investigated in irradiations using radioactive sources and special tests at CMS Castor Facility



Only SCSN81 scint tiles with sigma fiber readout and sizes similar to HE tiles are included in the plot

There is a reasonable match of these data with HE in-situ measurements

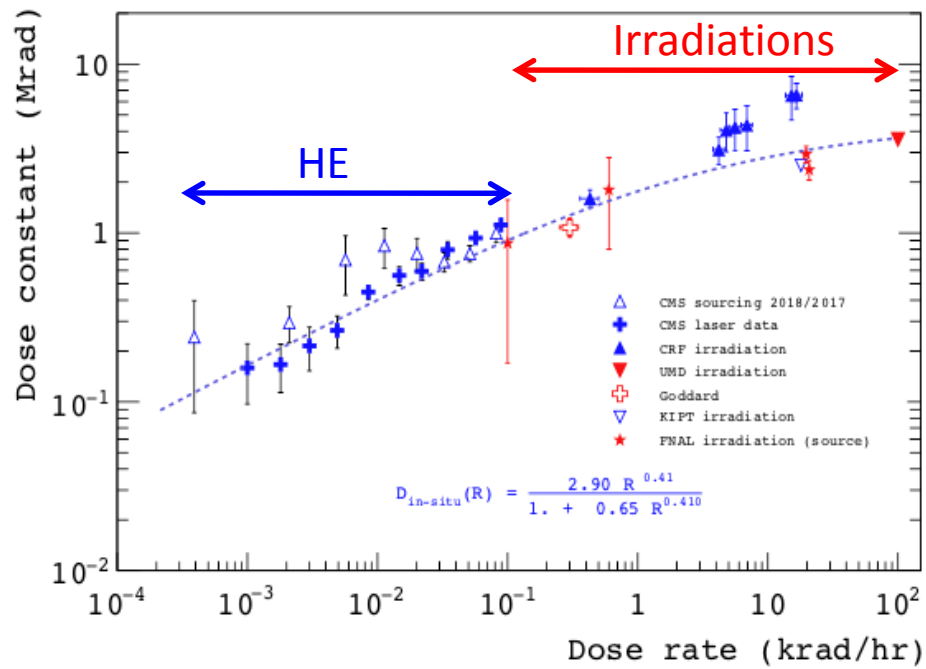
The Dose Rate Model

The present parameterization of the doserate dependence of the dose constant D comes from 2017 HE laser and sourcing data taken with SiPM readout

It is well represented by a simple function: $D = a * R^b$

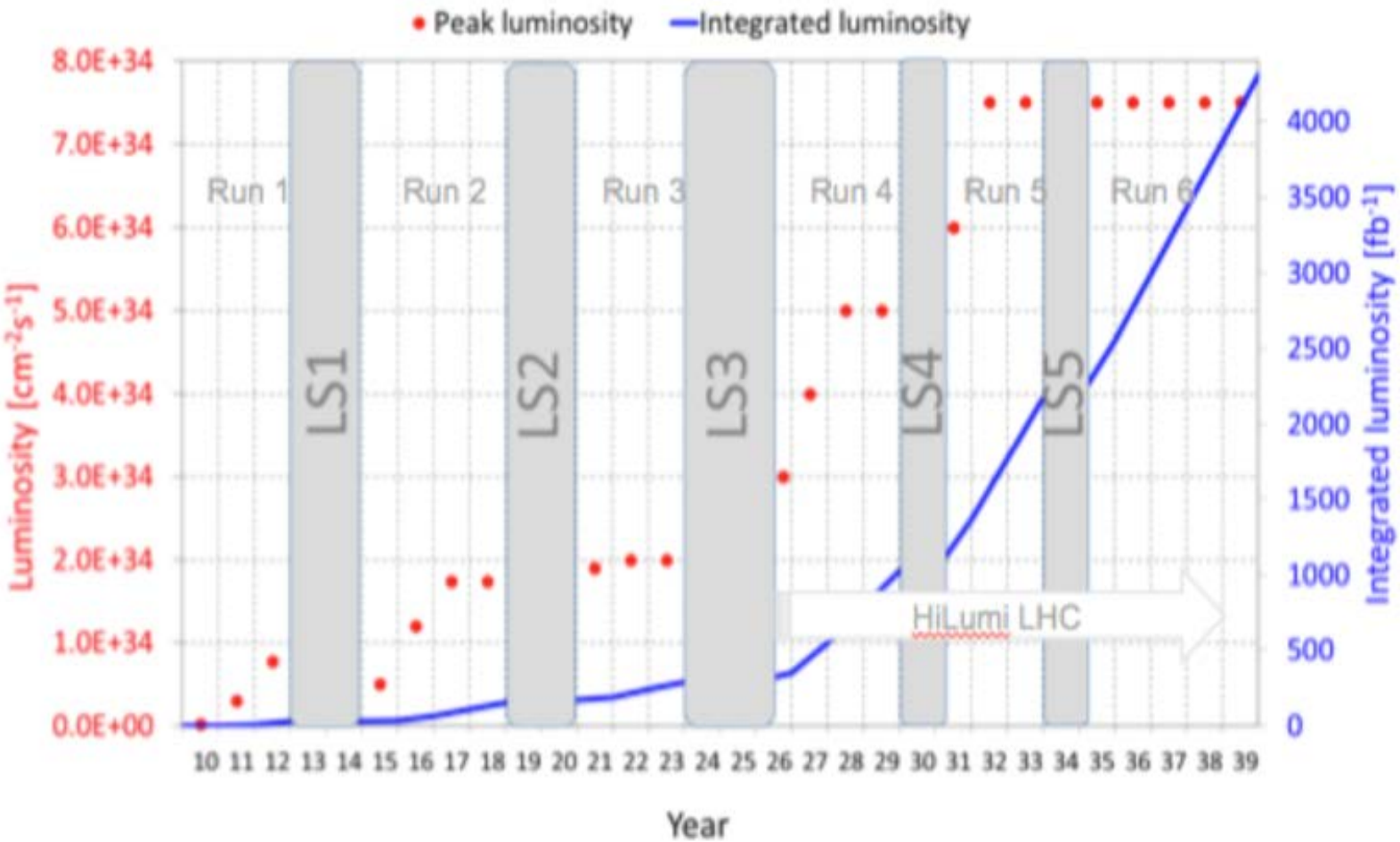
Irradiation data at higher dose rates show a clear flattening of this dependence at R > 1 krad/hr

High rate dependence is currently not well constrained, can be accommodated by adding one parameter in the fit



LHC Luminosity Profile

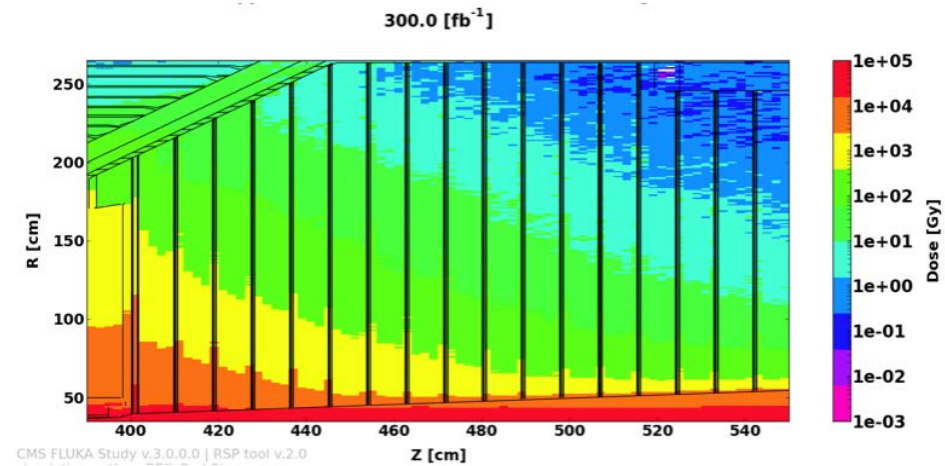
Since the radiation damage depends on the dose, we need to include the expected luminosity profile when predicting future damage



HE: Predictions for End of Run3

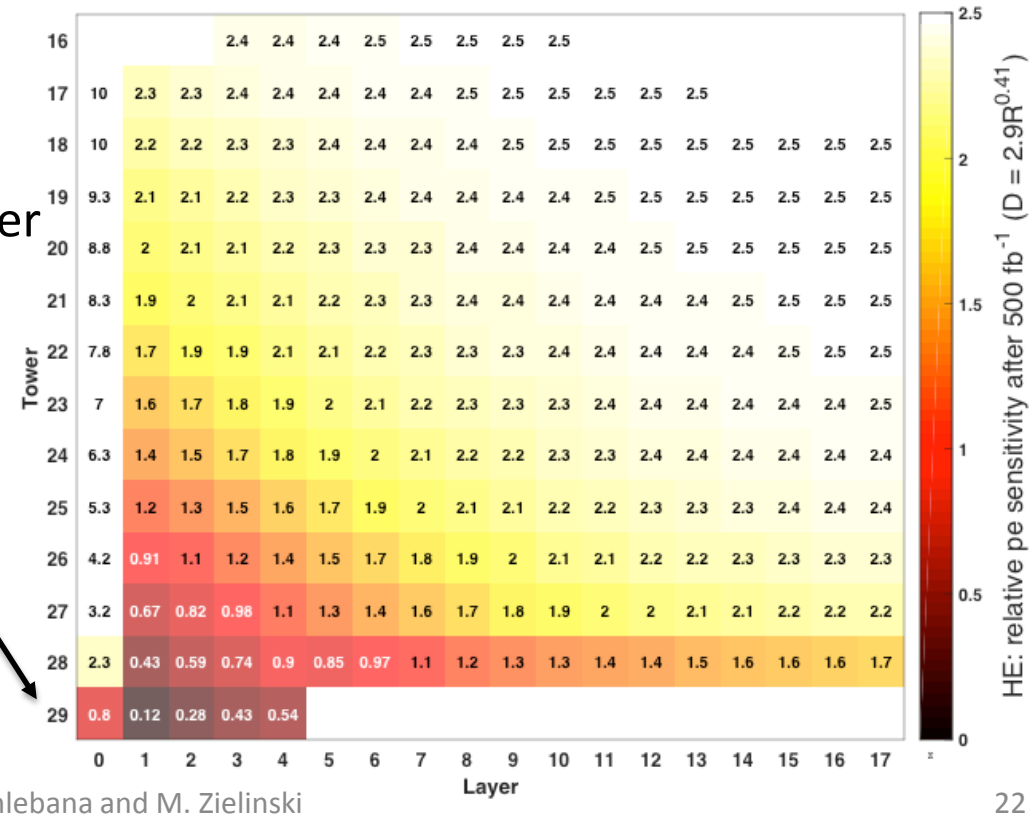
Included in the simulation

- SiPM PDE and dark current
- Doserate model prediction
- LHC luminosity profile
- High resolution Fluka maps
- L0 brightness and double readout



Impact of radiation damage on HE signal relative to a undamaged detector is compensated by the better performance of SiPMs

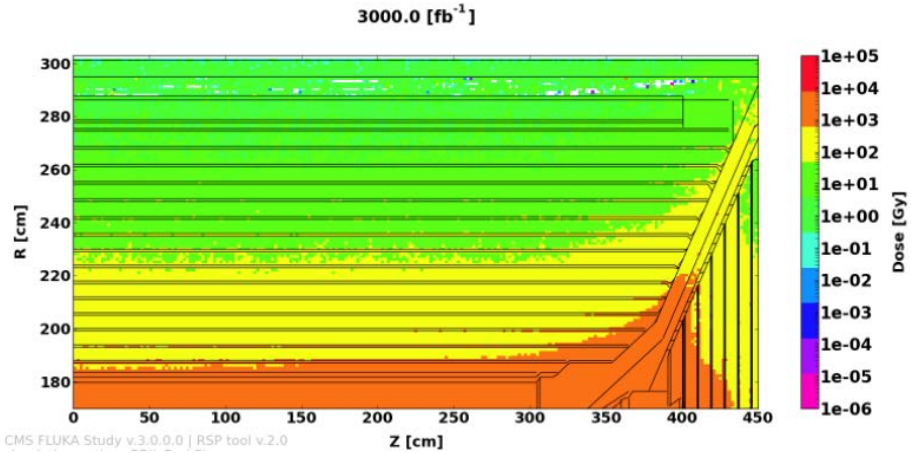
Tower 29 becomes marginal at 500 fb^{-1}



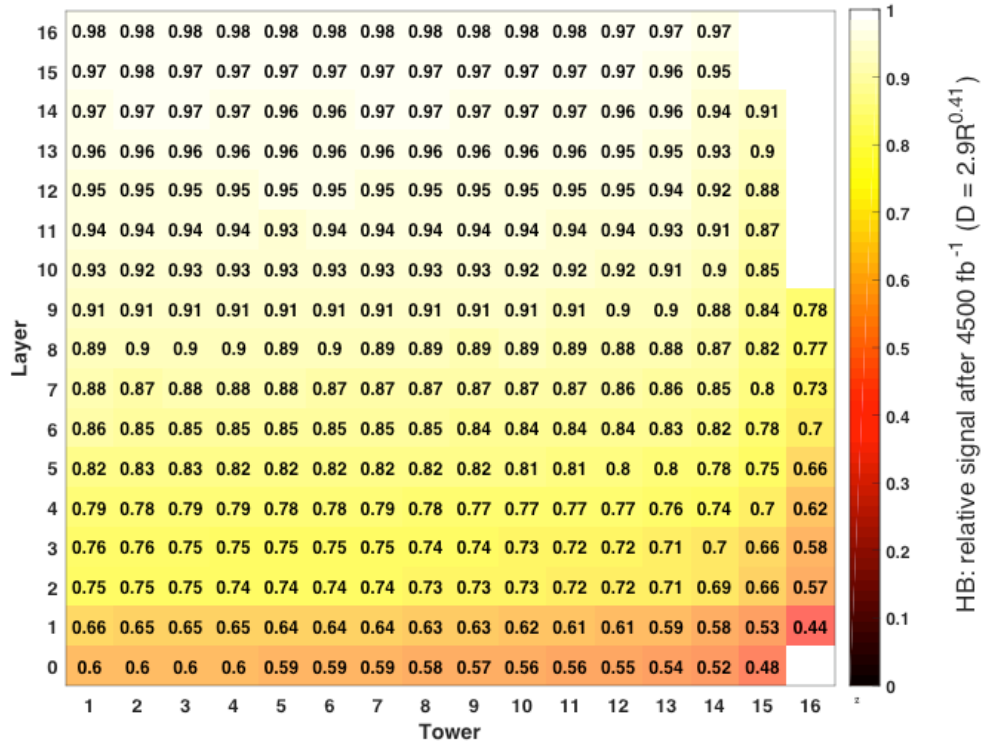
Not necessary to replace HE megatiles!

HB: predictions for the end of HL-LHC

Same model used to estimate the effects for HB



Expected light output deterioration by a factor of 2 or less does not justify HB megatile replacement during LS3



Impact on HCAL Operations and Upgrades (I)

CMS dropped the plans for selective megatile replacement in HE (during LS2) and in HB (during LS3)

- Multi-million dollar savings, simplified the upgrade schedule
- Avoided technical risks to ECAL

Led to improved operations of the HCAL laser system

- Regular gas exchanges, longer local runs, near real time DQM
- For future, system will be replaced with solid state laser

Impact on HE calibrations

- Phi-dependent calibrations were introduced
- Corrections for predicted damage were used for prompt reco before they were measured

Impact on CMS software

- Parameterizations of scintillator raddam and SiPM dark current have been implemented in CMSSW simulations
- Used for Upgrade Performance Studies and in Endcap, Barrel and HGCal TDRs

Impact on HCAL Operations and Upgrades (II)

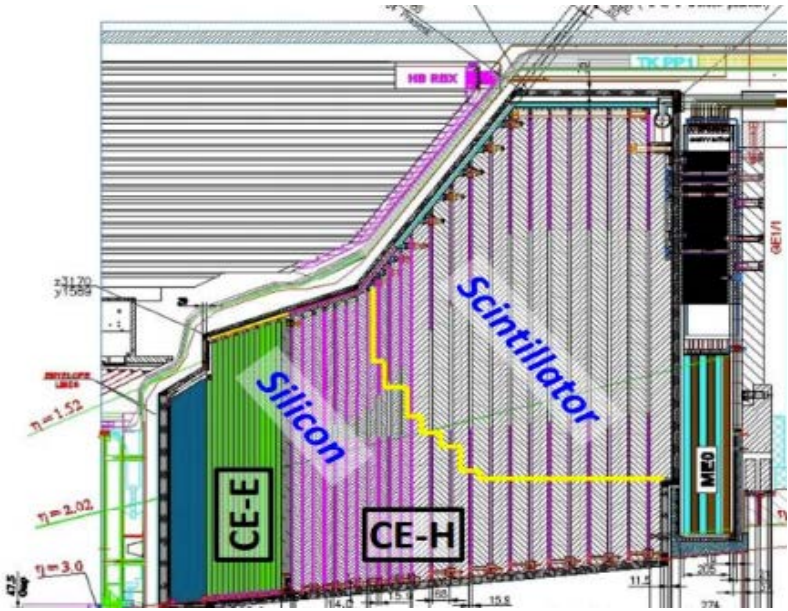
In LS3, HE will be replaced with the High Granularity Calorimeter

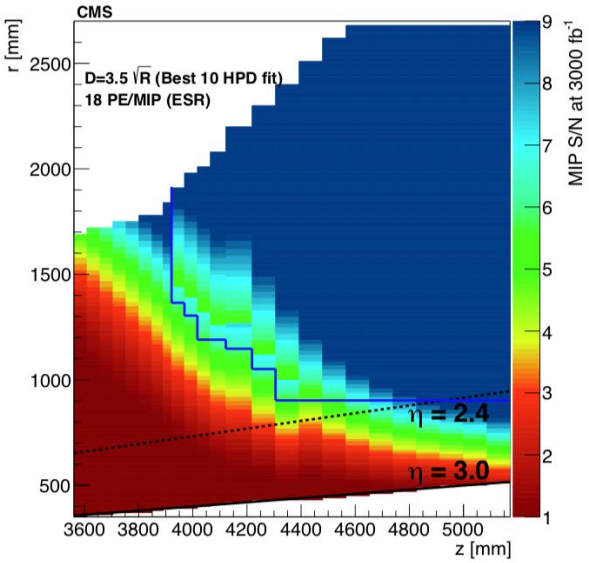
A mix of silicon and scintillator technologies in hadronic section (CE-H)

Dividing line between the two regions is optimized to limit radiation damage to scintillator and the level of SiPM dark current by the end of HL-LHC

Interestingly, SiPM dark current is more constraining than scintillator damage

CMS continues extensive R&D program of high dose irradiations to understand raddam to cold scintillators and to SiPM-on-tile readout for HGCal and MIP Timing Detector





Dan's Contributions

Insights: follow fundamentals, trust your physics sense

Leadership and mentoring: actively engaged in the Raddam Studies Group

Remain involved in analysis: Look at the data! wrote raddam analysis code in Matlab to look at aspects of laser and source data

Authored several books on using Matlab
very useful tools for quick explorations of data

Envisioned a comprehensive paper for JINST ~30 pages, submitted for HCAL DPG preapproval

Dan continues to remain active and engaged