# CMS Experience with HGCAL

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on behalf of the CMS Collaboration

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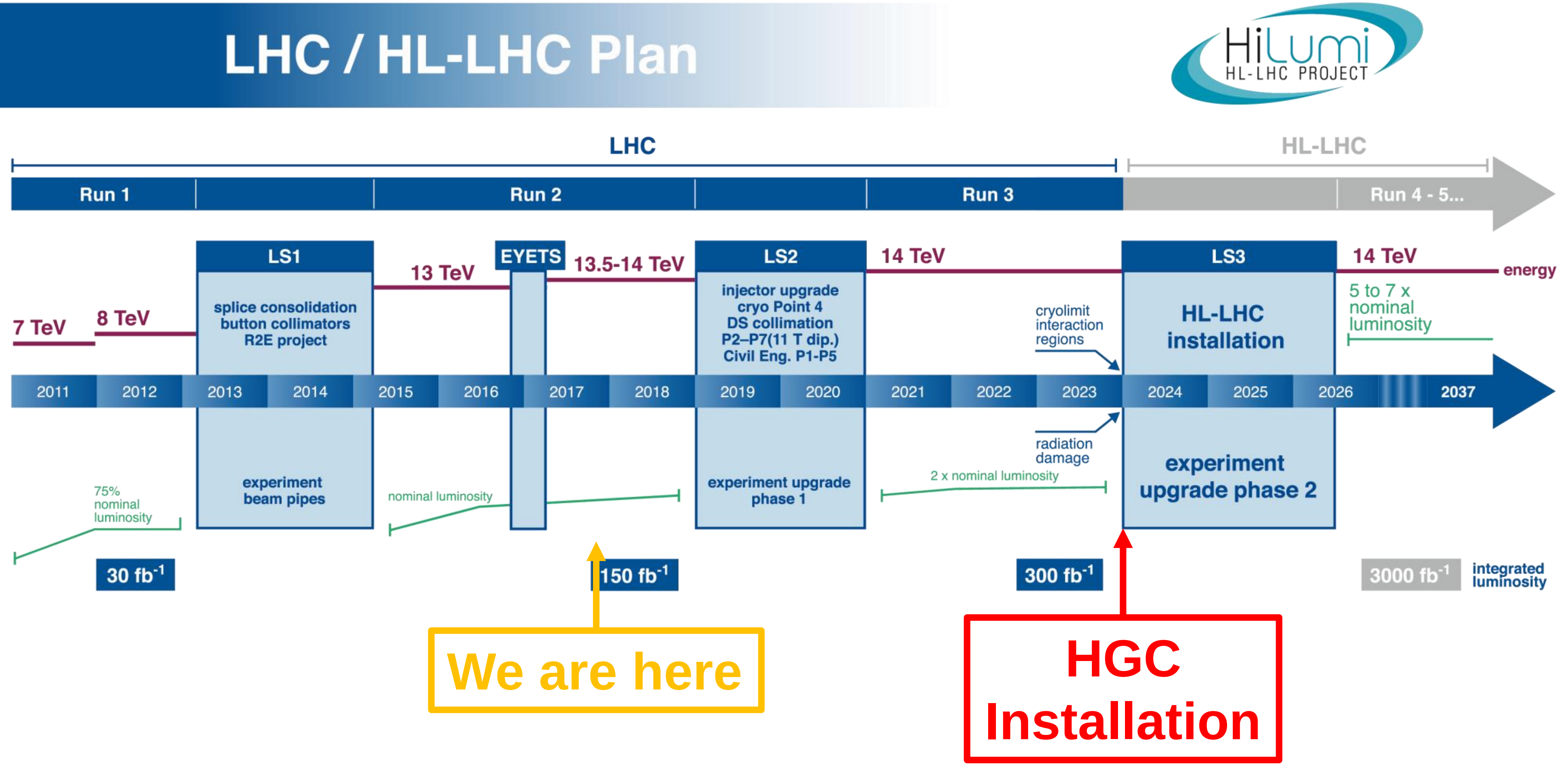
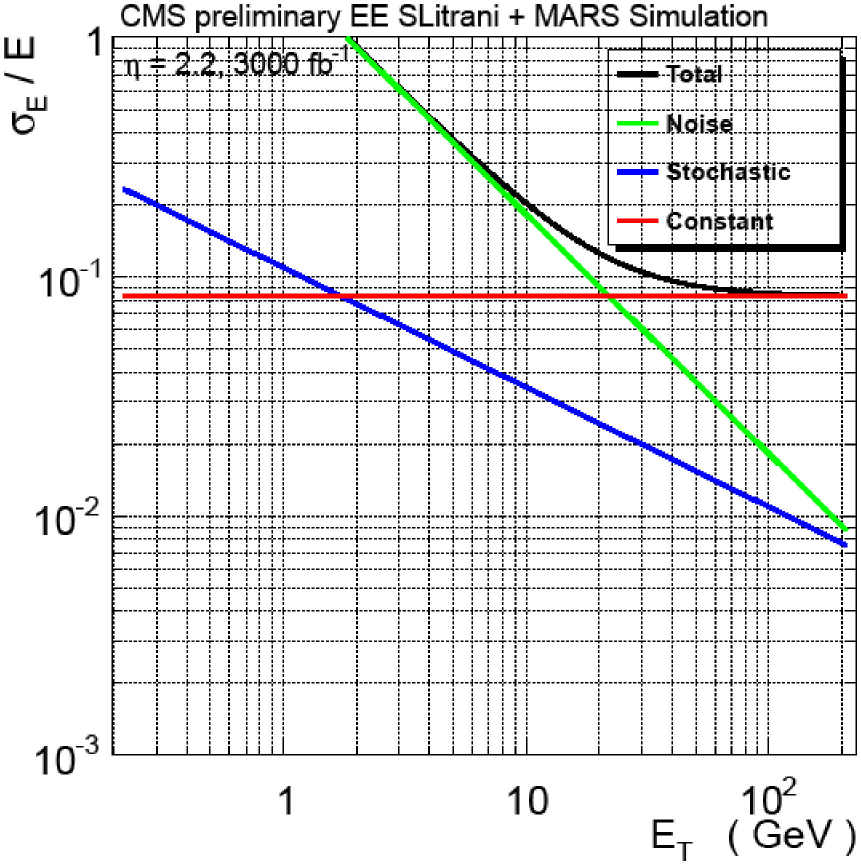
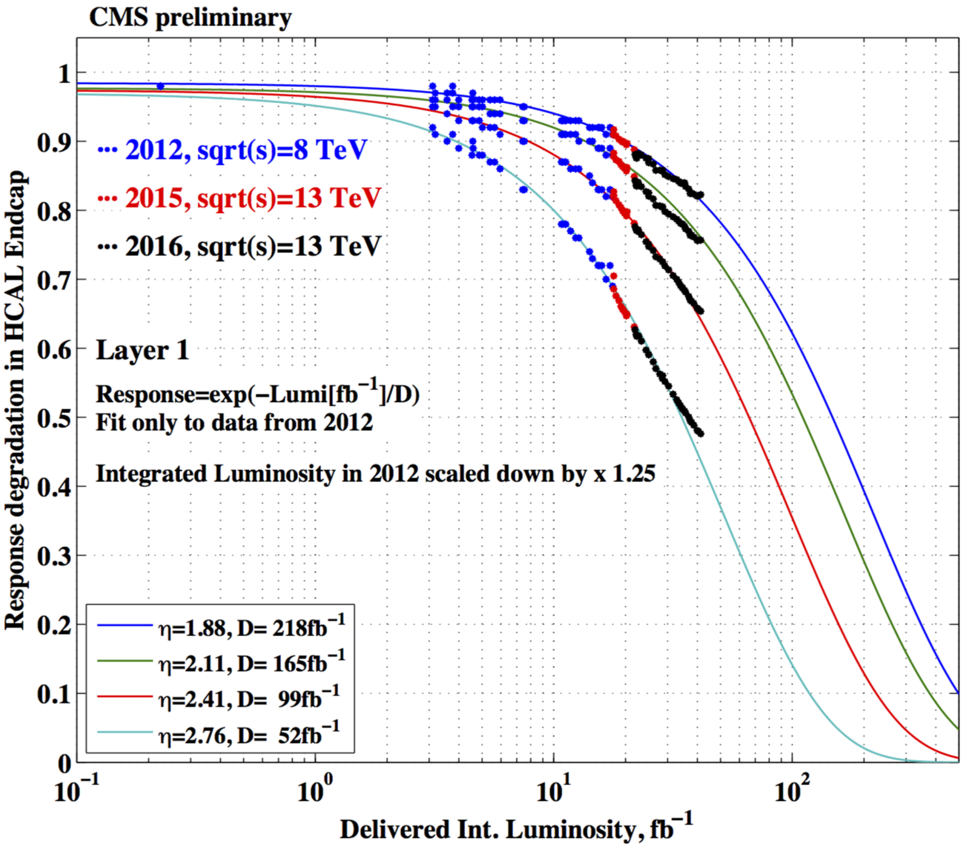
# The LHC Schedule



# CMS Calorimeters in 2035

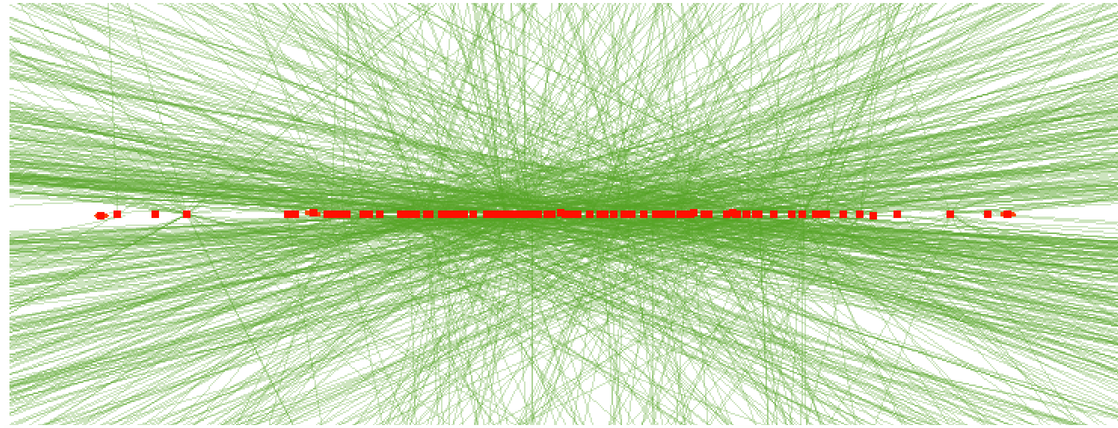


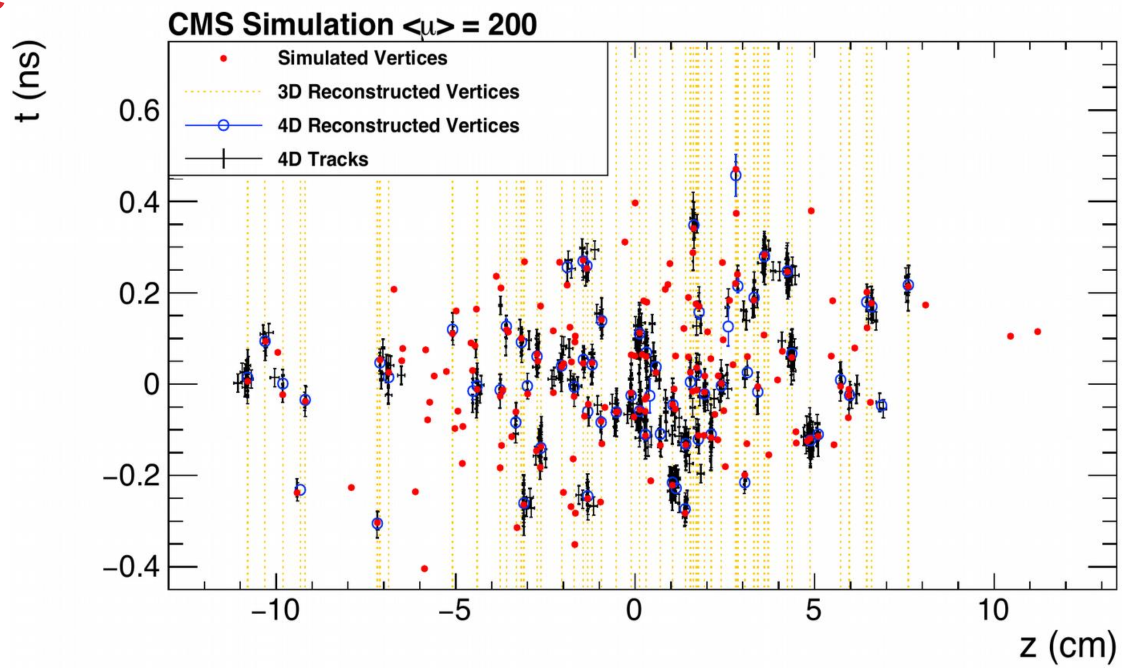




- Radiation damage on $PbWO_4$ crystals and plastic scintillators forces replacement of endcap calorimeters
  - Barrel calorimeters will only require replacement of readout electronics

# Challenges

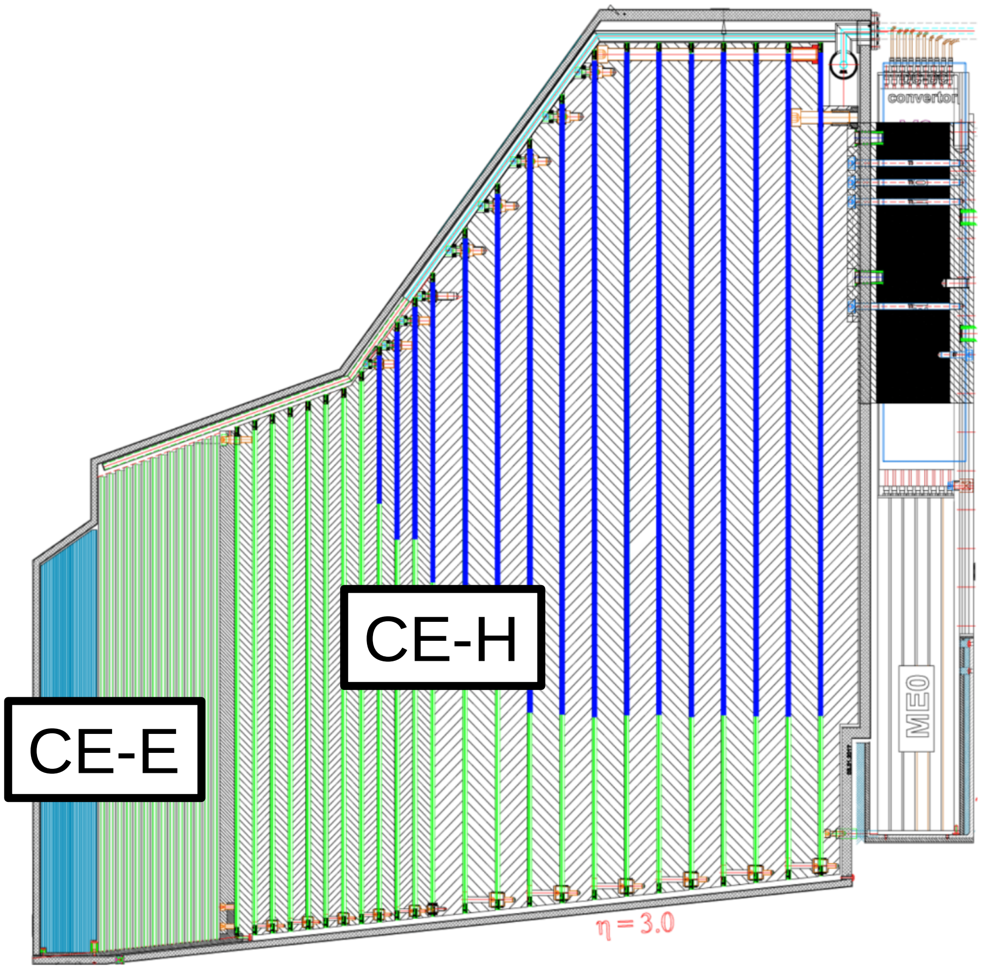
- Radiation-induced reduction of signal yield
  - Radiation-hard silicon sensors in high-dose region; plastic scintillator in low-dose region
- High number of simultaneous interactions
  - High granularity, longitudinal segmentation, precision timing allow for the separation of pile-up vertices





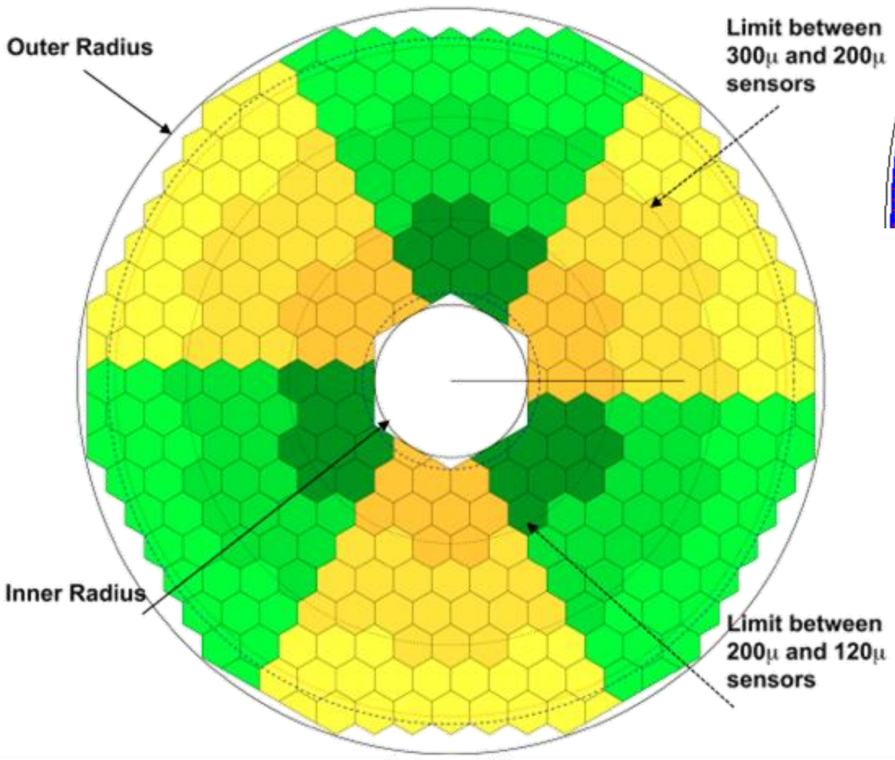
# The HGCAL Design

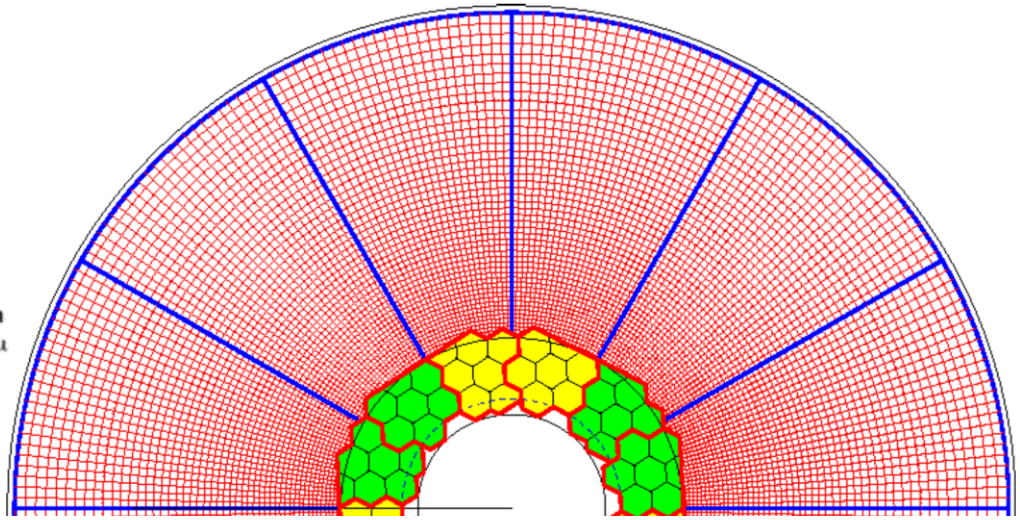
- Key parameters
  - 1.5<|η|<3.0
  - 600m[2] Si sensors
  - 500m[2] scintillator
  - 6M channels
- CE-E
  - Cu/CuW/Pb absorber
  - Silicon sensors
  - 28 layers; 25$X_0$, ~1.3λ
- CE-H
  - Steel absorber
  - Silicon and scintillator
  - 24 layers; ~8.5λ



# Mechanical Layout

**Si-only layer**
**Sensor thickness optimized vs radiation hardness**



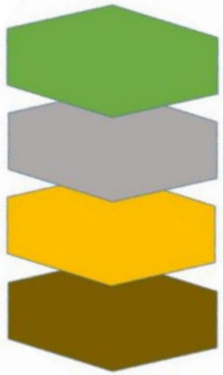



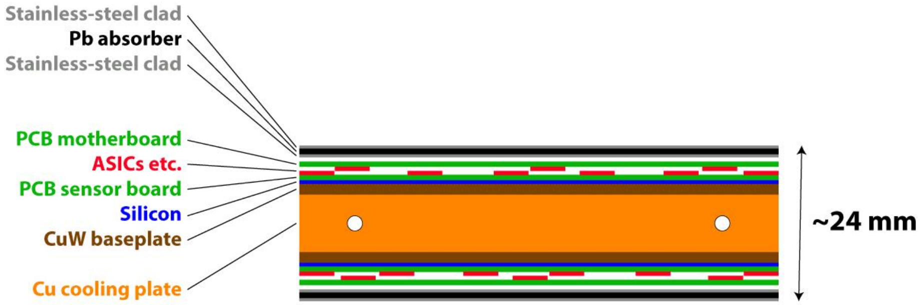
**Mixed Si-scintillator layer**
**Boundary optimized vs radiation hardness**
**Scintillator too in cold volume (-30C)**

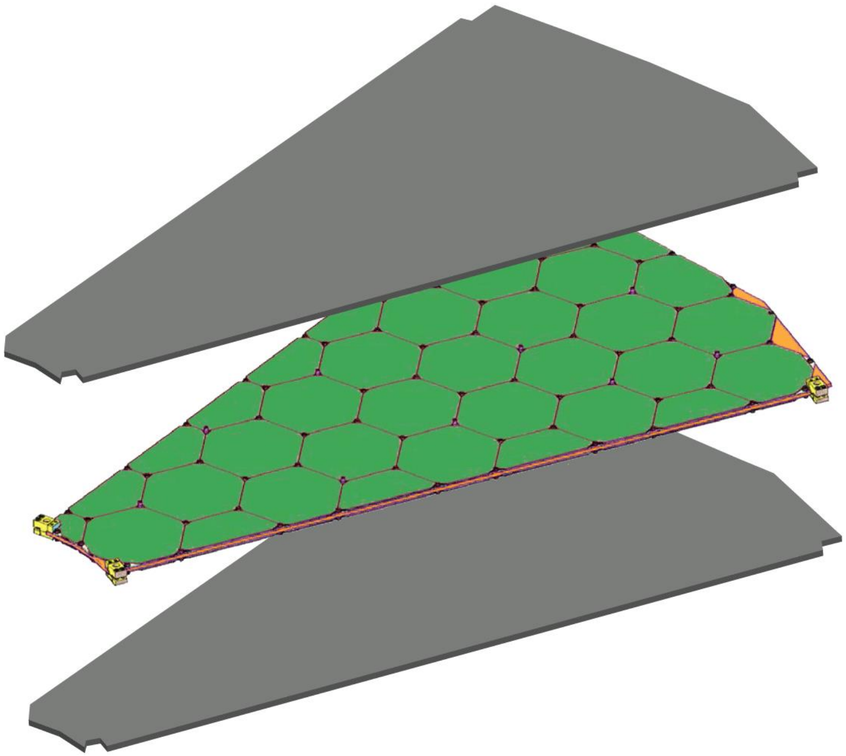
# CE-E Layer Design

**Hexagonal Module design:**
Glued stack of:

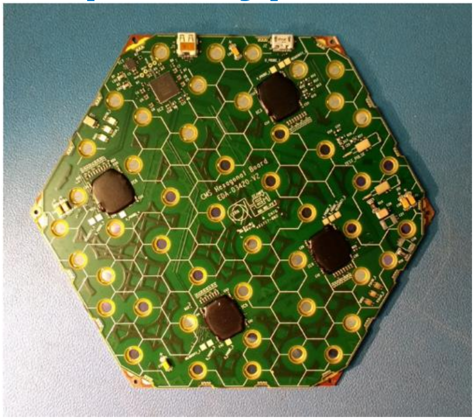
- **PCB,**
- **Sensor,**
- **Kapton,**
- **Baseplate**



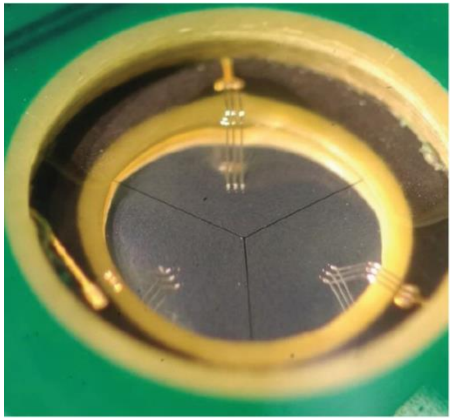


**6" module prototype**

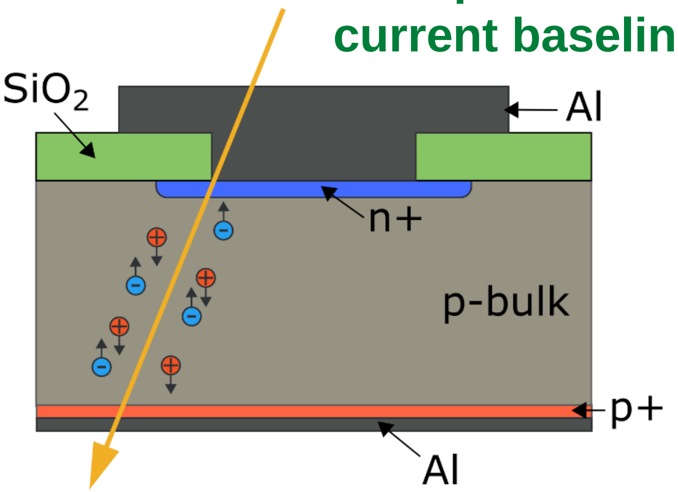


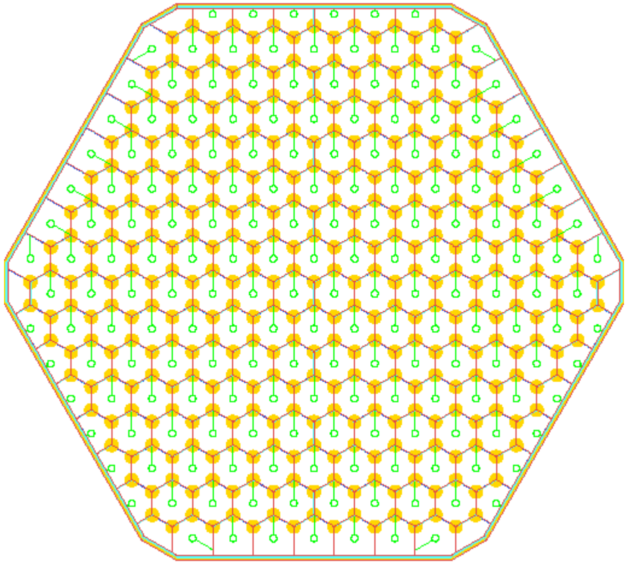
**Close up of wirebonds**



# Silicon Sensors

**n-on-p sensor current baseline**

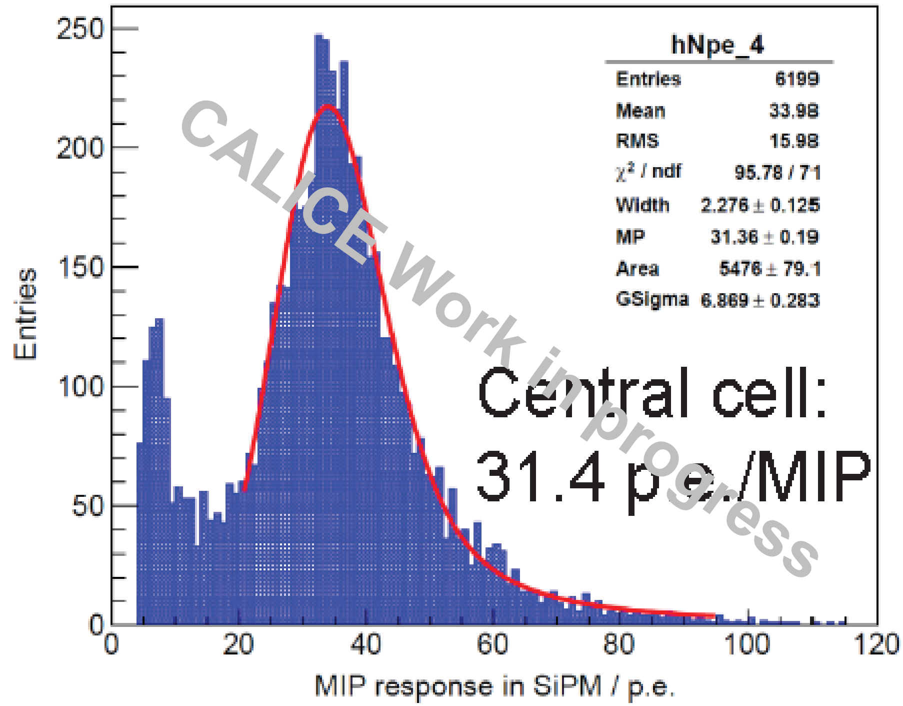


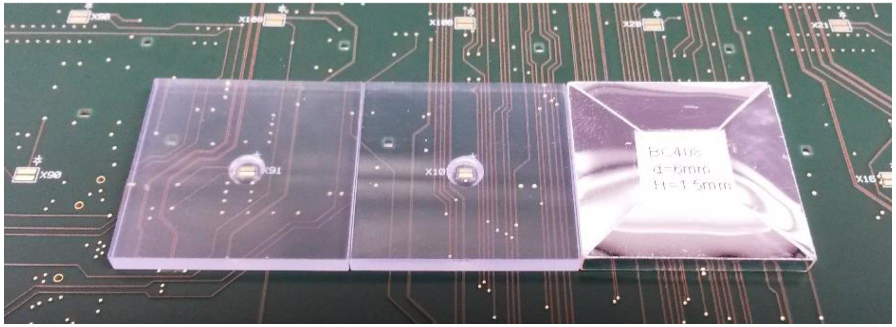



- Hexagonal sensor geometry
  - Largest tile-able polygon; maximize use of circular wafers
- Design goals
  - Sustain 1kV to mitigate radiation damage
  - Good S/N for MIP at the end of HL-LHC run period
    - Expected total dose and radiation fluence: ~100Mrad and ~$10^{16}$ $n_{eq}/cm^2$
- Current design
  - 8-inch sensor, 192 1$cm^2$ cells or 432 0.5$cm^2$ cells
  - Small-size calibration cells for single MIP sensitivity

# SiPM-on-Tile Setup

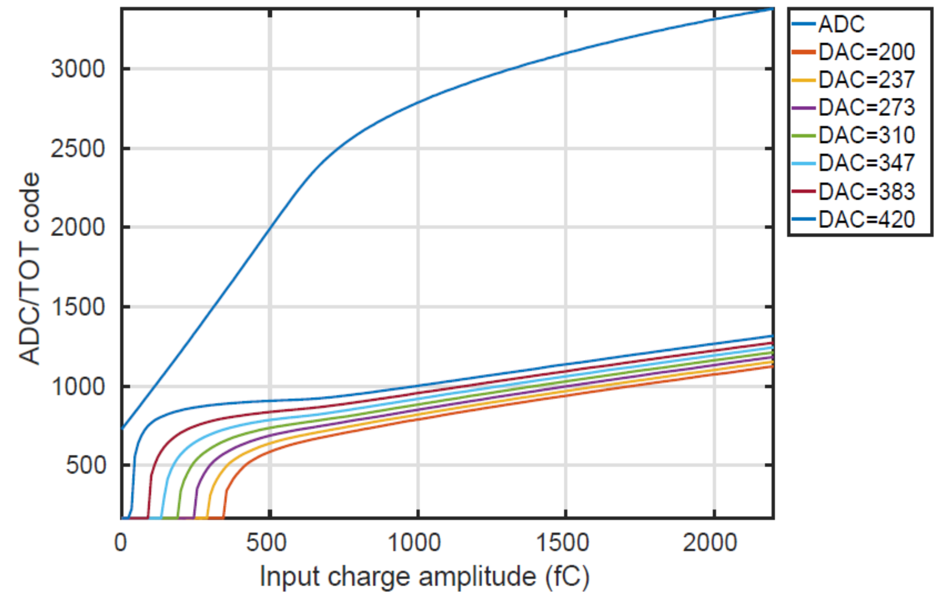
- Photosensor (SiPM) mounted directly on tile
  - Direct collection of scintillator light
  - Tile wrapped with reflective cover
  - Central dimple in tile optimizes light collection
- Cosmic-ray runs with prototype assembly
  - CALICE AHCAL prototype (similar structure to CE-H)

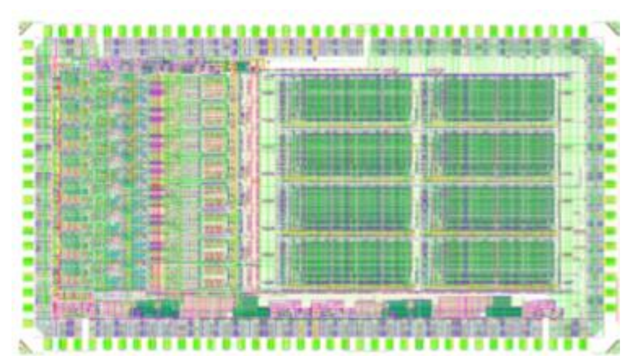


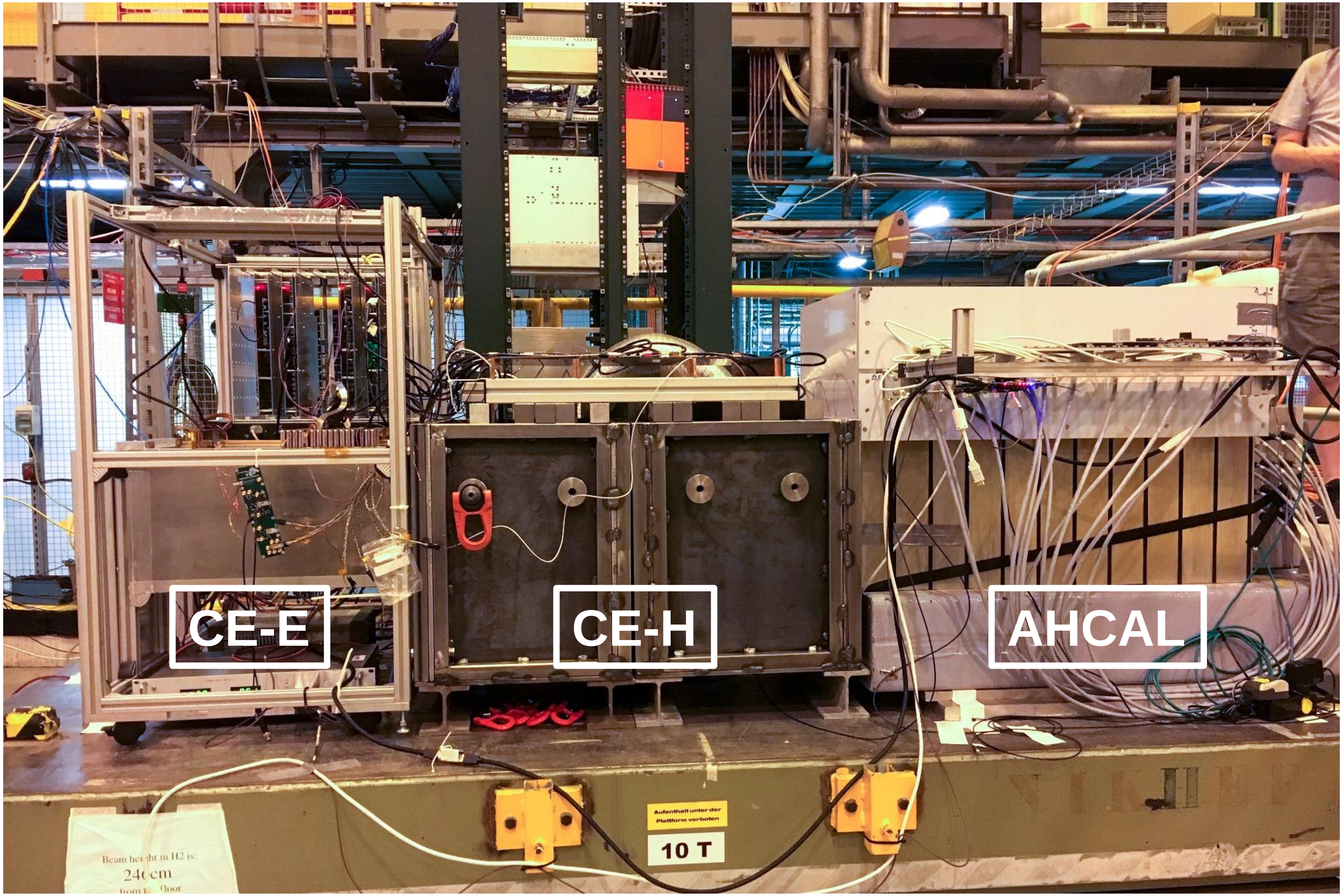
# FE Readout Electronics

- Requirements
  - Large dynamic range (0.4fC to 10pC)
  - Low power (<15mW/channel)
  - Timing information with 50ps accuracy
  - Low noise (2ke)
  - High radiation resistance
- Baseline
  - 130nm ASIC
  - ToA with 50ps binning
  - 12-bit ToT for 0.1-10pC; 11-bit ADC for 0-0.1pC
  - Buffers to accommodate 12.5μs L1 trigger latency
- Current status
  - SKIROC2-CMS ASIC designed for testbeam
  - HGROC_V1 submitted in July

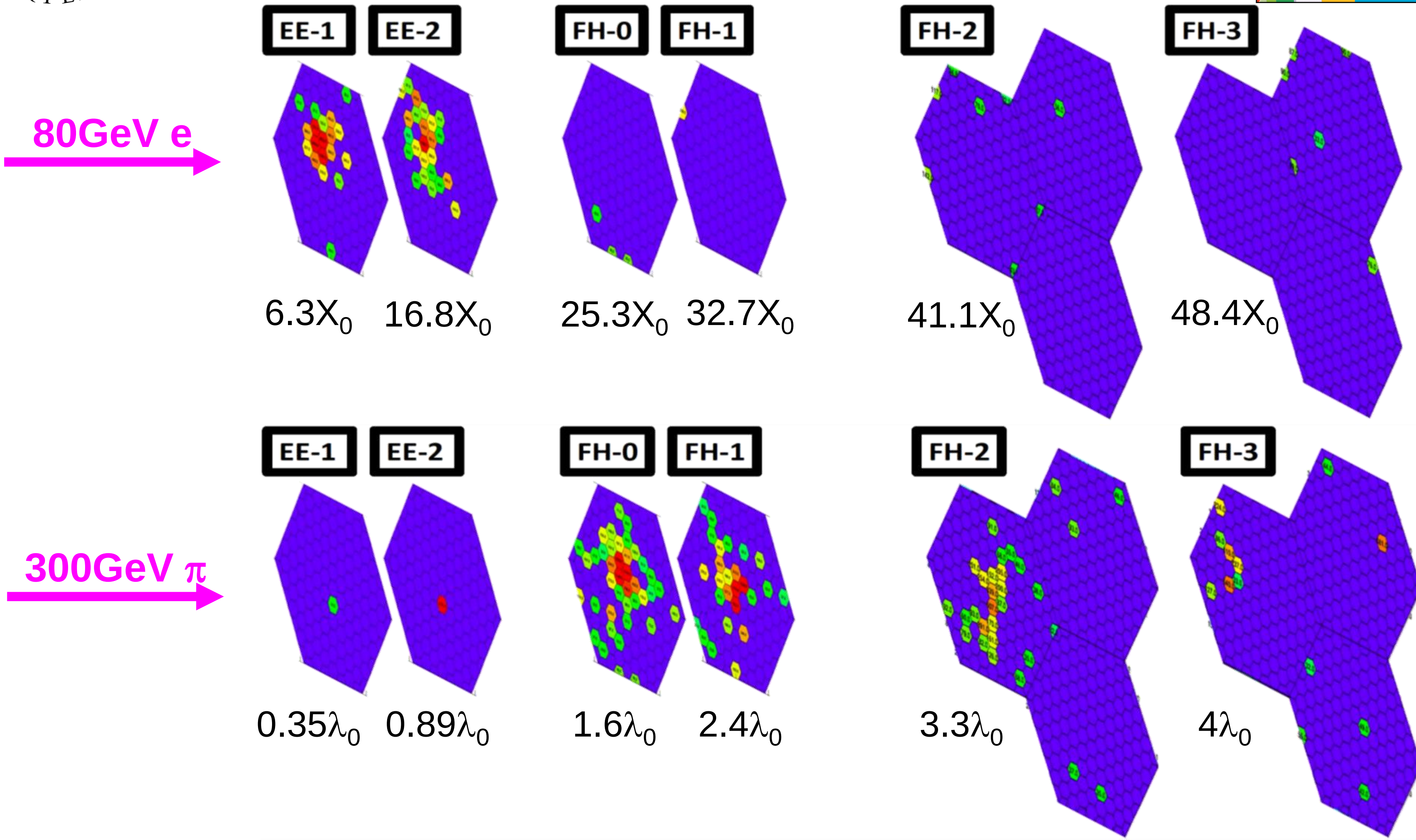


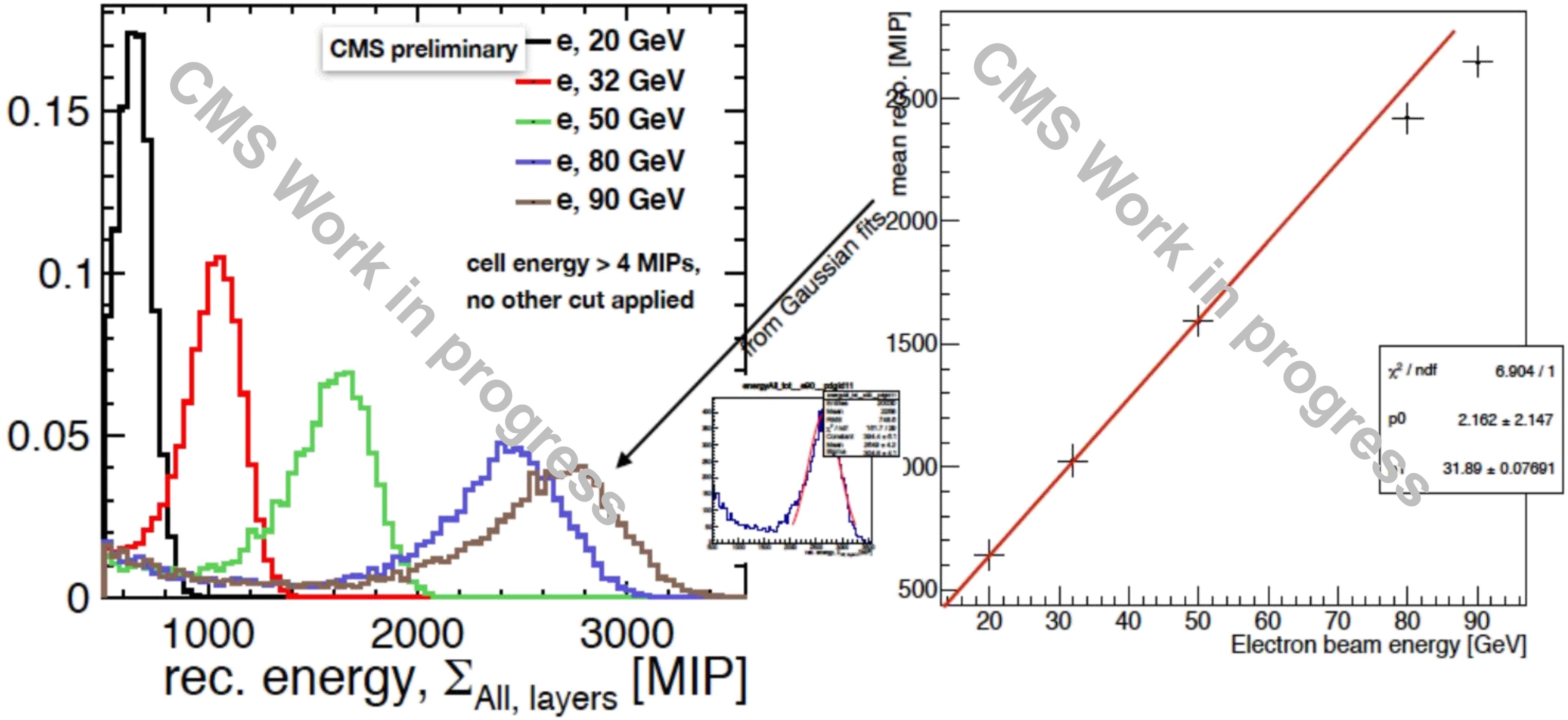
# CERN Test Beam - 2017



# Event Displays



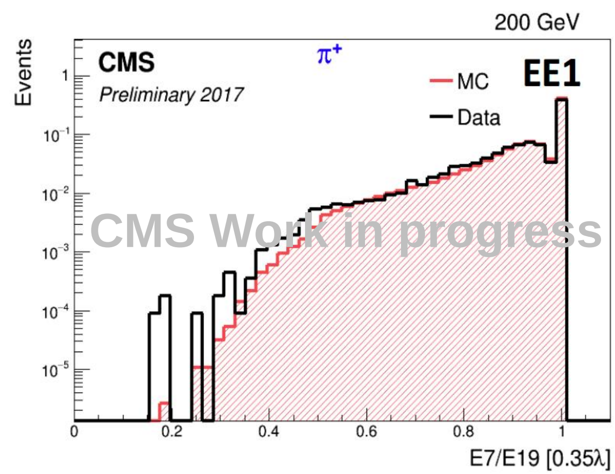
# Energy Linearity

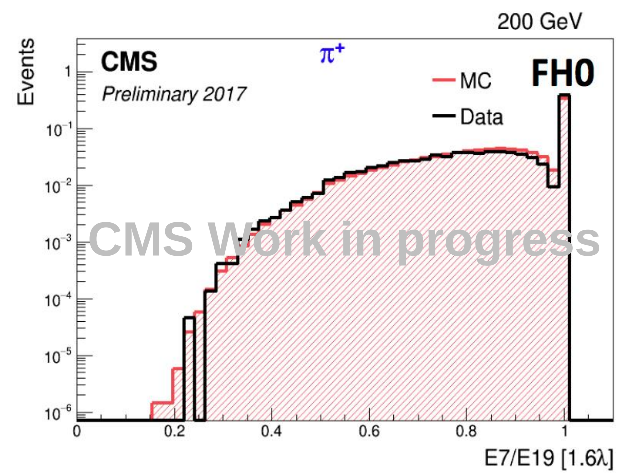



- Sum of fitted pulse amplitudes over all cells in all layers
  - Pedestal and common-mode noise subtracted
  - No weights applied: room for improvement
- Good energy measurement linearity
  - Ongoing analysis of 100-300GeV hadron beam results

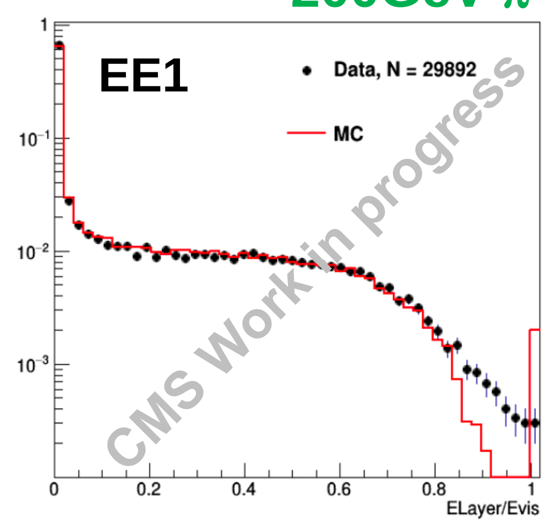
# Data vs. Simulation

- Transverse shower size: E7/E19
  - E7: highest energy cell + 6-cell ring
  - E19: highest energy cell + 2 rings
- Longitudinal shower profile: ELayer/Evis
  - ELayer: energy in given layer
  - Evis: total sum of energy in calorimeter
- Good agreement with simulation
  - Discrepancies under investigation

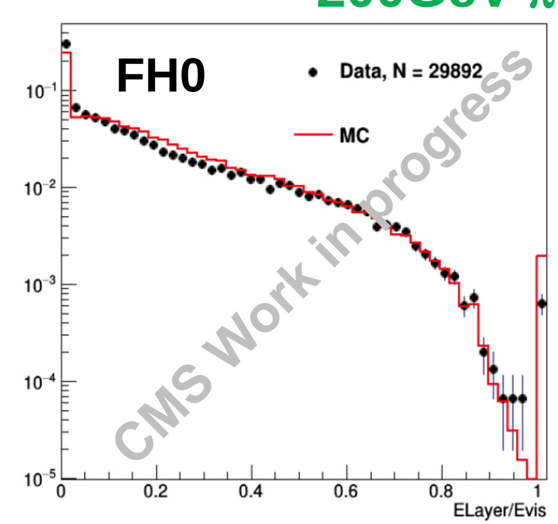


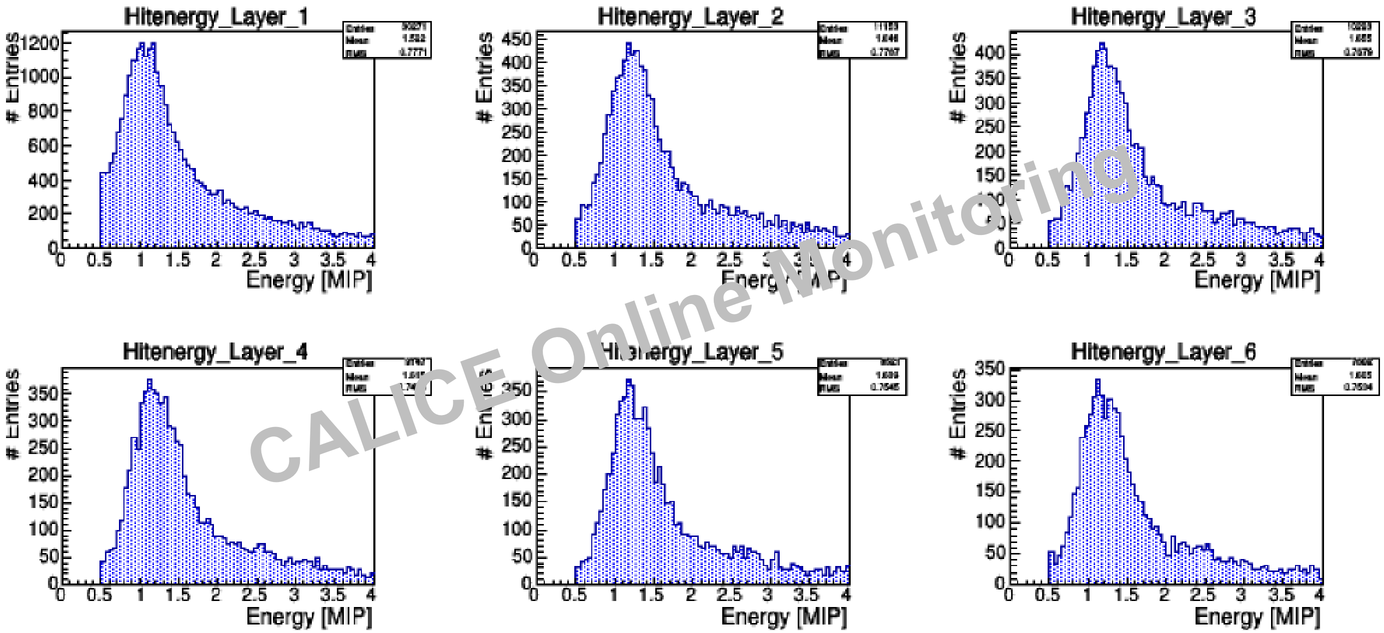

200GeV π




200GeV π

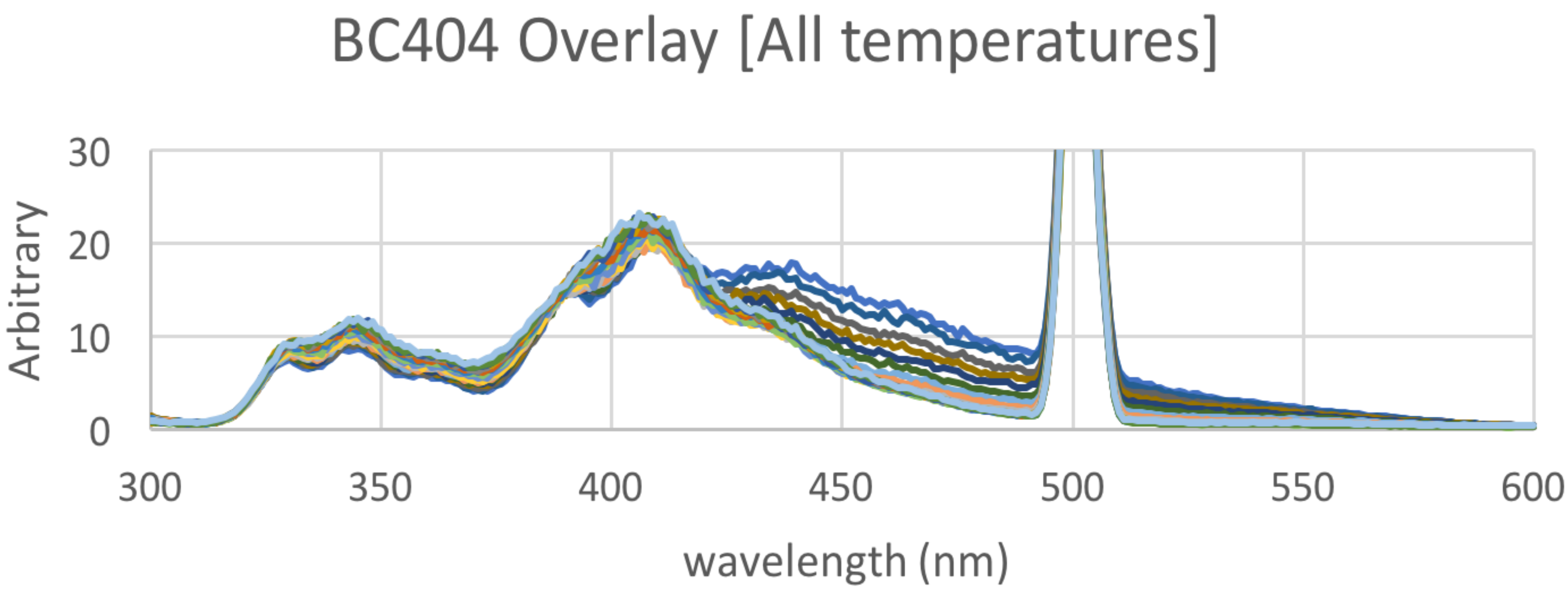


# AHCAL at Test Beam




- CALICE-AHCAL prototype
  - 12 36x36cm$^2$ layers; 144 3x3cm$^2$ scintillator tiles; 74mm steel plates (~5$\lambda$)
- 300GeV pion test beam
  - Online monitoring data with preliminary calibration
  - HGCAL and AHCAL integrated DAQ
  - Clear MIP peaks visible in shower

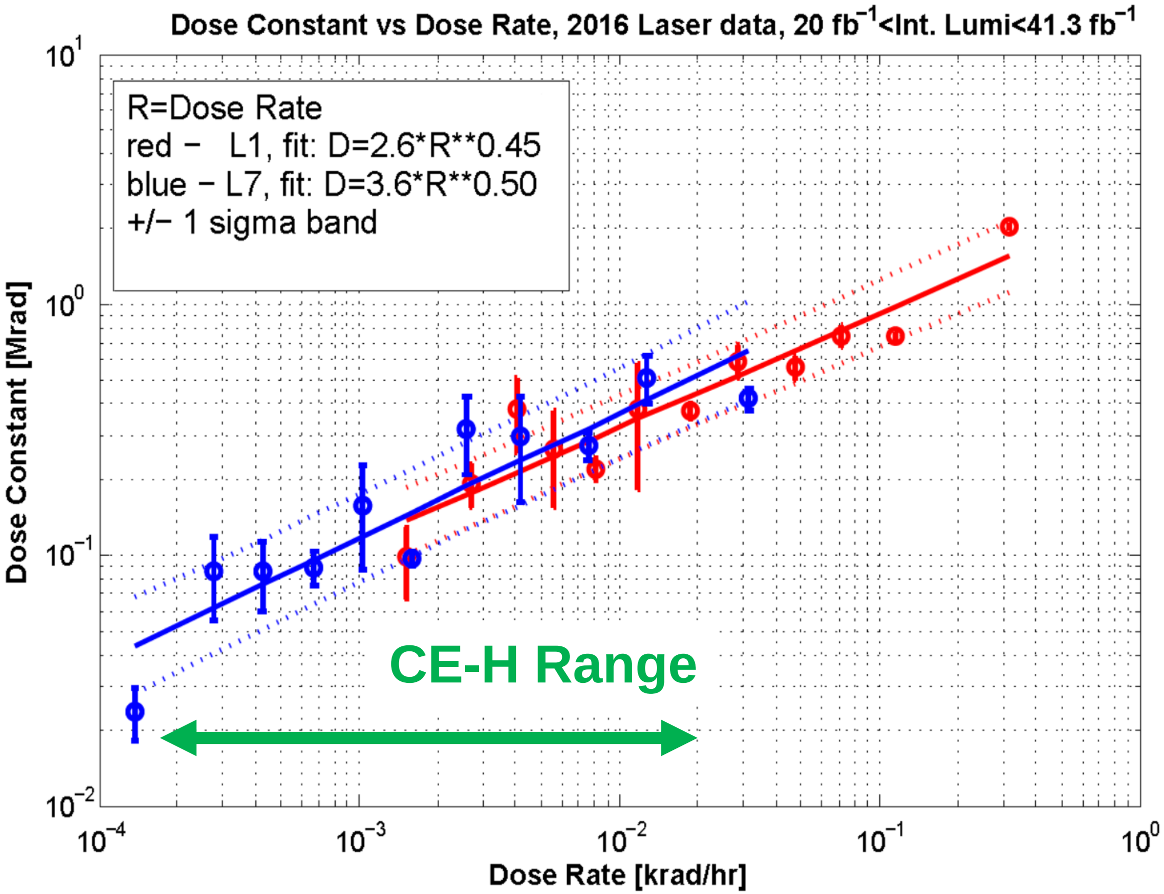
# Cold Scintillators




- Pulse shape and timing unaffected by temperature
  - Tested down to -180C (scintillator in liquid nitrogen)
- Radiation damage does not preclude usage
  - Lower temperature slows annealing, without affecting permanent damage

# Radiation Damage (1)

L(d) = L(0)·exp(-d/D); d: dose, D: dose constant

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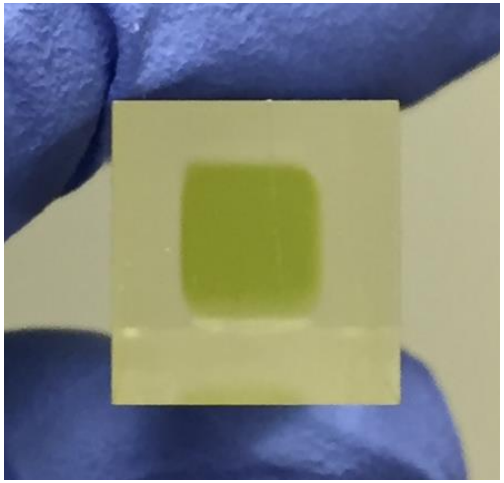
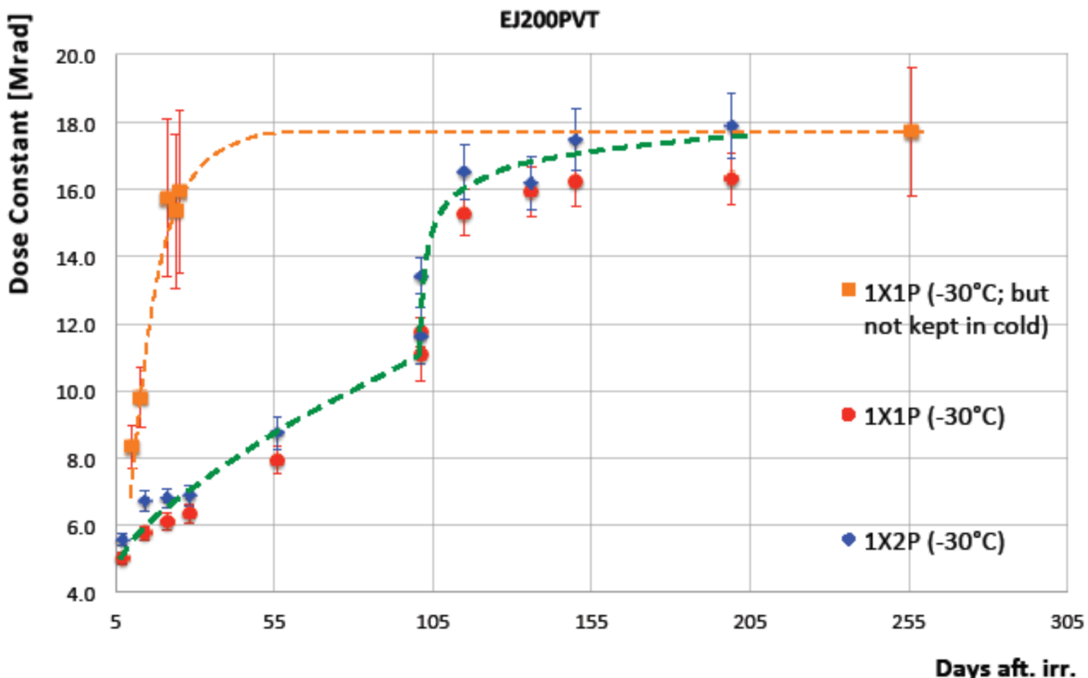
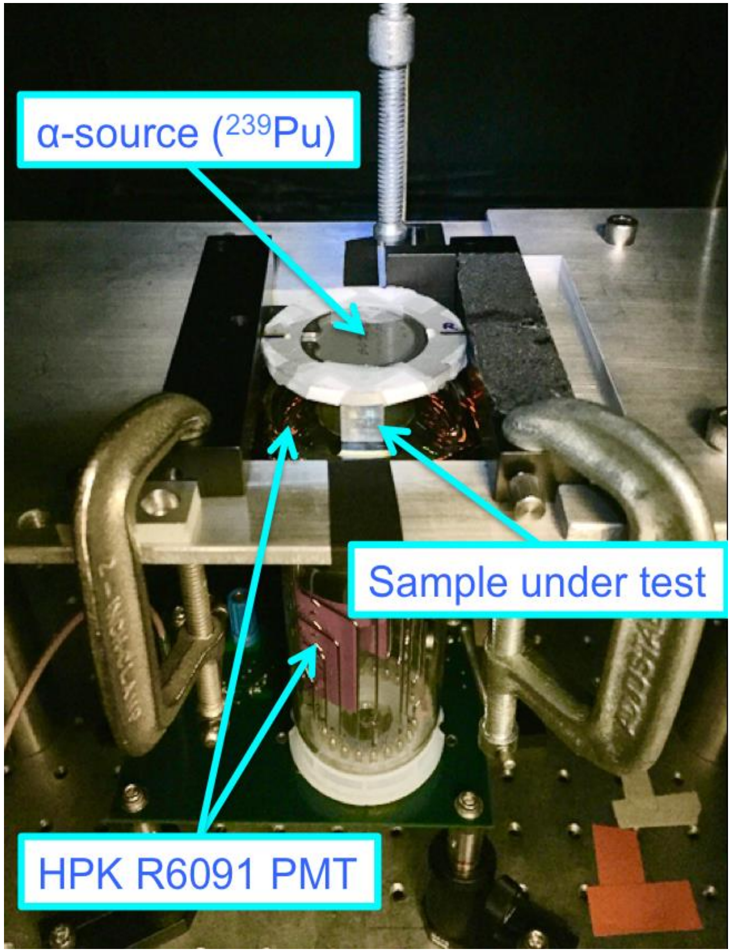
- Radiation damage (per unit of integrated dose) increases at low dose rates
  - Oxygen diffusion drives the dose-rate dependency



# Radiation Damage (2)




- Monitoring annealing of damaged scintillator
  - 1x1x5cm$^3$ samples of plastic scintillator
  - Light yield with $\alpha$-source
  - Low temperature slows annealing, but no difference in permanent damage

# Summary

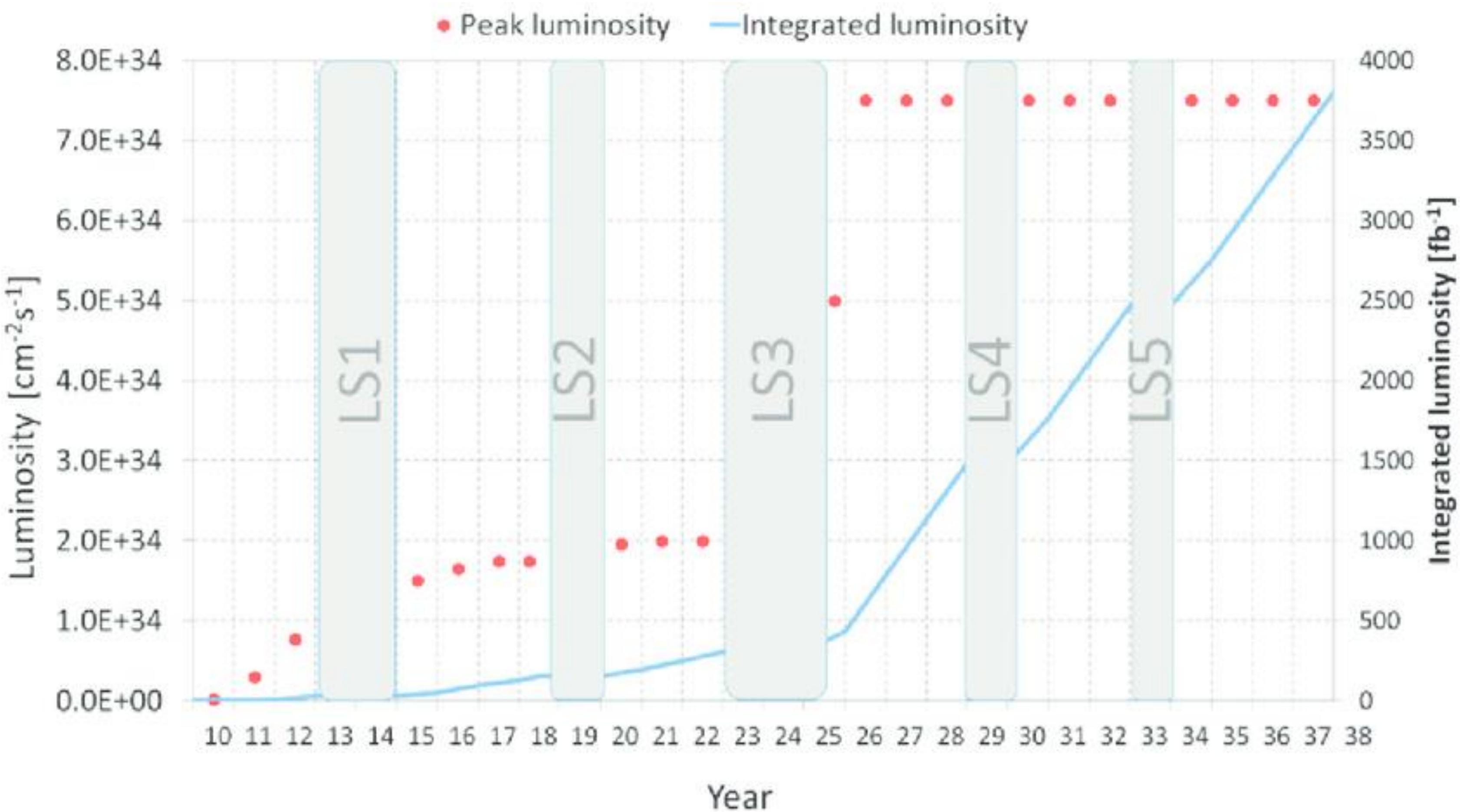
- HGCAL expected to run in very hostile environment
  - Radiation, pile-up
- Flexible system provides multiple measurements
  - Energy, tracking, timing
- Active R&D program studies implementation of innovative solutions
  - Mechanics, electronics, reconstruction algorithms
- Steady progress along schedule
  - TDR scheduled for end of year

# Backup

# References


- F. Pitters, “The CMS High-Granularity Calorimeter for Operation at the High-Luminosity LHC”, TIPP 2017
- J. Borg, “Electronics and Triggering Challenges for the CMS High Granularity Calorimeter”, TIPP 2017
- F. Romeo, “Construction and rst beam-tests of silicon-tungsten prototype modules for the CMS High Granularity Calorimeter for HL-LHC”, TIPP 2017
- J.-B. Sauvan, “The CMS High Granularity Calorimeter for the High Luminosity LHC”, CHEF 2017
- T. Quast, “Construction and beam-tests of silicon-tungsten prototype modules for the CMS High Granularity Calorimeter for HL-LHC”, CHEF 2017
- E. Pree, “Large-Area Silicon Detectors for the CMS High Granularity Calorimeter”, CHEF 2017
- F. Ricci-Tam, “Scintillator performance at low dose rates and low temperatures for the CMS High Granularity Calorimeter for HL-LHC”, CHEF 2017
- A. Lobanov, “Electronics and Triggering Challenges for the CMS High Granularity Calorimeter”, CHEF 2017

# The LHC Roadmap



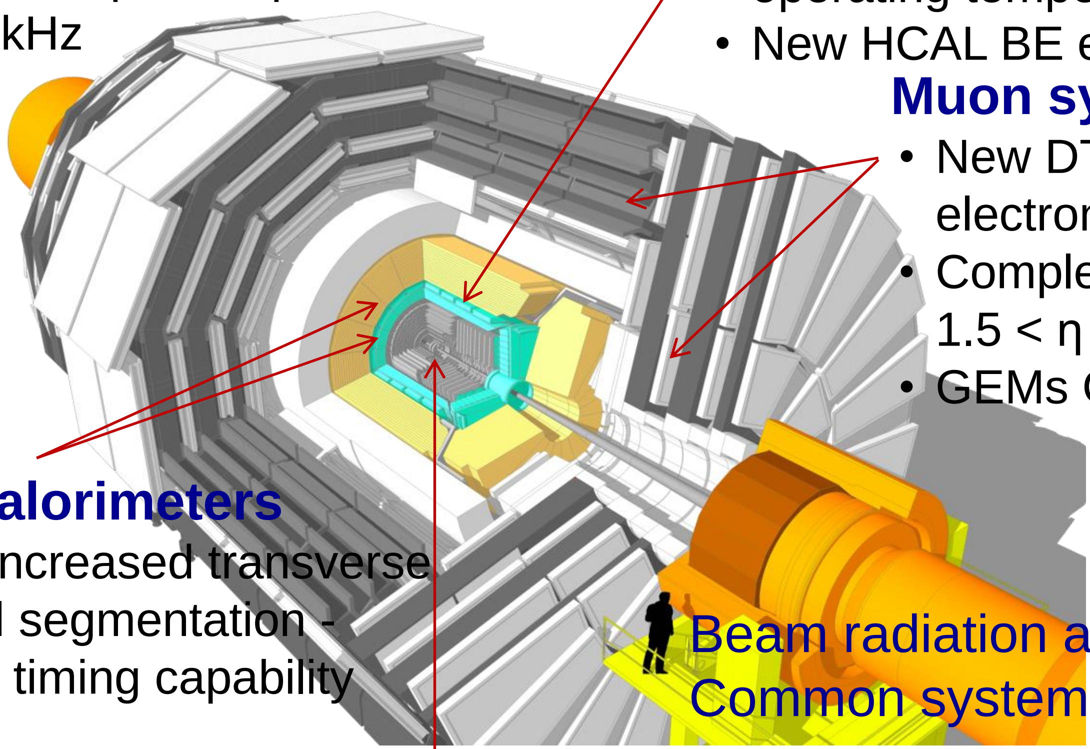

- Luminosity leveled at $7.5 \cdot 10^{34} cm^{-2}s^{-1}$

# CMS HL-LHC Upgrades

### Trigger/HLT/DAQ
- Track information in Trigger (hardware)
- Trigger latency 12.5 µs - output rate 750 kHz
- HLT output 7.5 kHz

### Barrel calorimeter
- New EM FE/BE electronics; lower operating temperature (8°C)
- New HCAL BE electronics

### Muon systems
- New DT & CSC FE/BE electronics
- Complete RPC coverage $1.5 < \eta < 2.4$
- GEMs GE1/1, GE2/1, ME0

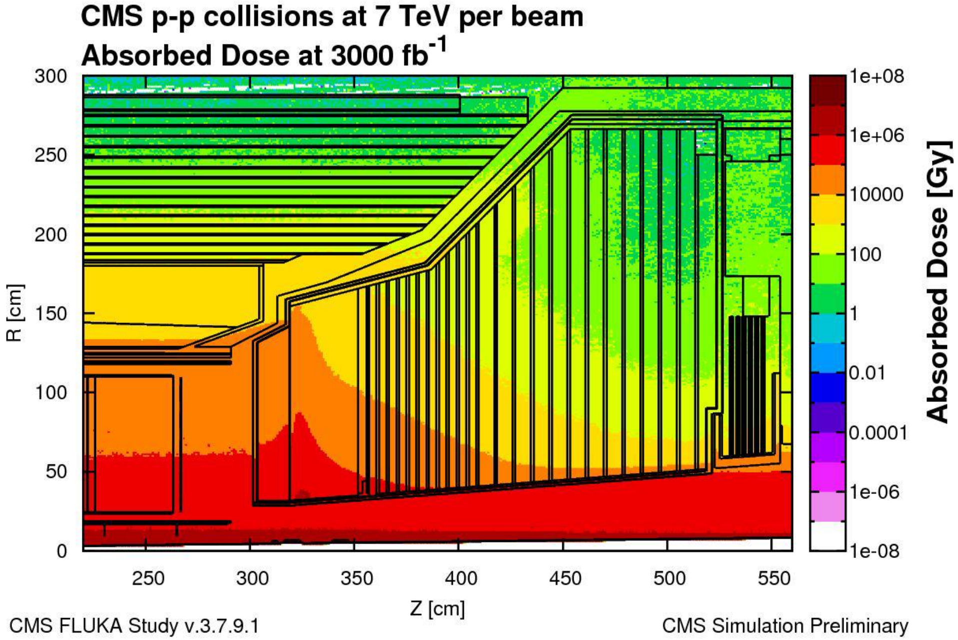


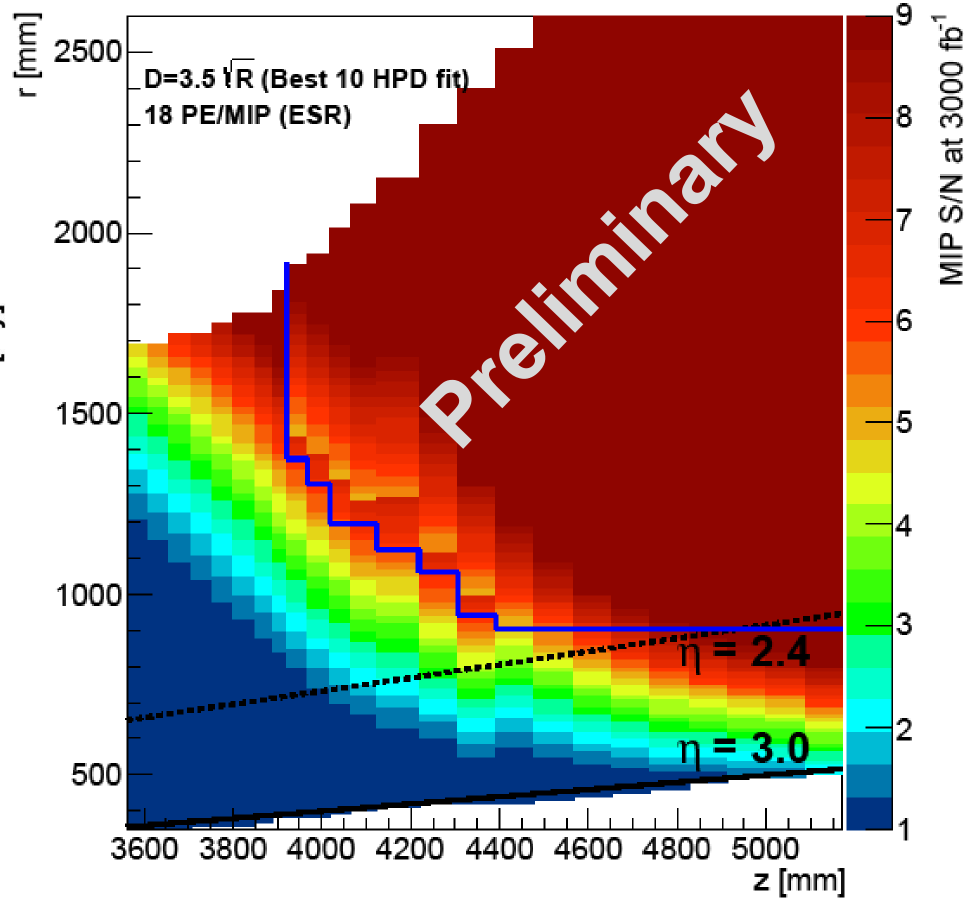
### New Endcap Calorimeters
- Rad. tolerant - increased transverse and longitudinal segmentation - intrinsic precise timing capability

Beam radiation and luminosity
Common systems & infrastructure

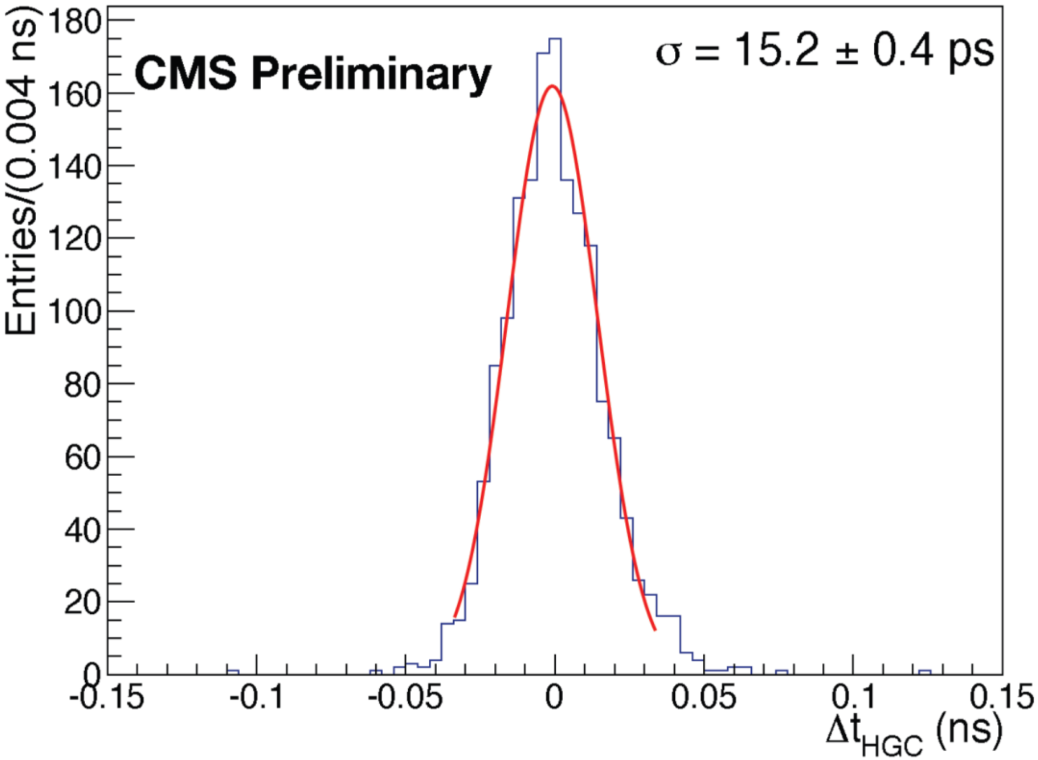
### New Tracker
- Rad. tolerant - increased granularity - lighter
- 40 MHz selective readout ($p_T \geq 2$ GeV) in Outer Tracker for Trigger
- Extended coverage to $\eta \simeq 3.8$

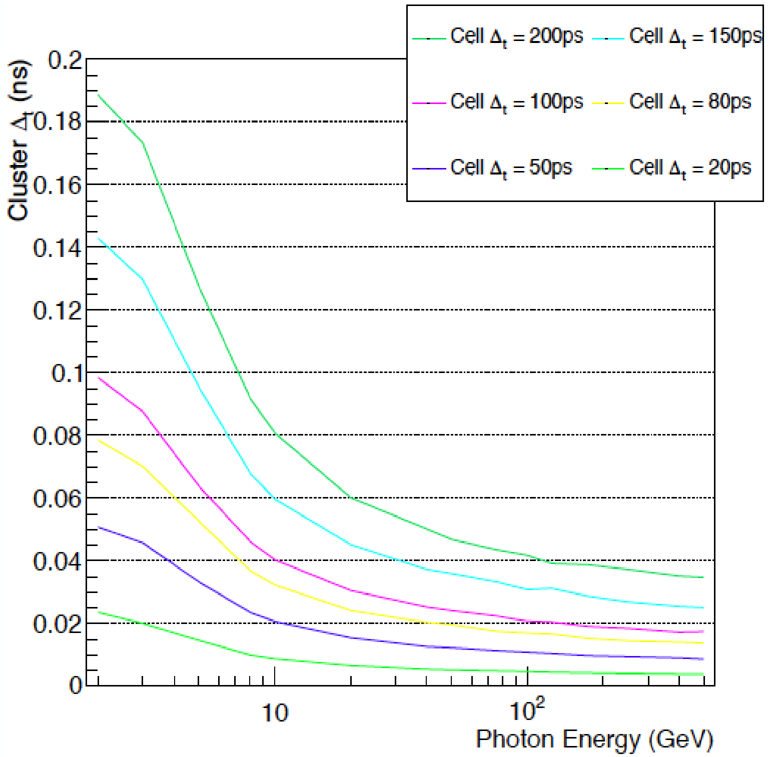
# Radiation Considerations



# Timing Performance

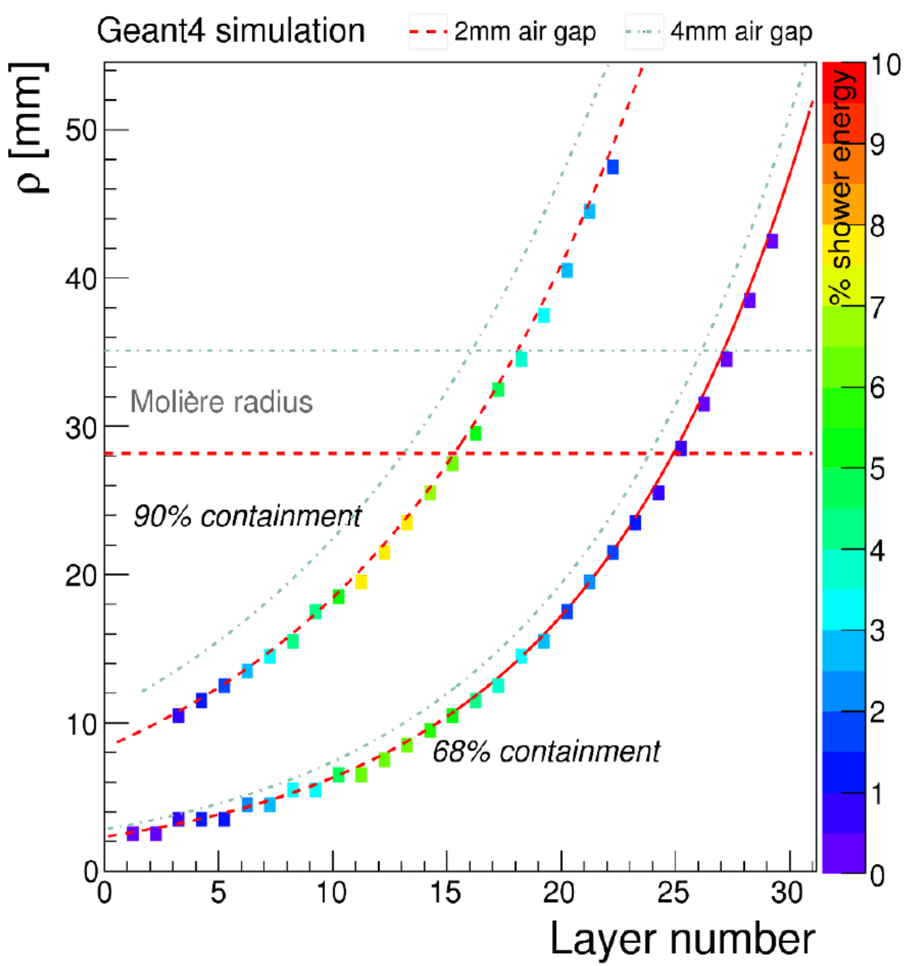


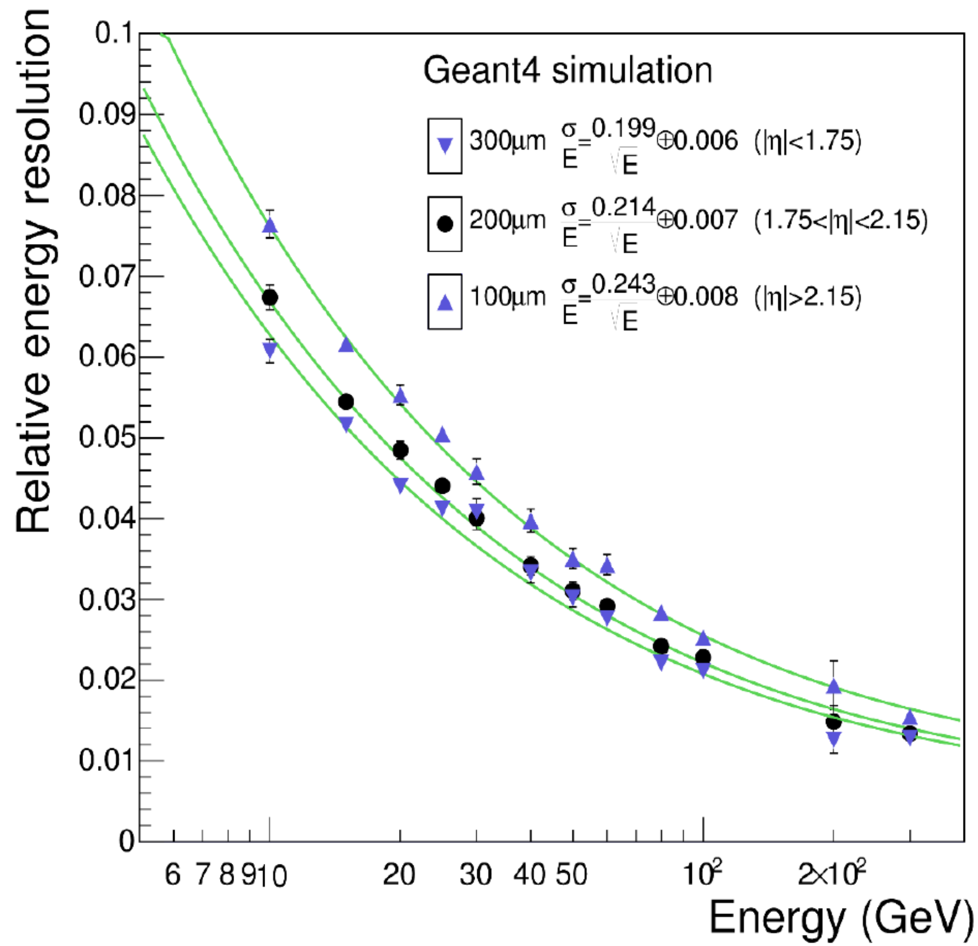




Δt is 68% effective RMS
20ps * c = 6mm

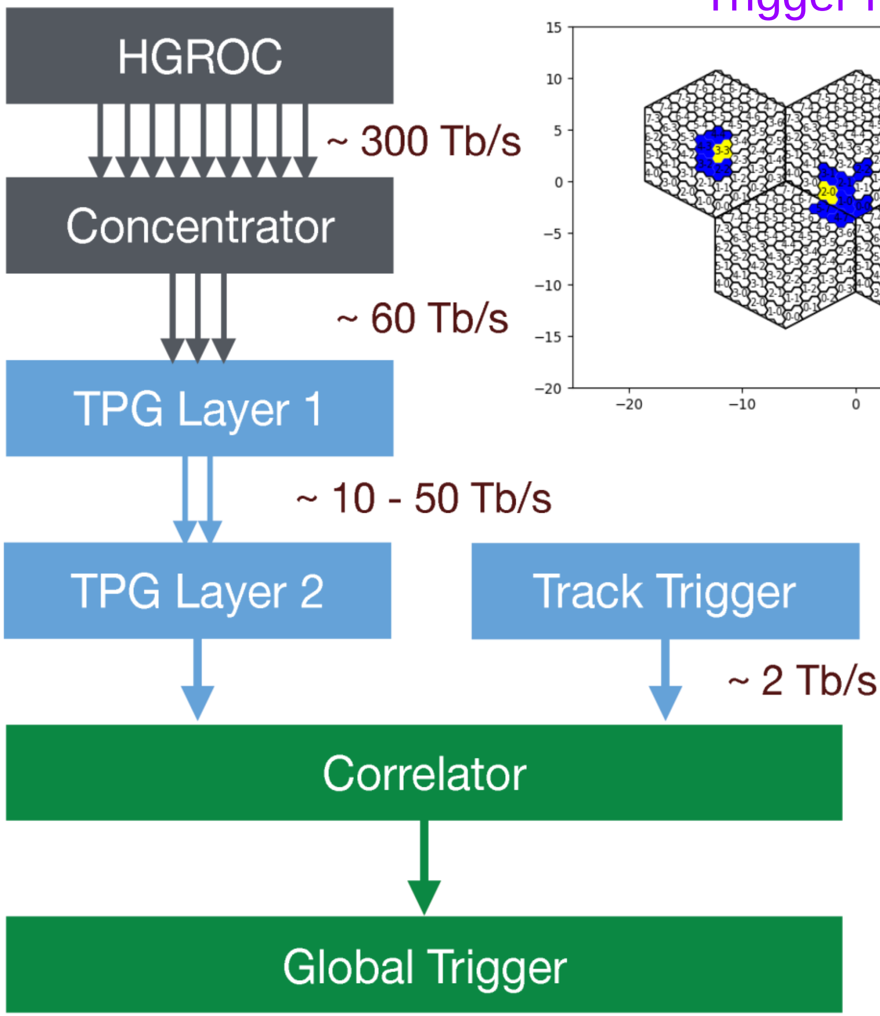
- HGC special timing layer, 25 cells
  - 32GeV electron FNAL test beam
  - Reference: MCP w/ Δt~5ps
  - Cell time resolution: 25ps
  - Cluster time resolution: 15ps
- Cluster resolution <20ps with E(γ)>10GeV and cell Δt = 50ps

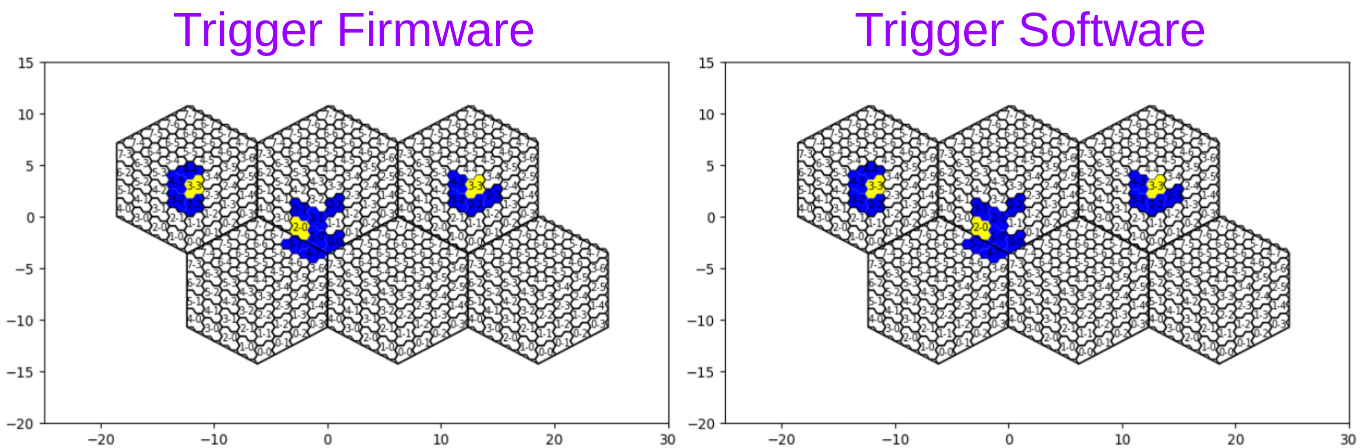
# Expected Performance



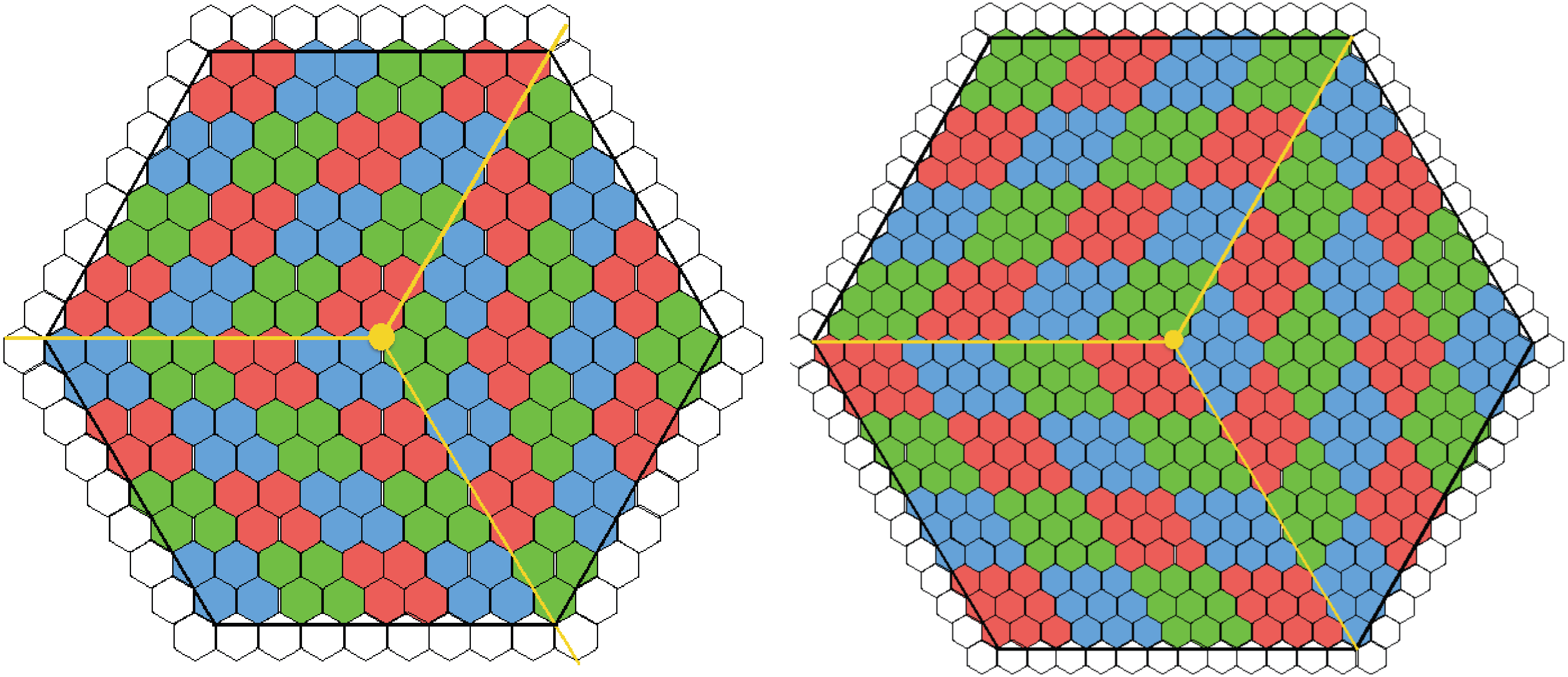
# Trigger Electronics



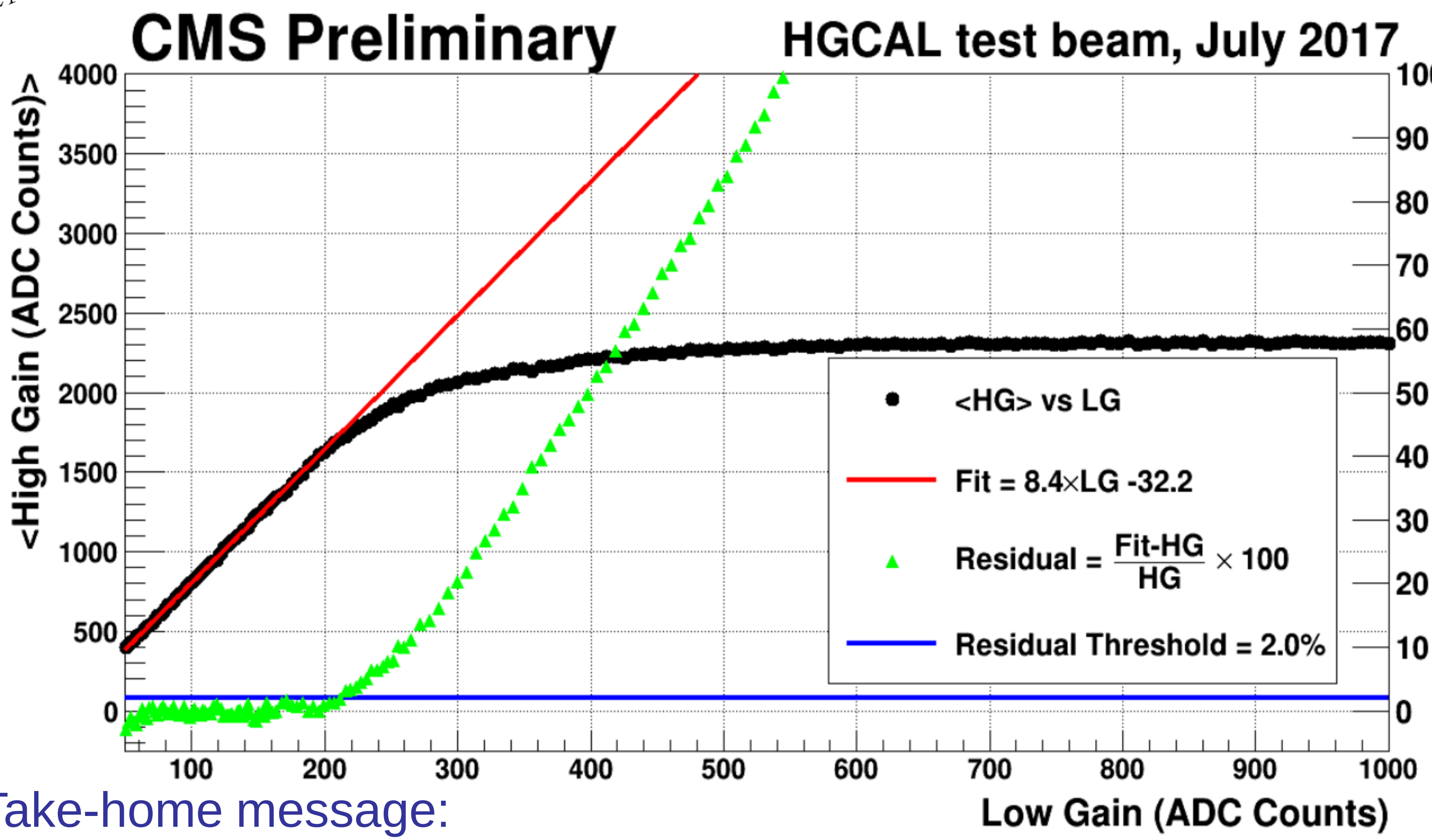




- Front-end (HGROC)
  - Reduced energy resolution (ADC/TOT linearization)
  - Reduced granularity (4/9 cells per trigger cell)
- Back-end
  - ATCA board w/ UltraScale FPGA (standard for CMS trigger and DAQ systems)
  - Firmware simulation in perfect agreement with software

# Trigger Cells



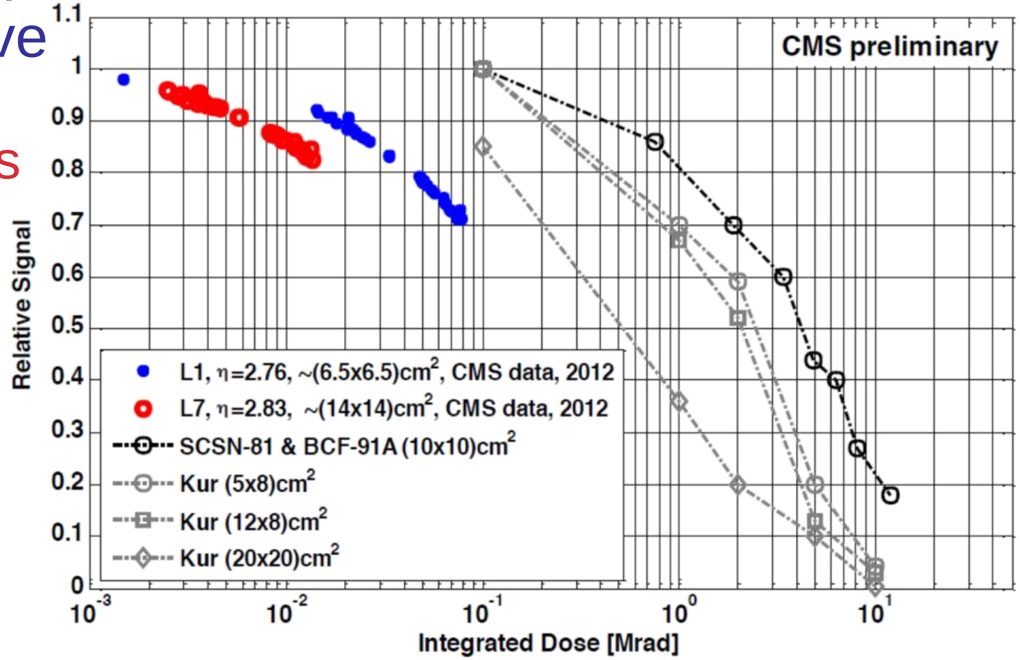
# SKIROC2-CMS




- Take-home message:
  - linear fit works in linear region (low-gain ADC up to 200)
  - Residuals below 2% threshold
  - For this SKIROC: transition point at high-gain ADC ~ 1600; 9 high-gain ADC counts ~ 1 low-gain ADC count

# CMS HCAL Ageing

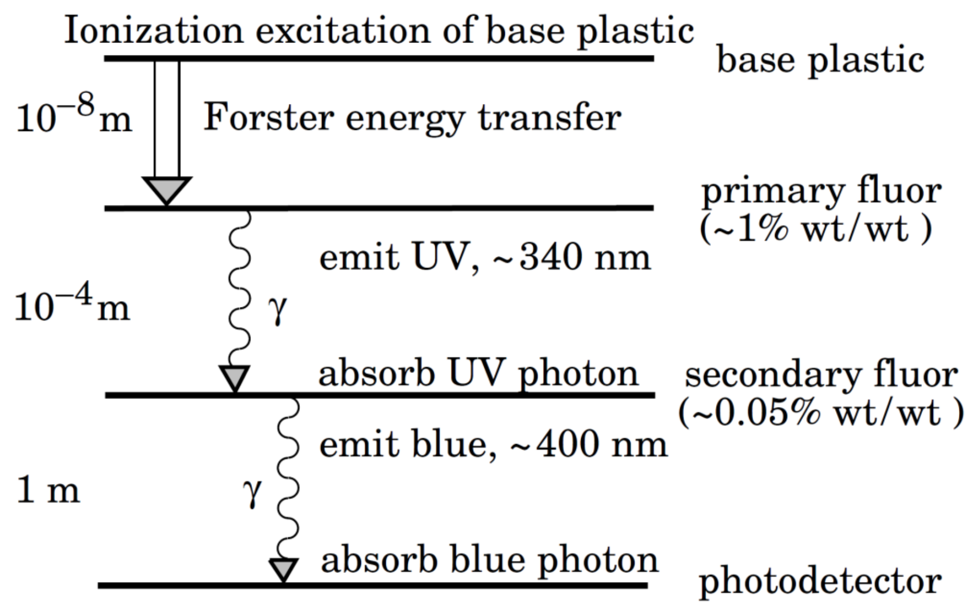
- The CMS Hadronic calorimeter uses plastic scintillator as active material
  - It is know that radiation breaks the plastic and creates “color centers” which absorb scintillation light
- The crucial question is: how long will it take the HCAL to become dark?
  - The lesson from 2012 data: shorter than it was originally thought
- R&D efforts aims at identifying a more radiation-tolerant material usable in HCAL upgrade
  - Time scale: Long-Shutdown 3 upgrades (2024-2026)




After an irradiation of 10krad, we see the light-yield reduction predicted for 1Mrad

# How does a Scintillator work?

- An organic scintillator is typically composed of three parts
  - A polymer base (typically PVT, polystyrene, or Silicon-based materials)
  - A primary dopant (~1%)
  - A secondary dopant (~0.05%)
- Particles excite the base, the excitation of the base can migrate to the primary dopant, producing detectable light
  - In crystals, excitons transfer the energy; in liquids, solvent-solvent interactions and collisions
- The secondary dopant shifts the light to longer wavelengths, to make it more easily detected
  - Maximize the overlap with the wavelength range at which photodetectors are most efficient




Effects of radiation:

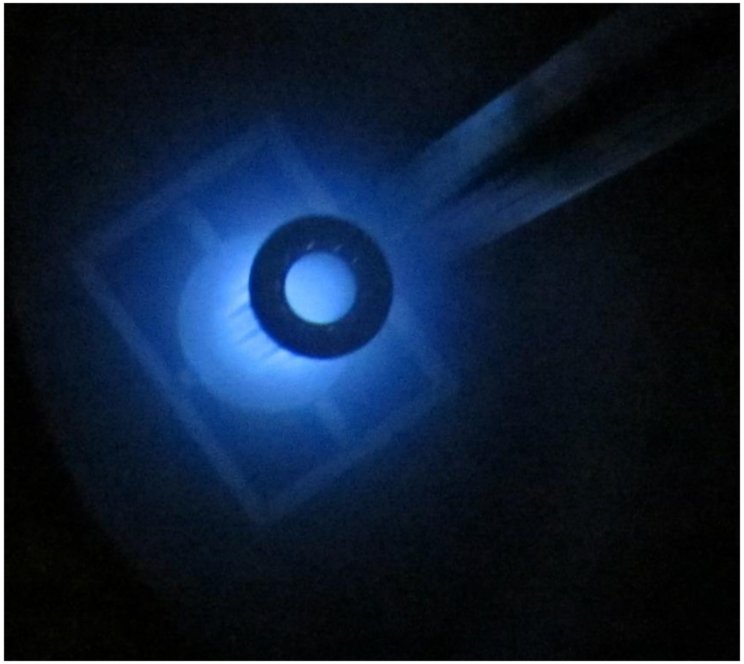
- Breaks polymer chains and create radicals that absorb UV light
- Damages fluors, reducing their ability to shift light to longer wavelengths

Some parameters to model radiation damage

- Presence of oxygen
- Total irradiation dose and dose rate
- Temperature of irradiation

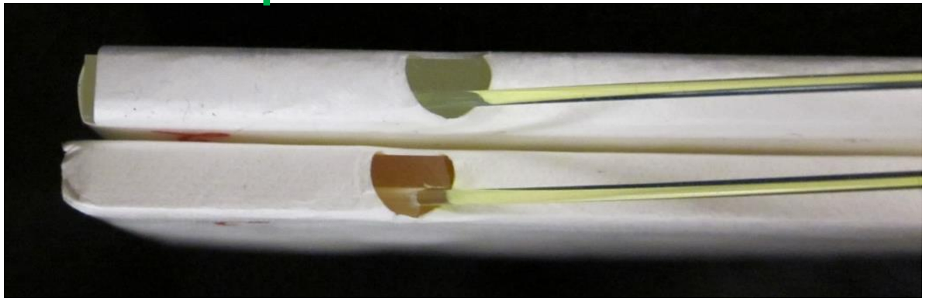
# R & D Directions and Plans

- Identify candidate materials offering improved radiation tolerance
  - Tune dopant concentration
  - Emit at a longer wavelength
- Irradiate materials in different environmental conditions, at different total doses and dose rates
  - Radioactive sources (Co-60, Cs-137)
  - LHC beam halo
- Measure light yield with different and complementary methods
  - Spectrofluorometers, cosmic rays, radioactive sources
- Map light-yield reduction as a function of multiple parameters
  - $O_2$ concentration; total dose; dose rate; temperature; dopant concentration…



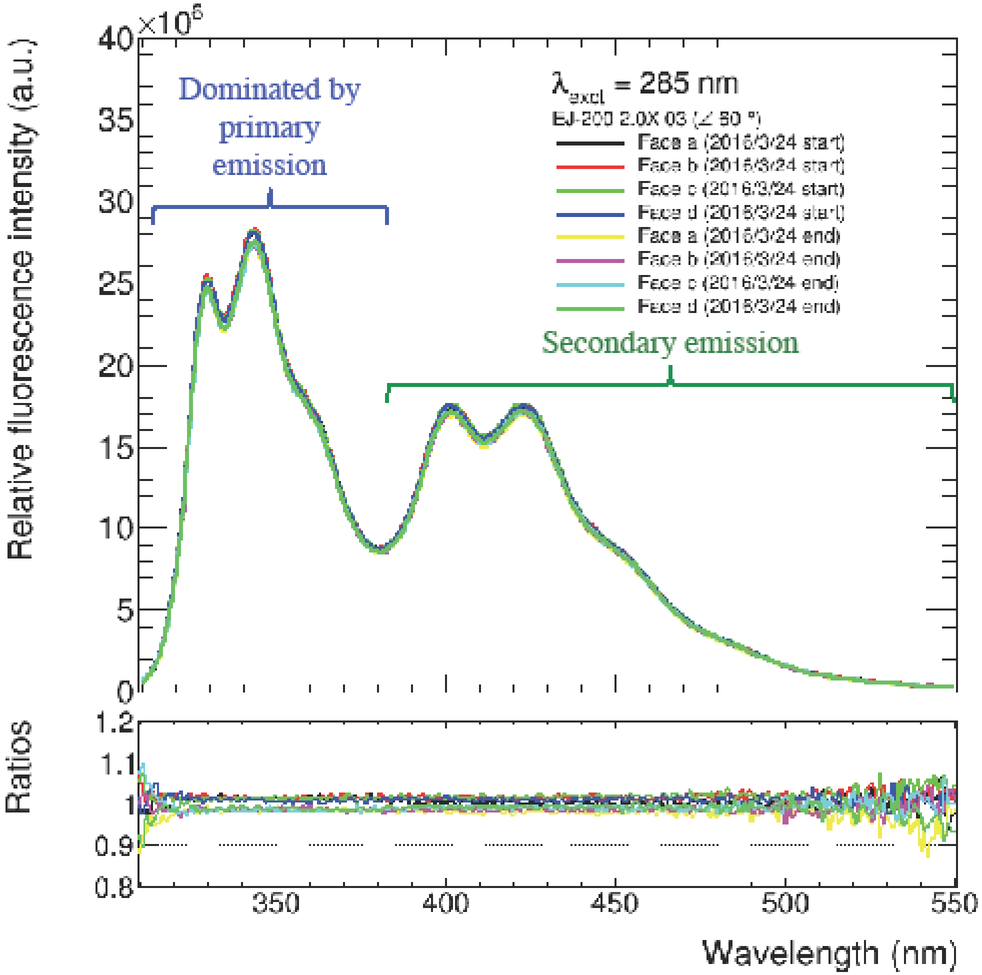
UMD Co-60 source

Irradiated plastic scintillator vs. new



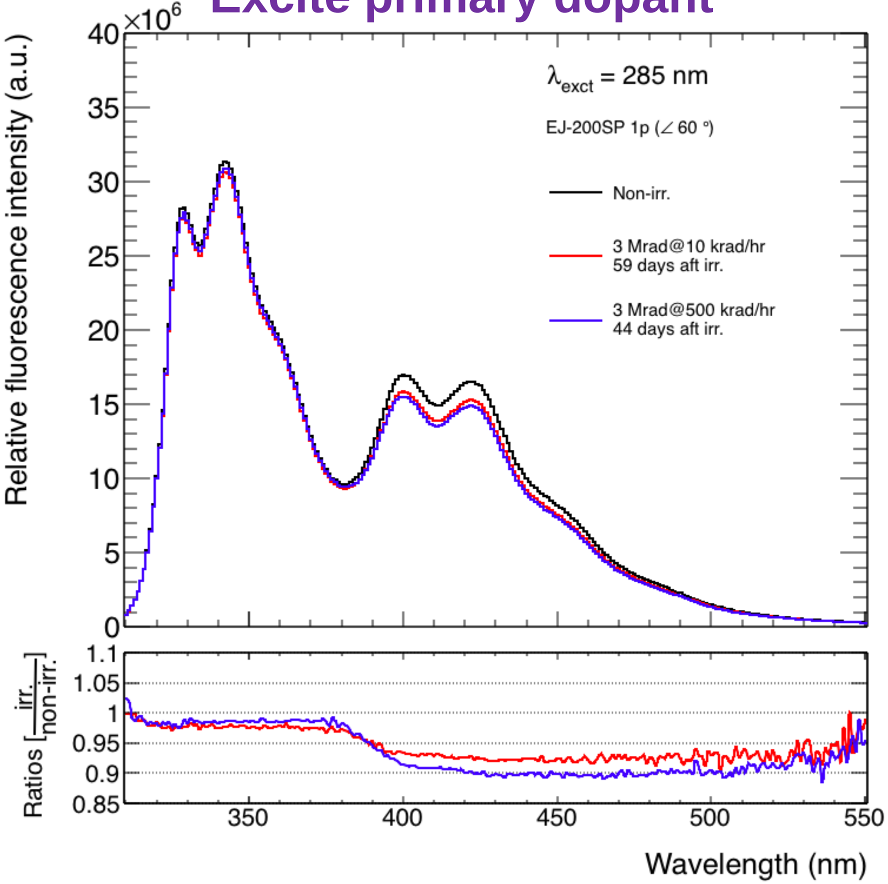
# Spectrophotometry

- Very challenging measurement
  - Typical user needs accurate measurement of peak positions, not peak amplitude
- Tuned procedure until reached satisfactory level of repeatability
  - Repeated measurements during a day vary within <2%
    - Include uncertainty on machine conditions, placement of sample by operator, inhomogeneity among sample sides
- Possible to probe effect of radiation on dopants separately by varying excitation wavelength
  - E.g. blue scintillator: 285nm (excite primary), 350nm (cross primary/secondary), 400nm (excite exclusively secondary)

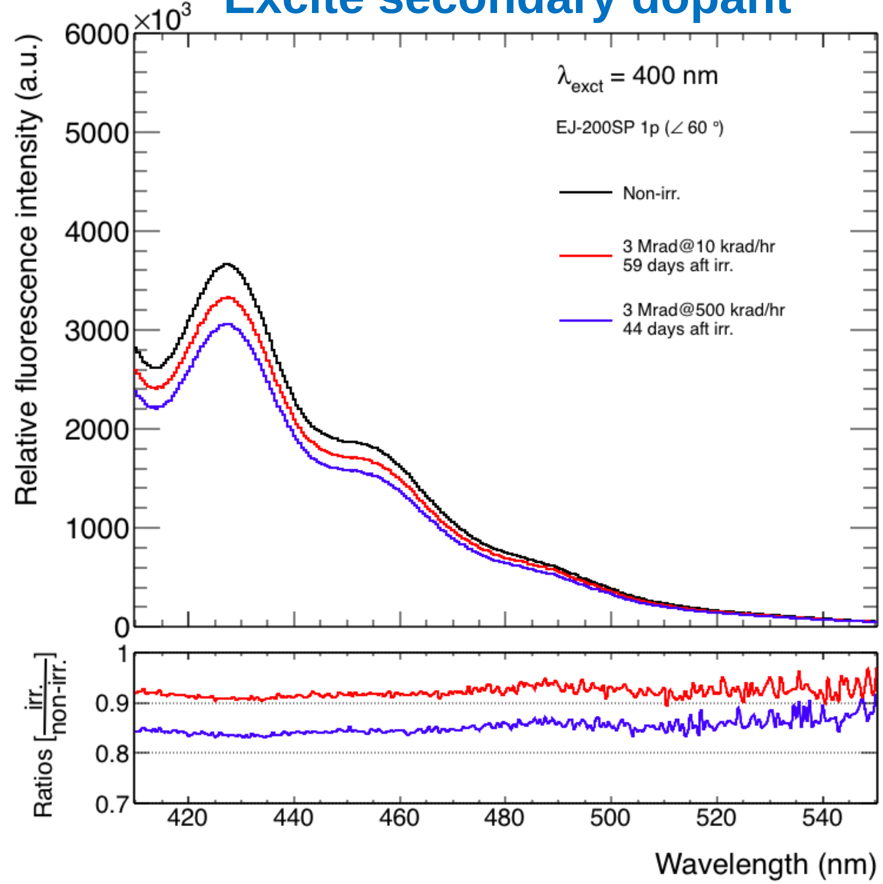


# Spectrofluorometry

### Excite primary dopant



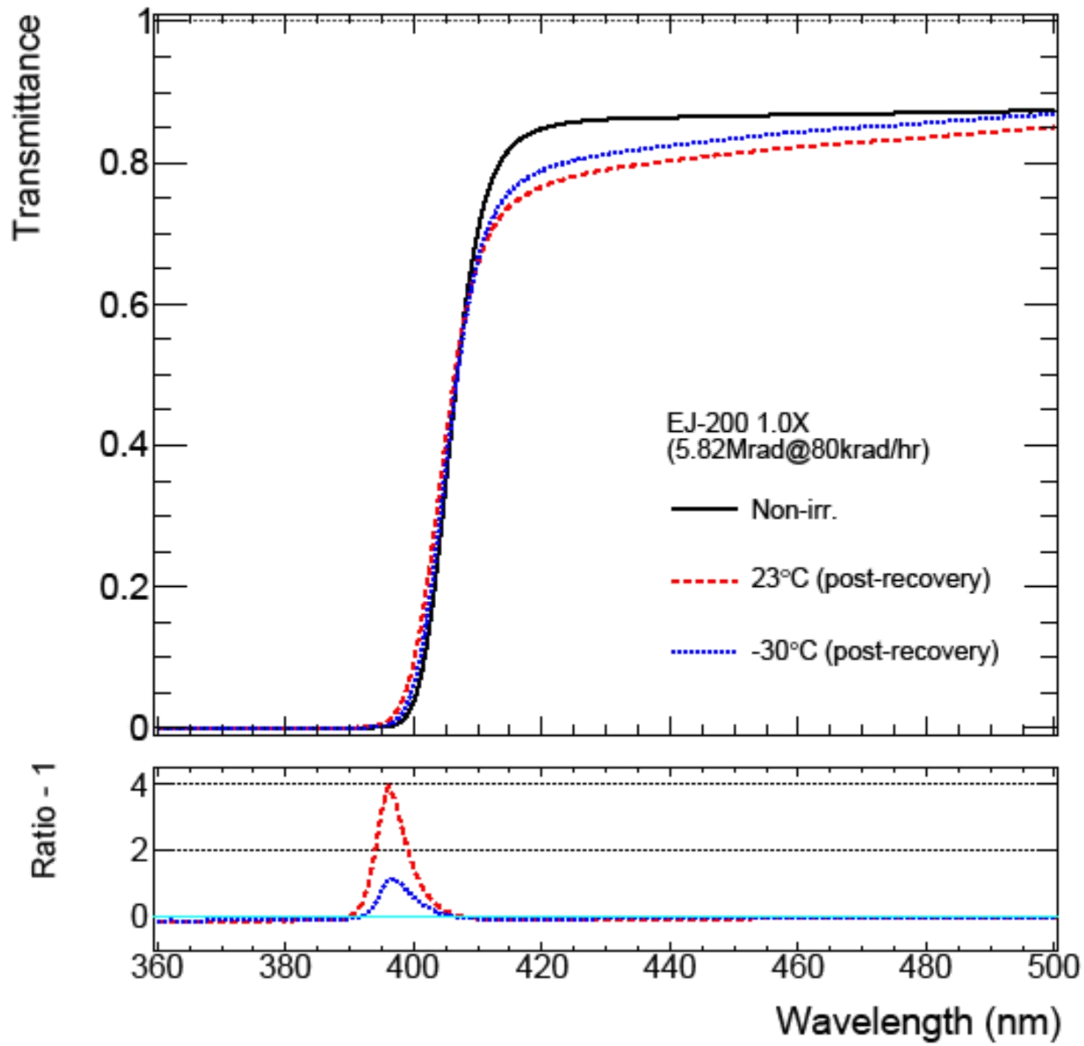

### Excite secondary dopant




- Promising technique to understand effect of radiation on material
  - One can excite separately dopants

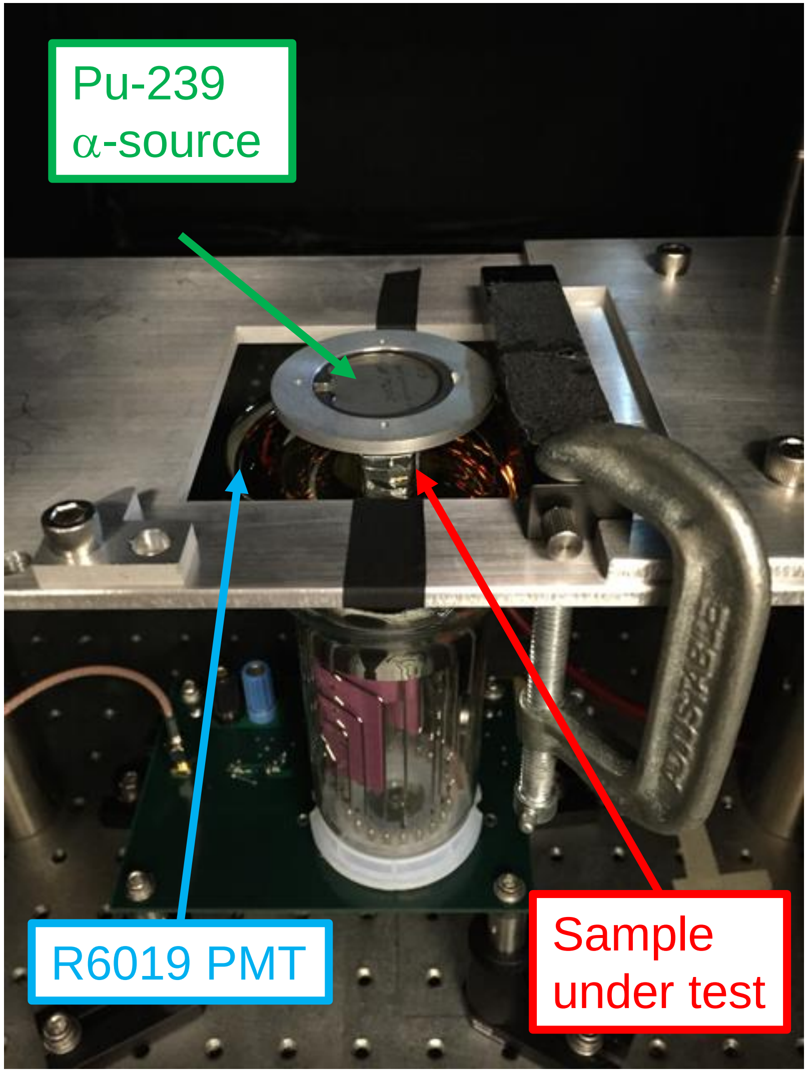
# Cold / Warm Irradiation

- Measurement details
  - Commercial EJ-200
  - 5.82Mrad at 80krad/hr, NIST
  - Irradiation at 23C vs. -30C
  - Samples annealed about 20 weeks at room temperature
- Observations
  - Peak at ~400nm (absorption maximum of secondary dopant) seems to indicate damage of secondary dopants
    - Less dopant to absorb light → higher transmittance
  - Comparable transmittance above 410nm after annealing



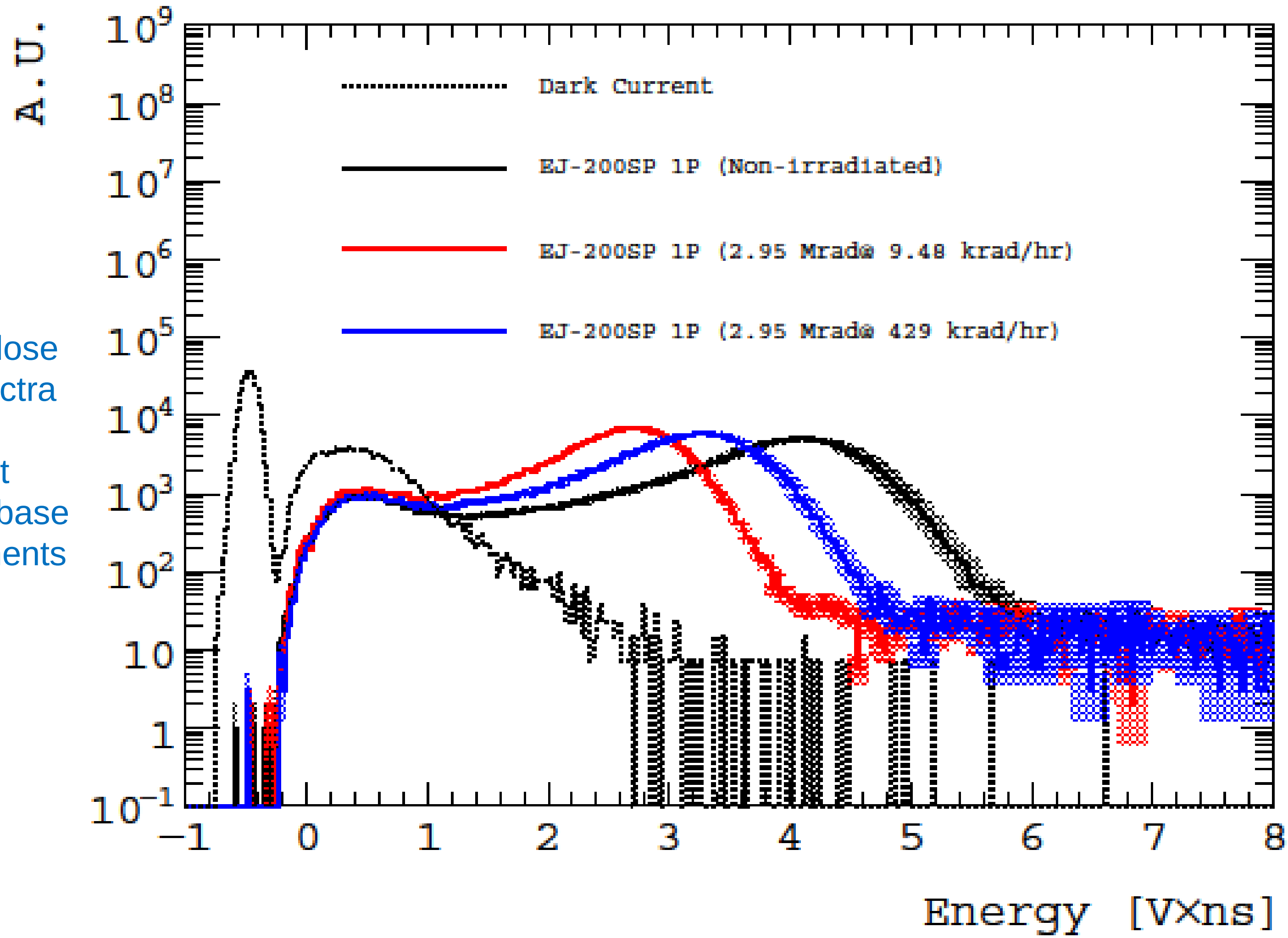
# Alpha Source Measurements

- Sensitive to complete chain of light-production
  - Source releases energy in the base, and the whole chain of dopants and energy transfers is exercised
    - Spectrophotometer cannot produce UV light to mimic base-to-primary transfer
  - Somewhat sensitive to bulk damage
    - Energy released at small depth; light transverses about 1cm of scintillator to reach PMT
- Provides complementary measurement to transmission and emission spectra
  - Closer to actual operation of scintillator in detector



# Dose-rate Effect

Hatched area: systematic uncertainty

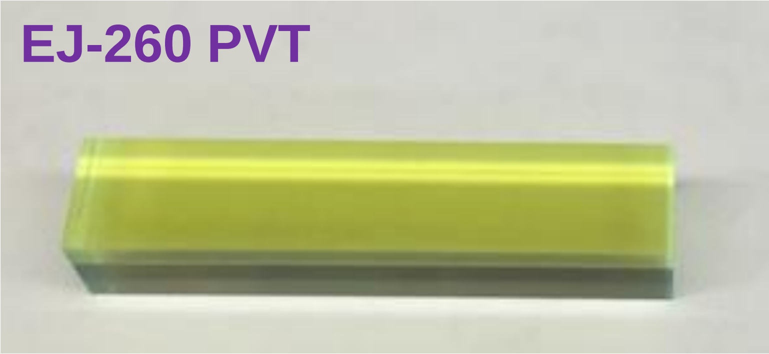



Clear demonstration of dose rate effect; emission spectra seemed to indicate the opposite, suggesting that there is an effect on the base that emission measurements are not sensitive to

The over-doped EJ-200 sample produces similar energy distributions

# Base-Material Studies

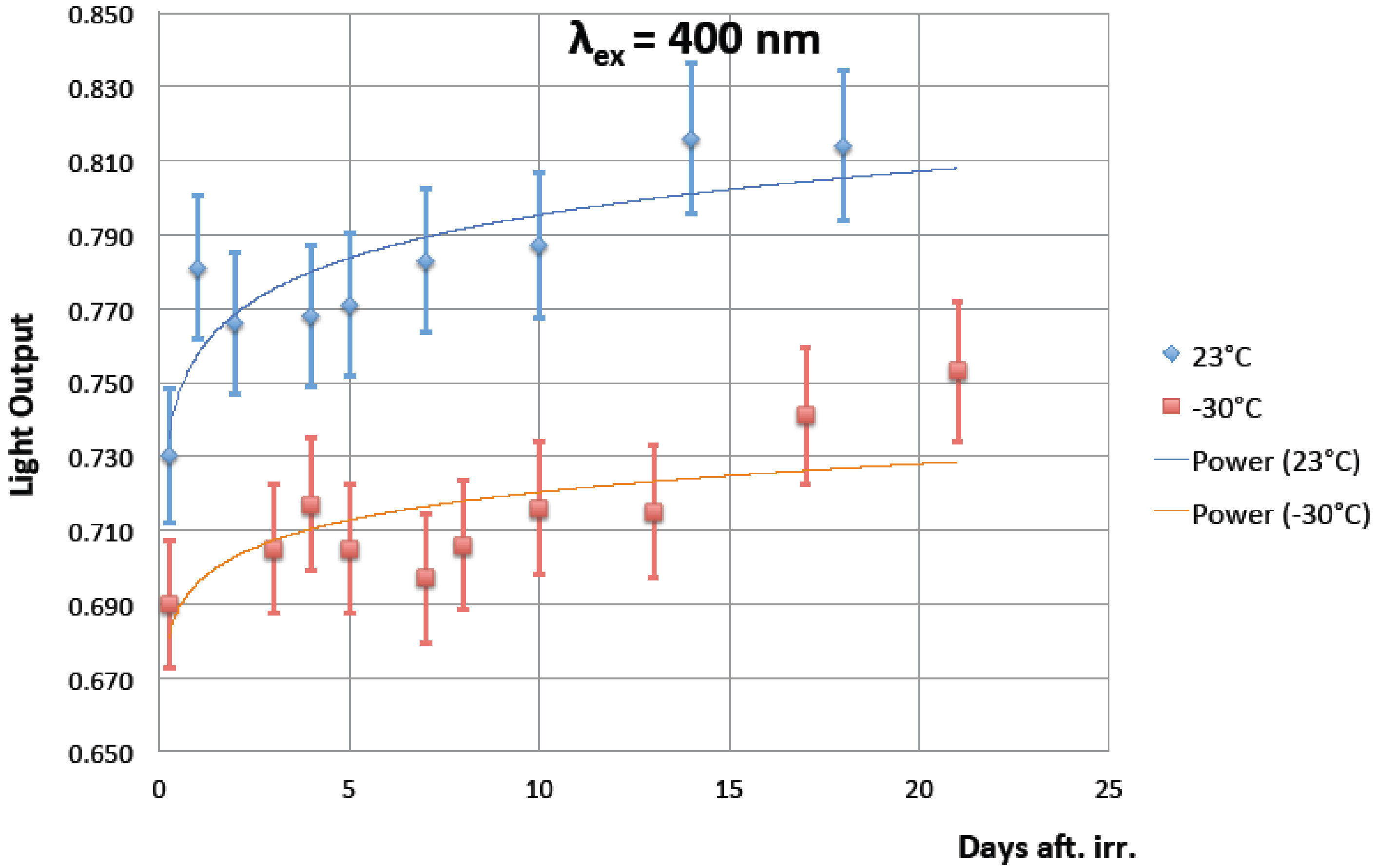
- Started investigation of scintillator produced with same dopant configuration, and different base
  - Green and blue fluors
  - Normal concentration of fluors; over-doped primary (2x); over-doped secondary (2x)
  - Polyvinyltoluene and polystyrene base (note: current HE scintillator is PS-based)
- Completed measurement of emission and absorption spectra to define initial properties
  - Started campaign of irradiations
- Plan to perform systematic study of radiation effect on PVT- and PS-based scintillators
  - Backup: over-doped samples





**Co-60 Irradiation at NIST**
**7Mrad @ 500krad/hr**

# (Surface) Annealing




- Monitor evolution of ratio between integrals of emission spectra (irradiated vs. reference) to estimate annealing time
  - Emission measurement sensitive to (mostly) annealing of surface
  - Faster annealing time w.r.t. transmission measurements
    - Consistent with being sensitive to surface effect only

# Over-doping Studies

**EJ-200 1X1P PVT** **EJ-200 1X2P PVT** **EJ-200 2X1P PVT**

**EJ-200 1X1P PS** **EJ-200 1X2P PS** **EJ-200 2X1P PS**

- Co-60 irradiation, 7Mrad @ 0500krad/hr
- Polystyrene vs polyvinyltoluene blue scintillators
  - 1X1P: commercial version; 1X2P and 2X1P: over-doped versions (the concentration of the secondary or primary dopant is doubled)
- Pictures suggest that over-doping helps preserve the scintillator clear, and confirm that PVT seems to hold better than PS
  - Important note: the 1X1P and 1X2P samples annealed for about 12 hours longer than the 2X1P