The upgrade of the CMS hadron calorimeter with silicon photomultipliers

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on behalf of the CMS collaboration

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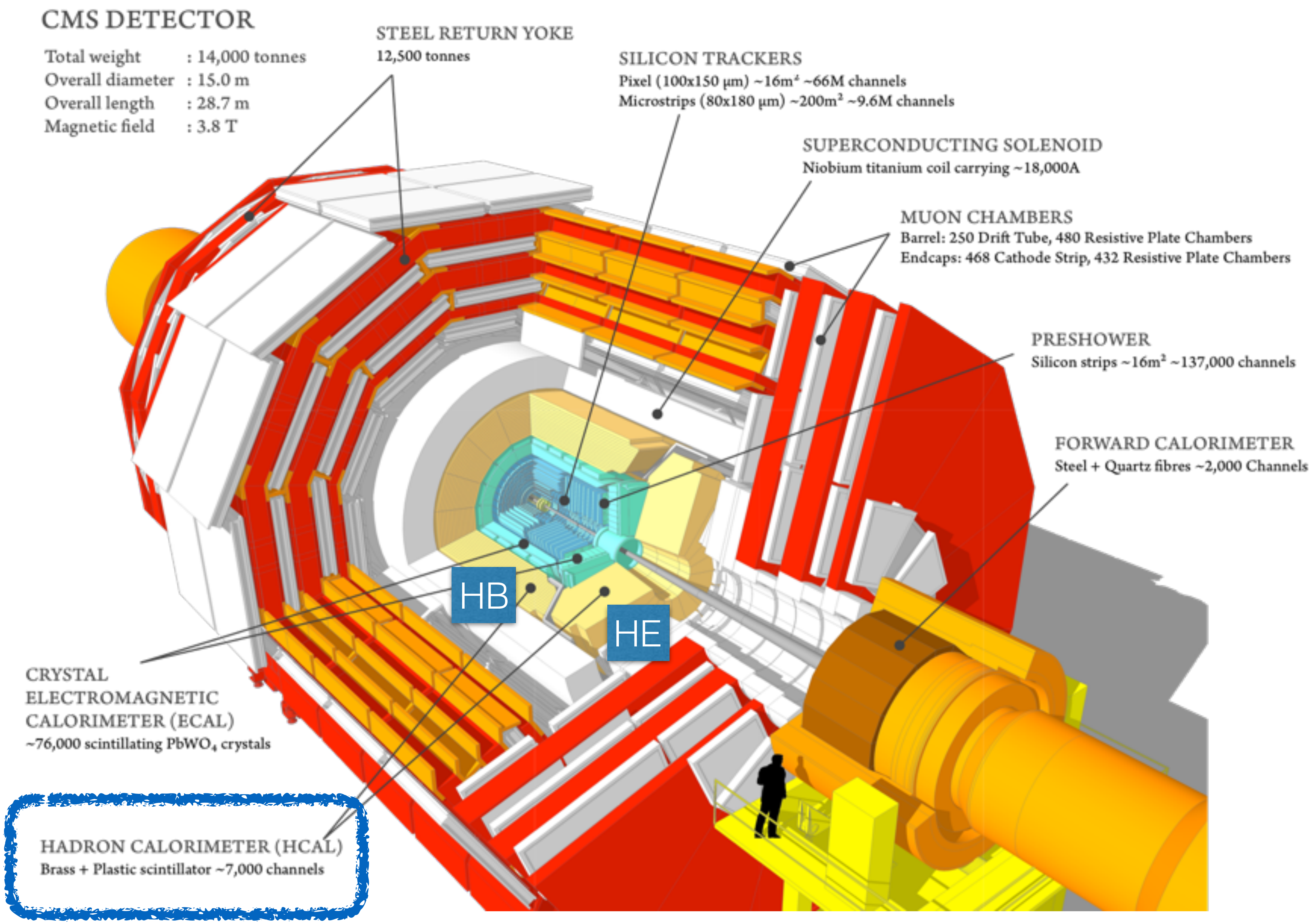
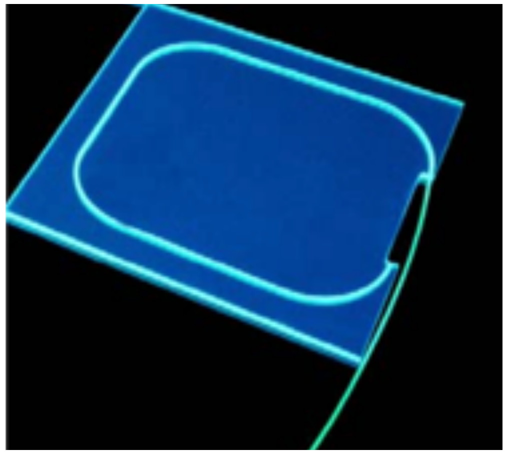
Introduction: CMS HCAL

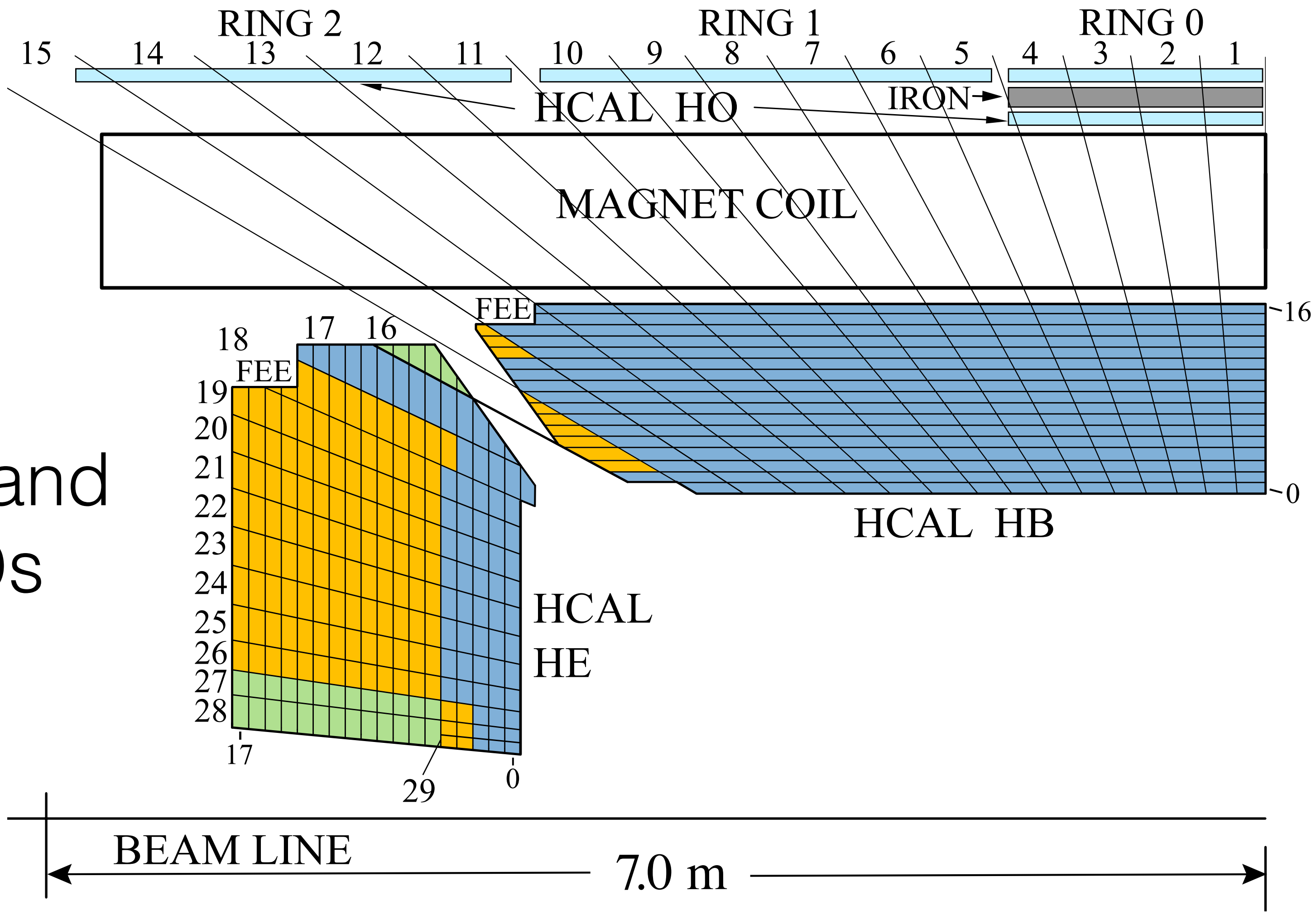


Introduction: CMS HCAL

HCAL = hadron calorimeter

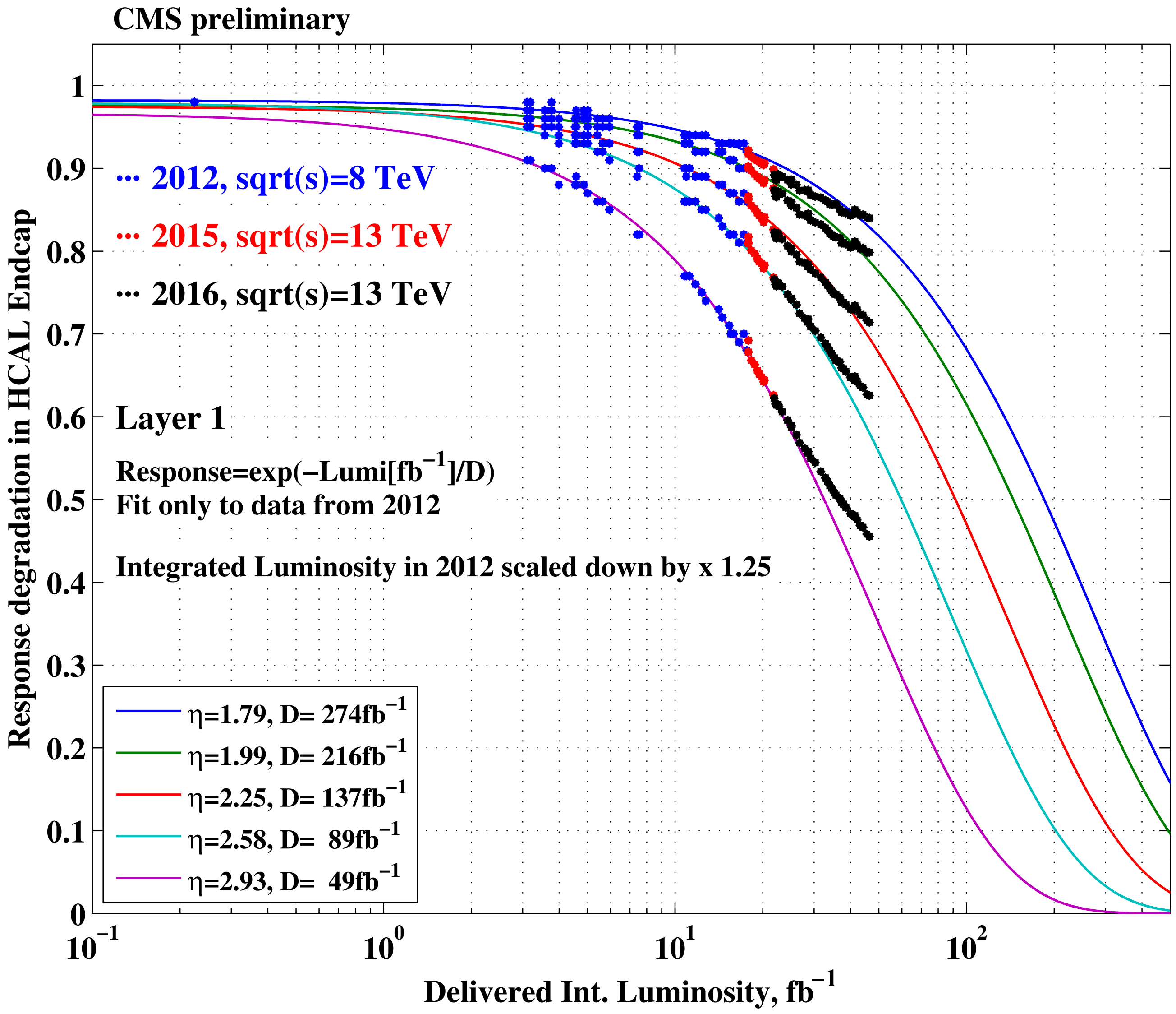


- 17 layers of brass absorber and scintillator tiles in barrel (HB) and endcap (HE) sections
- Wavelength-shifting fibers transport scintillation light
- Currently using Hybrid Photo Diodes (HPD) to collect light from scintillator
- QIE8 ASIC to integrate and digitize signal from HPDs
- Limited depth segmentation (1 — 3 depths)



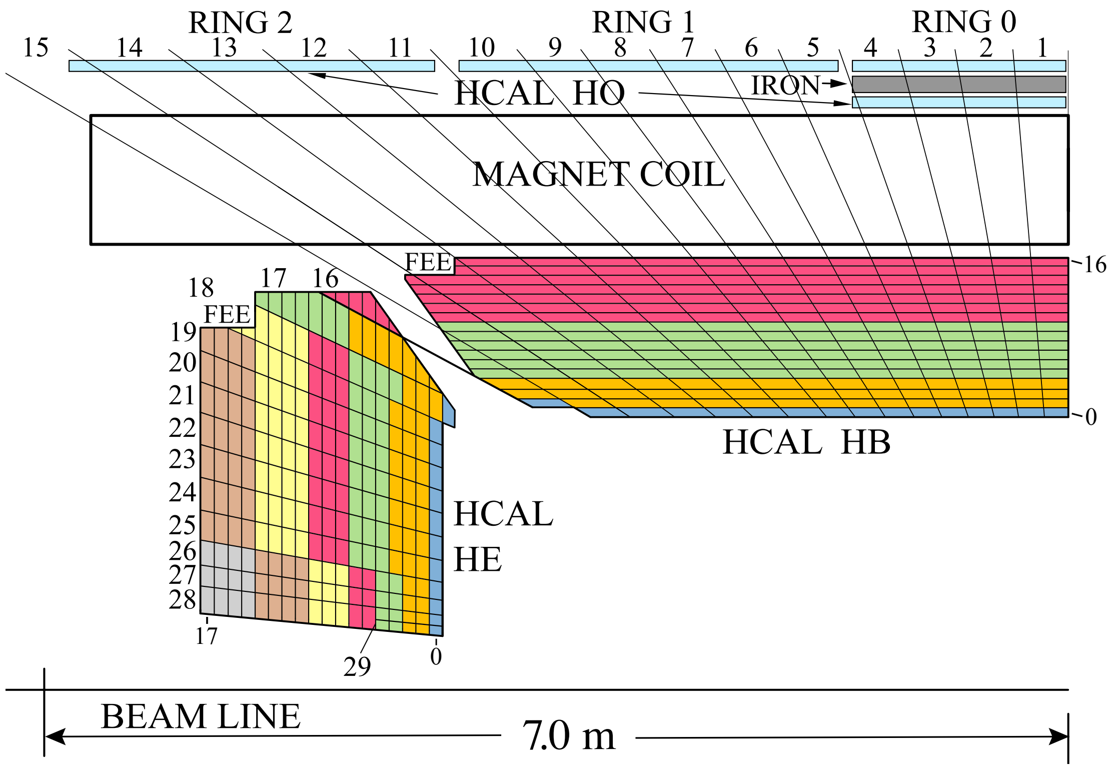
Motivation for upgrade

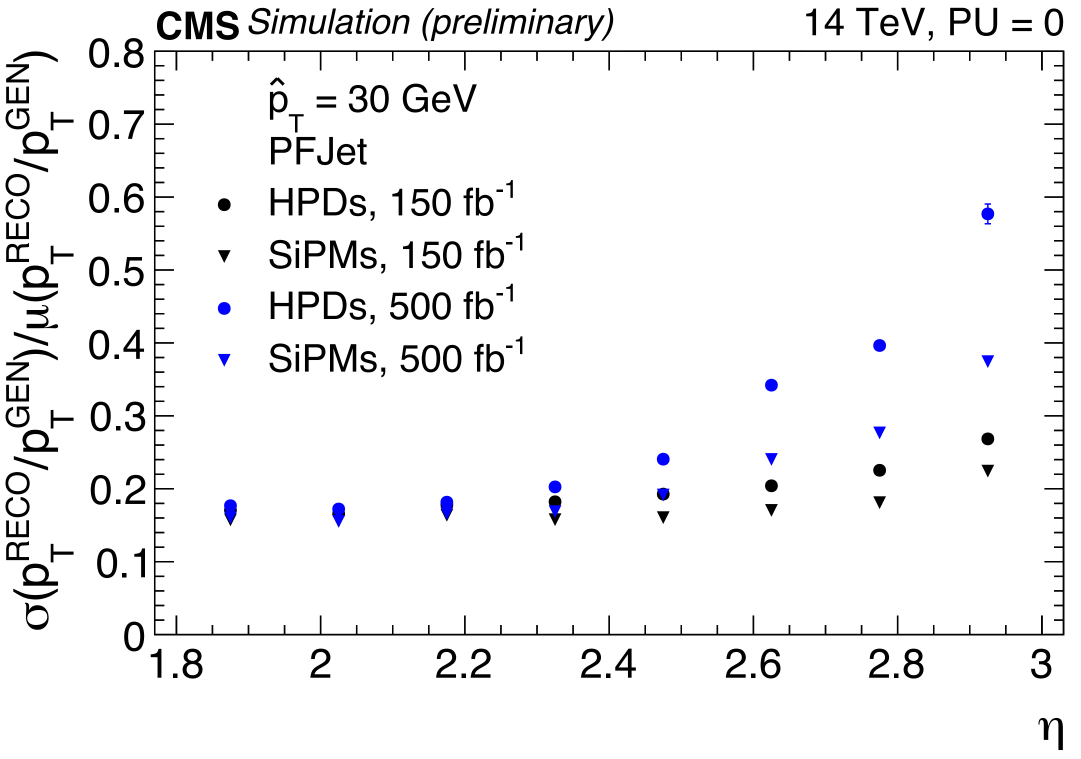
- Higher than expected radiation damage to scintillator tiles resulting in increased signal loss
- Radiation damage “dose rate model” arxiv:1608.07267
    - signal loss depends exponentially on accumulated dose, with decay constant D depending on dose rate: ~exp(-dose/D[Mrad])
    - Less damage for higher dose rate
    - Caused by chemical effects related to oxygen diffusion



Motivation for upgrade

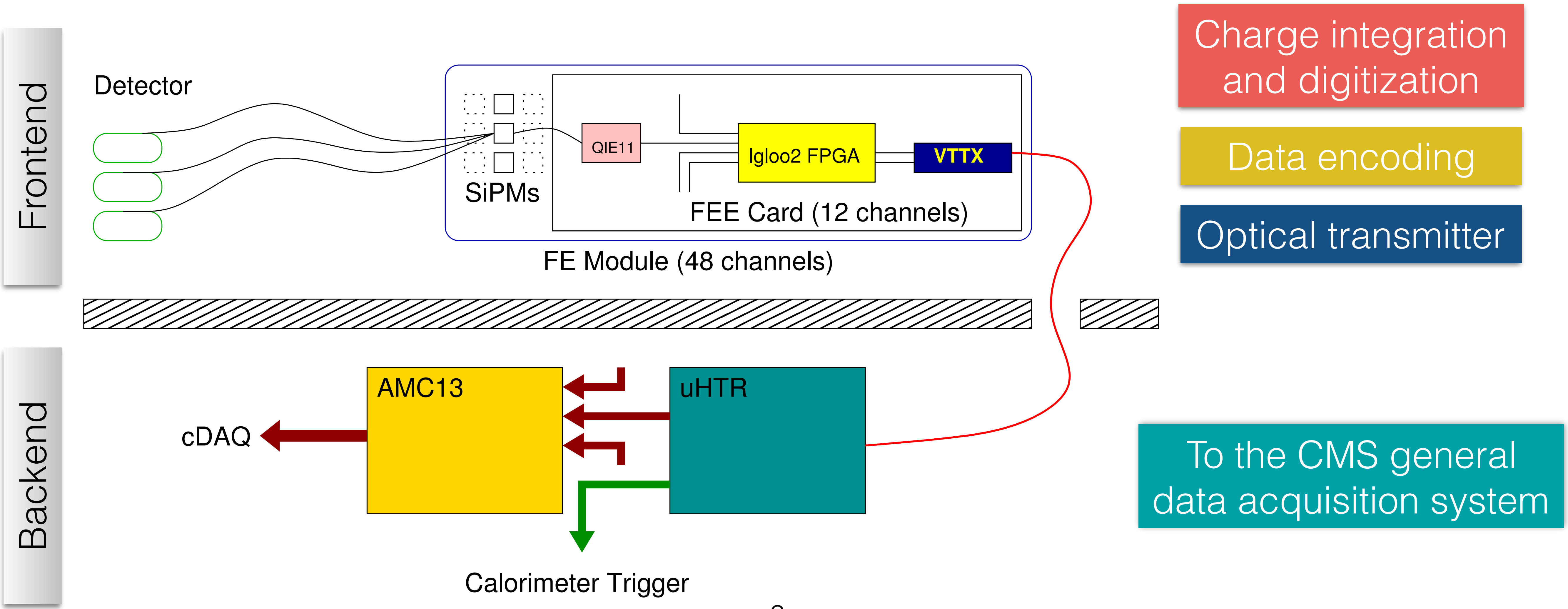
- Effect of radiation damage can be mitigated by replacing HPDs with Silicon PhotoMultipliers (SiPMs):
  - 3x photon detection efficiency (PDE) → increase signal size
  - Much smaller → more channels → finer depth segmentation → more precise calibration to handle depth-dependent radiation damage
  - Recovers performance for physics quantities such as E_T^{miss} and jet energy resolution



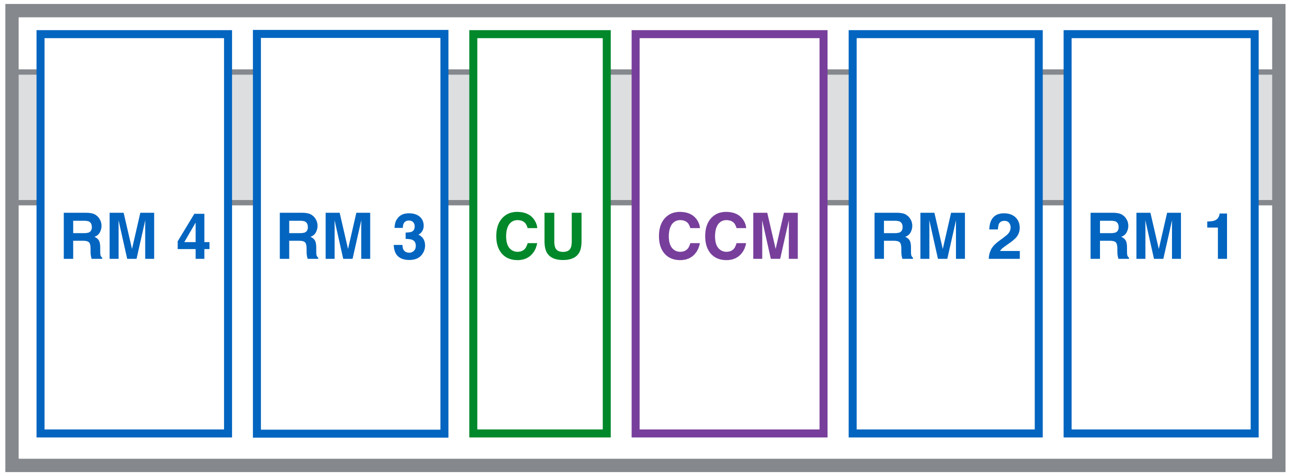


Overview of upgraded system

- First large installation of SiPMs in a radiation environment (1×10^{12} 1MeV neutrons/cm^2)
- Upgraded HE frontend (~7k channels) to be installed early 2017, upgraded HB frontend (~9.2k channels) to be installed during LHC LS2 (2019)

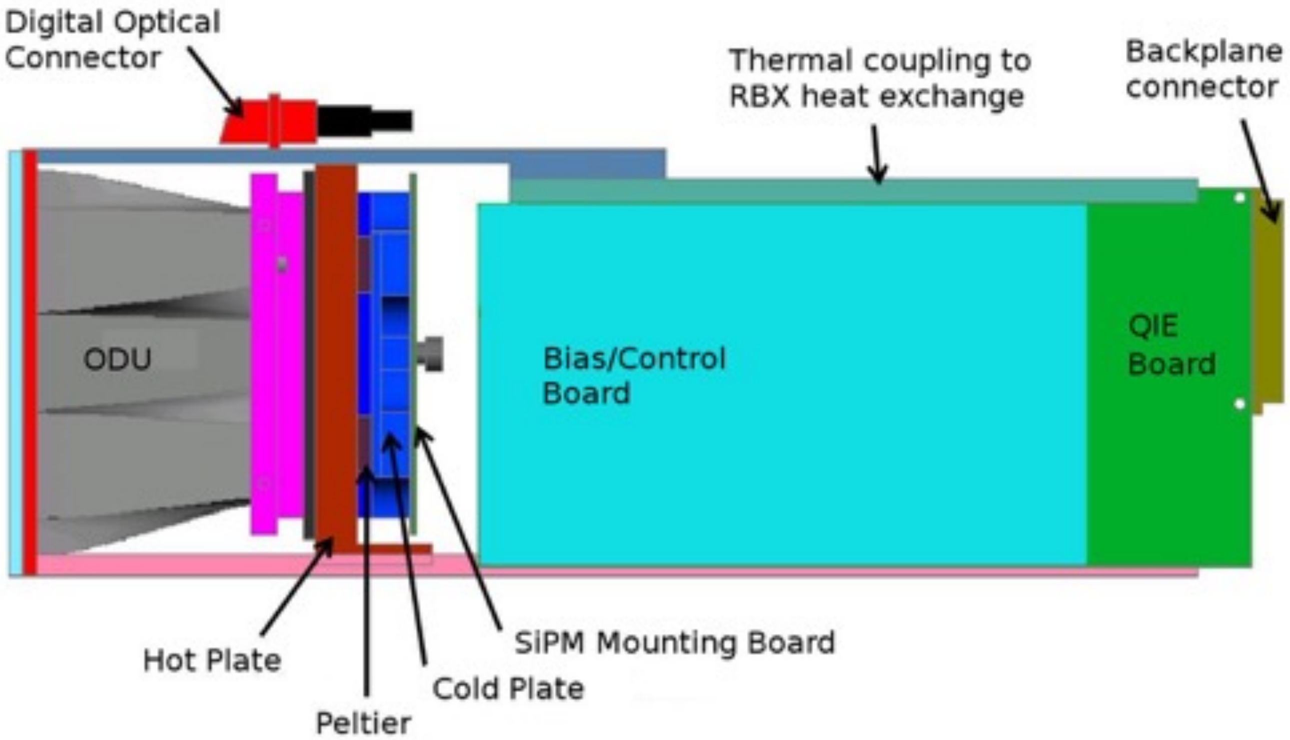


Frontend overview



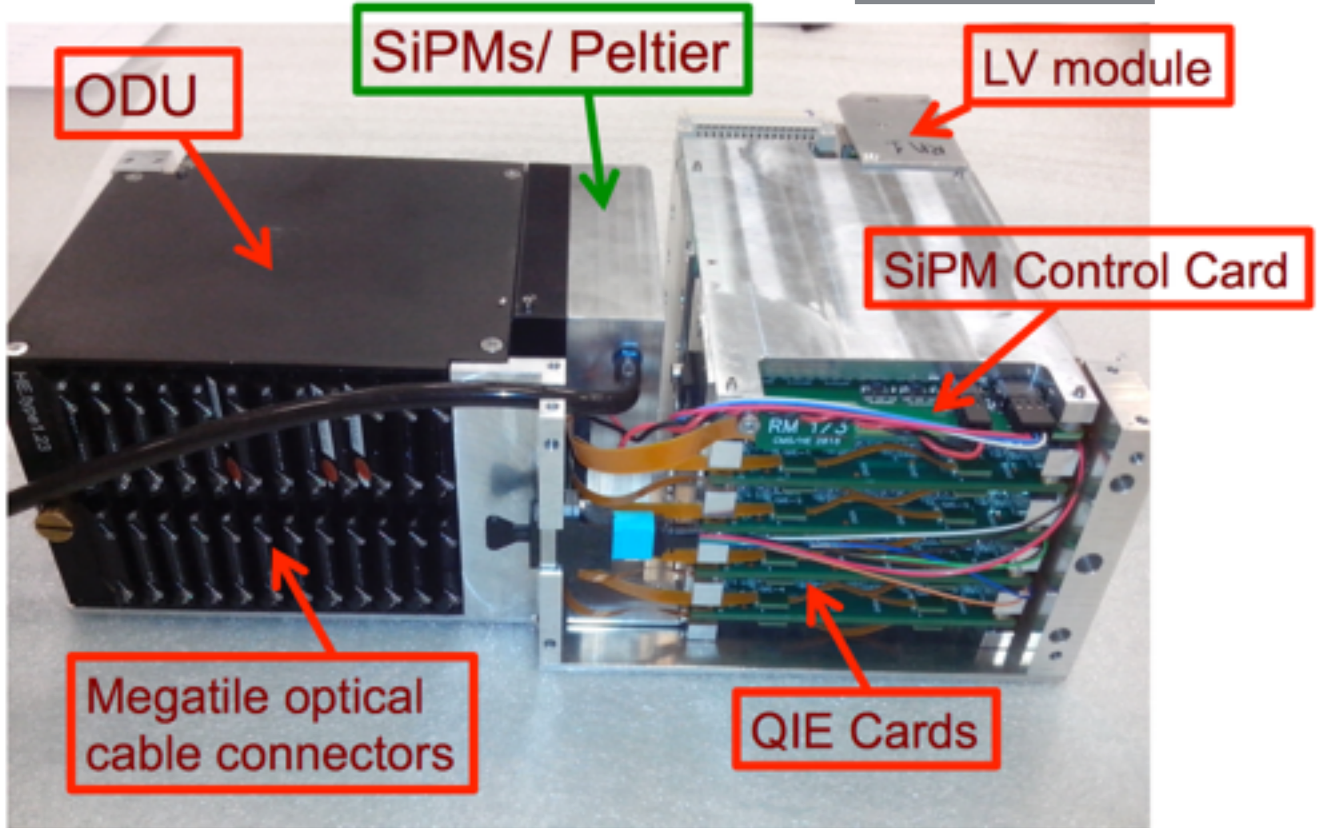
RM: readout module
CU: calibration unit with LED
CCM: clock, control & monitoring

Readout box schematic



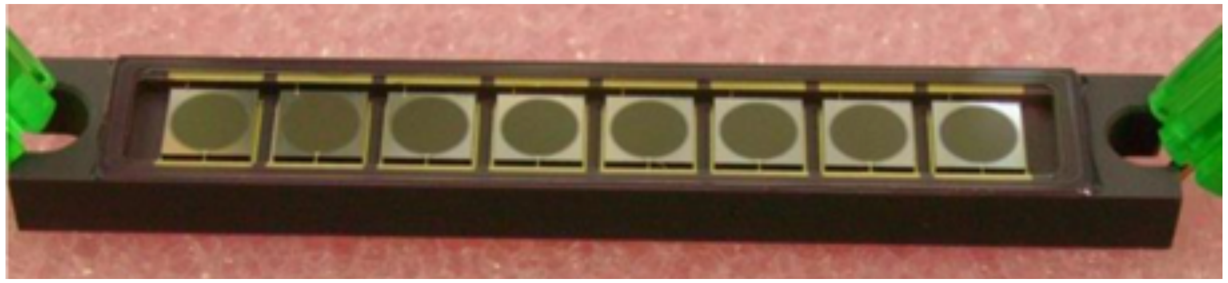
Readout module schematic

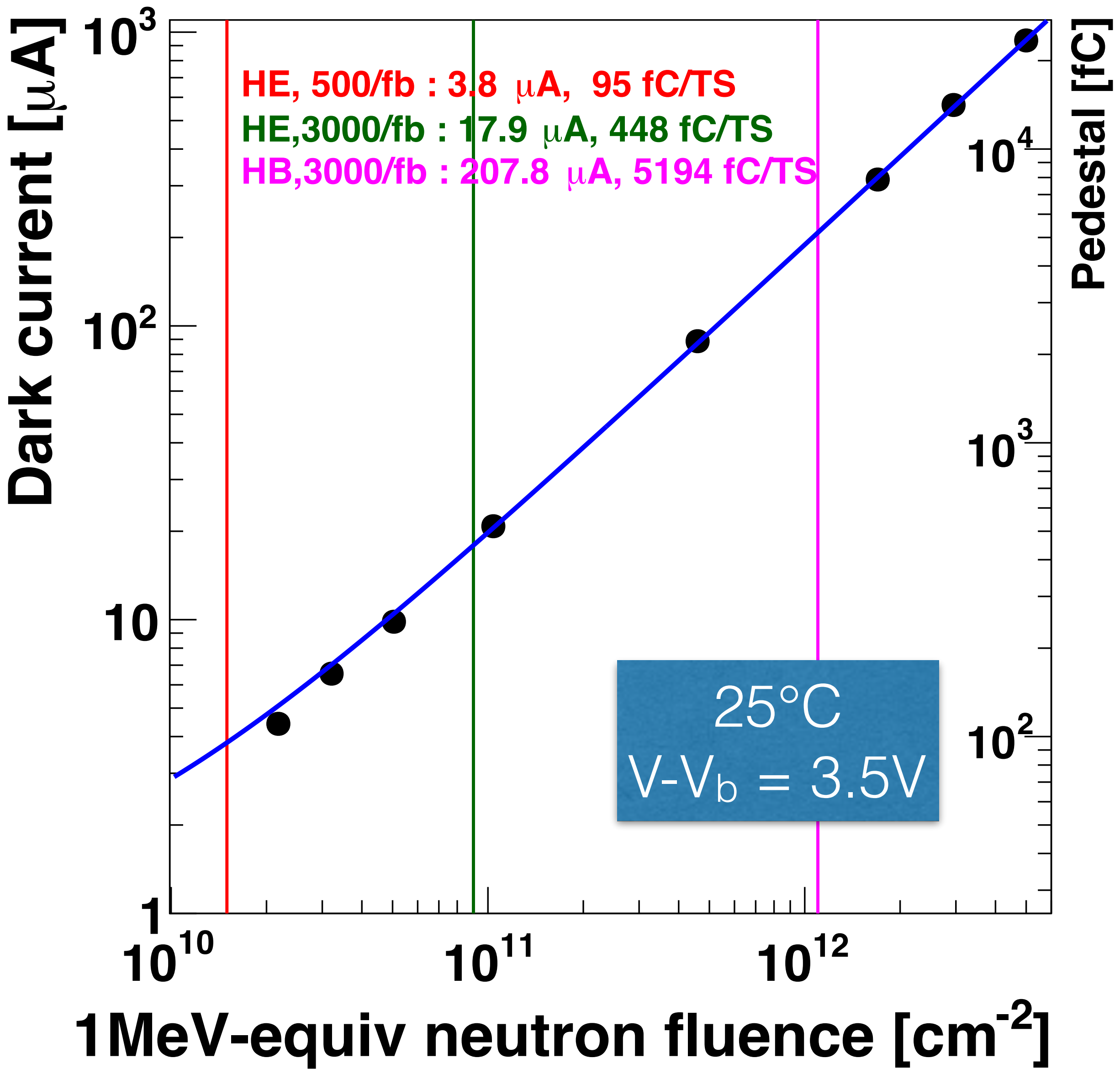
HE RM



SiPMs

- Produced by Hamamatsu
- 4500 pixels/mm2, each pixel is operated in Geiger mode, signal is sum of all fired pixels
- 2 sizes: 2.8 mm and 3.3 mm diameter to handle varying number of layers that are added together
- Fast recovery time of 10 ns → effective pixel count increases by factor of ~3
- 8 SiPMs in one package
- Increase in dark current after irradiation is well-understood and at manageable level

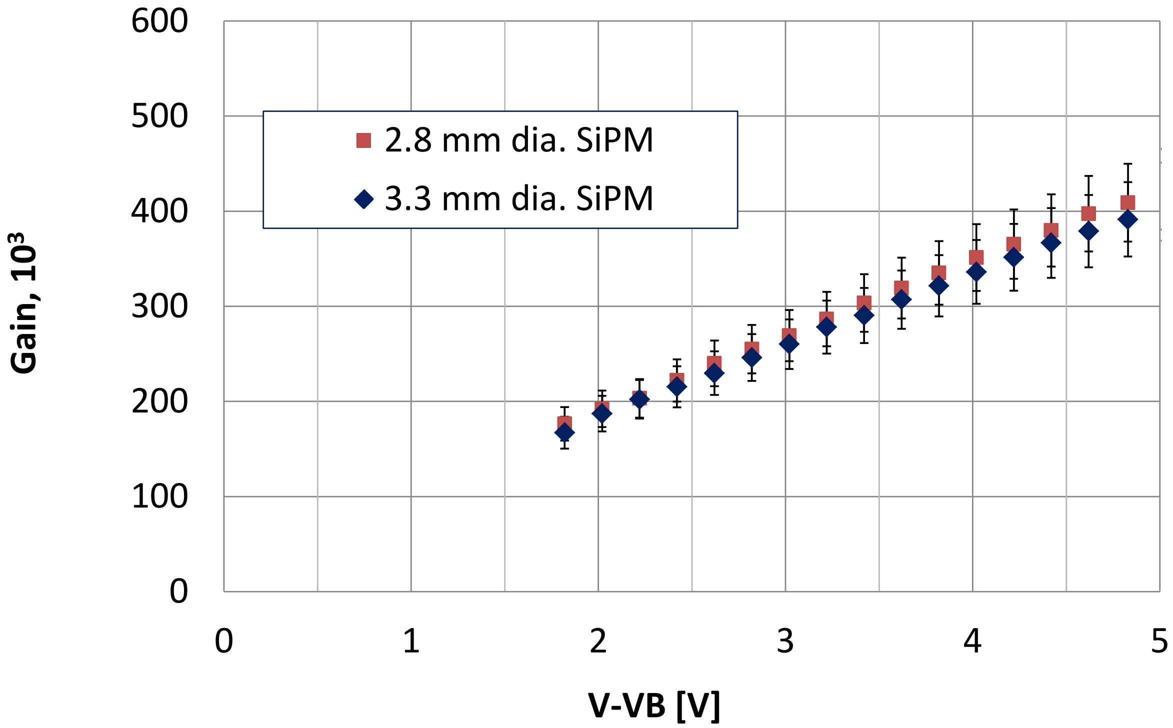


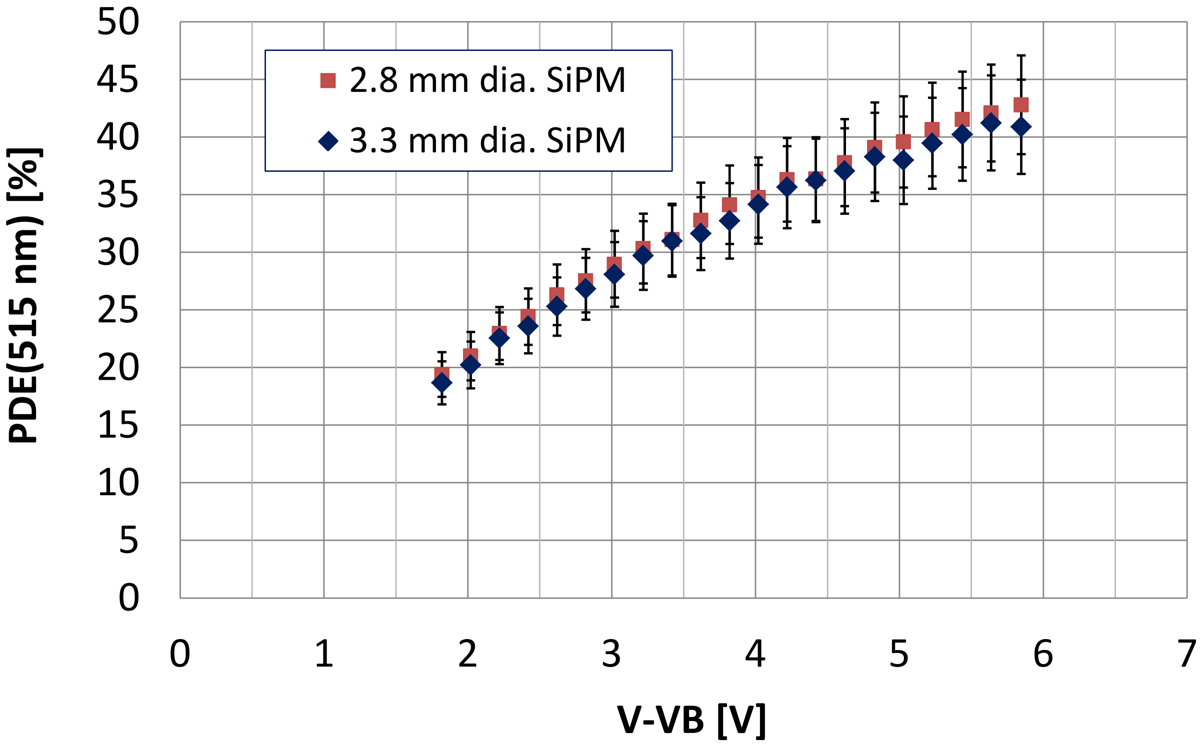


SiPMs

Advantages compared to HPDs:

- Smaller size
- Operate at much lower voltage (~70V vs ~8000V) and have no magnetic field sensitivity
  → avoid high-energy anomalous noise present with HPDs
- Better photon detection efficiency, ~30%
- Very high gain, factor 150-200 larger than HPDs, depending on operating point





SiPM control electronics

Goal: achieve SiPM gain stability and accuracy to within 1%

Infrastructure needed:

1. Precise bias voltage control
2. Precise temperature control (~2%/°C gain sensitivity)

Bias voltage (BV) control

- Generate bulk BV from backplane power
- Step down to operational voltage for each SiPM individually

Peltier cooling

- run SiPMs at 5°C
- online control loop via slow controls to monitor and adjust
- temperature sensor next to SiPMs
- 12-bit DAC resulting in 0.01°C control precision

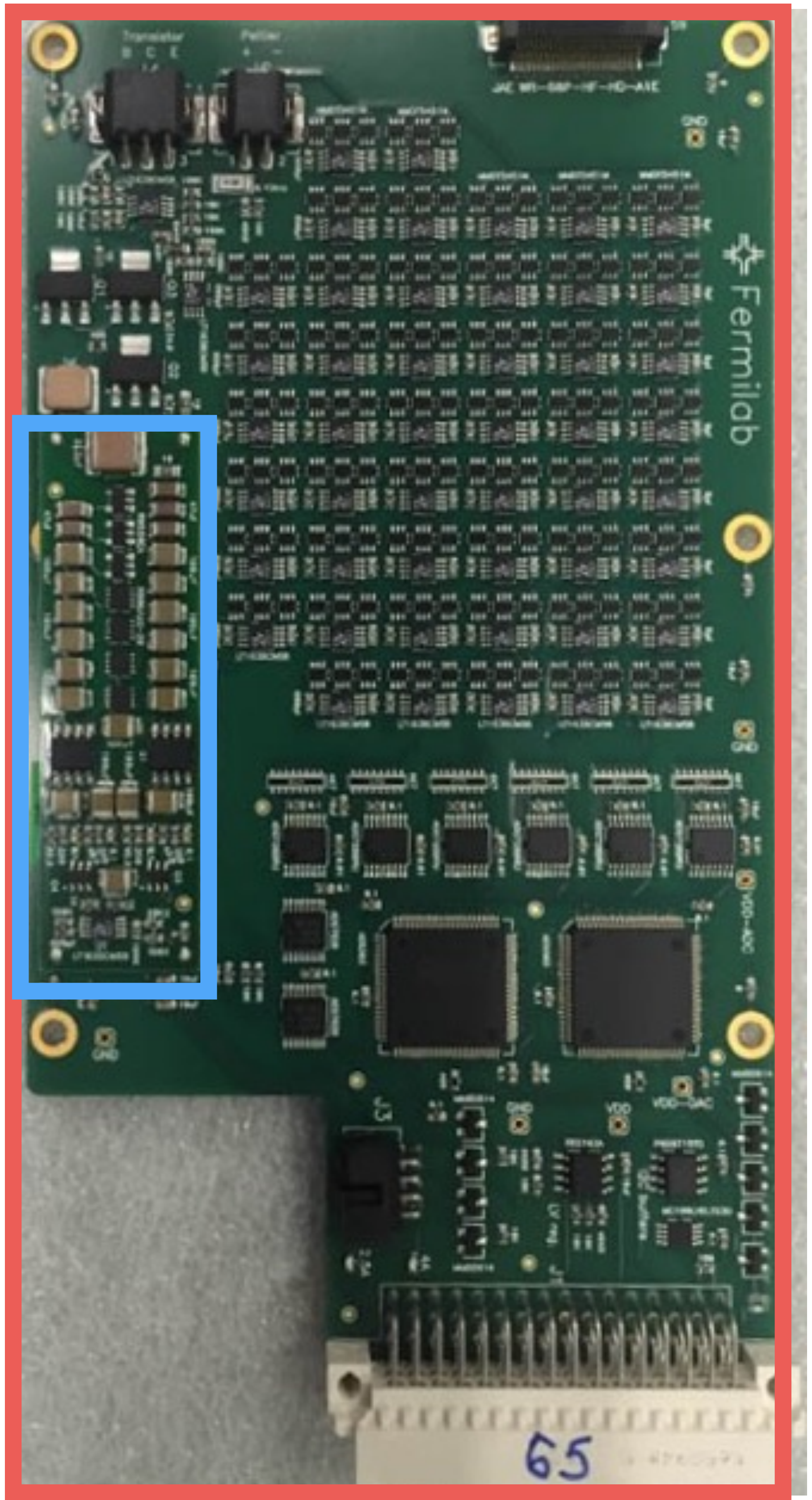
SiPM control electronics

BV converter board

- mounted on control board
- custom boost converter:
  9.5V on backplane → O(100V)

Control board:

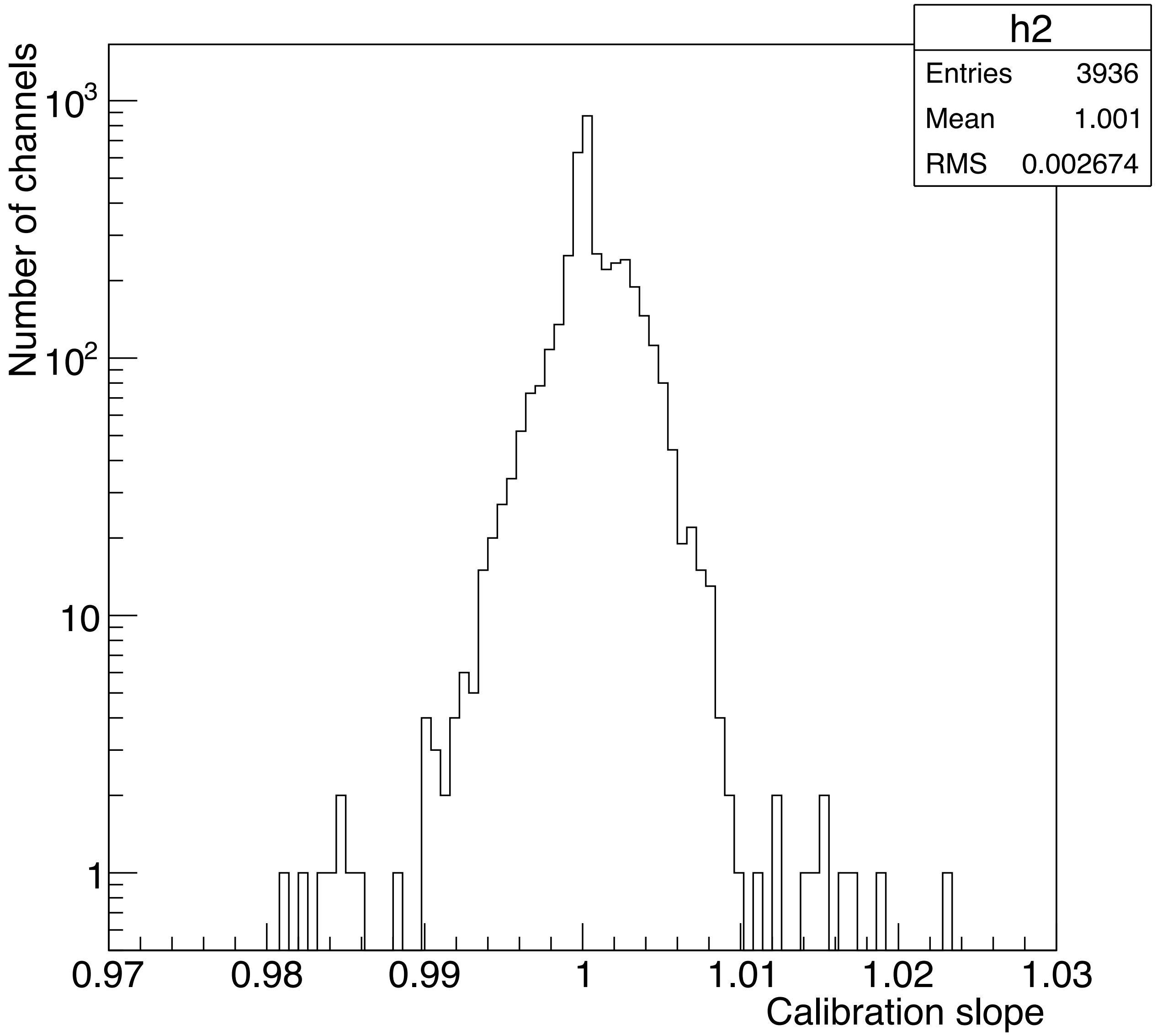
- bulk BV stepped down to ~70V
  - separately per channel
  - 20 mV LSB (1% precision on gain for $V-V_b = 3V$)
  - 3—7 mV ripple/noise
- 1 control board per RM (i.e. 48 SiPM channels)
- measures SiPM leakage current
- measures temperature and humidity



SiPM control electronics

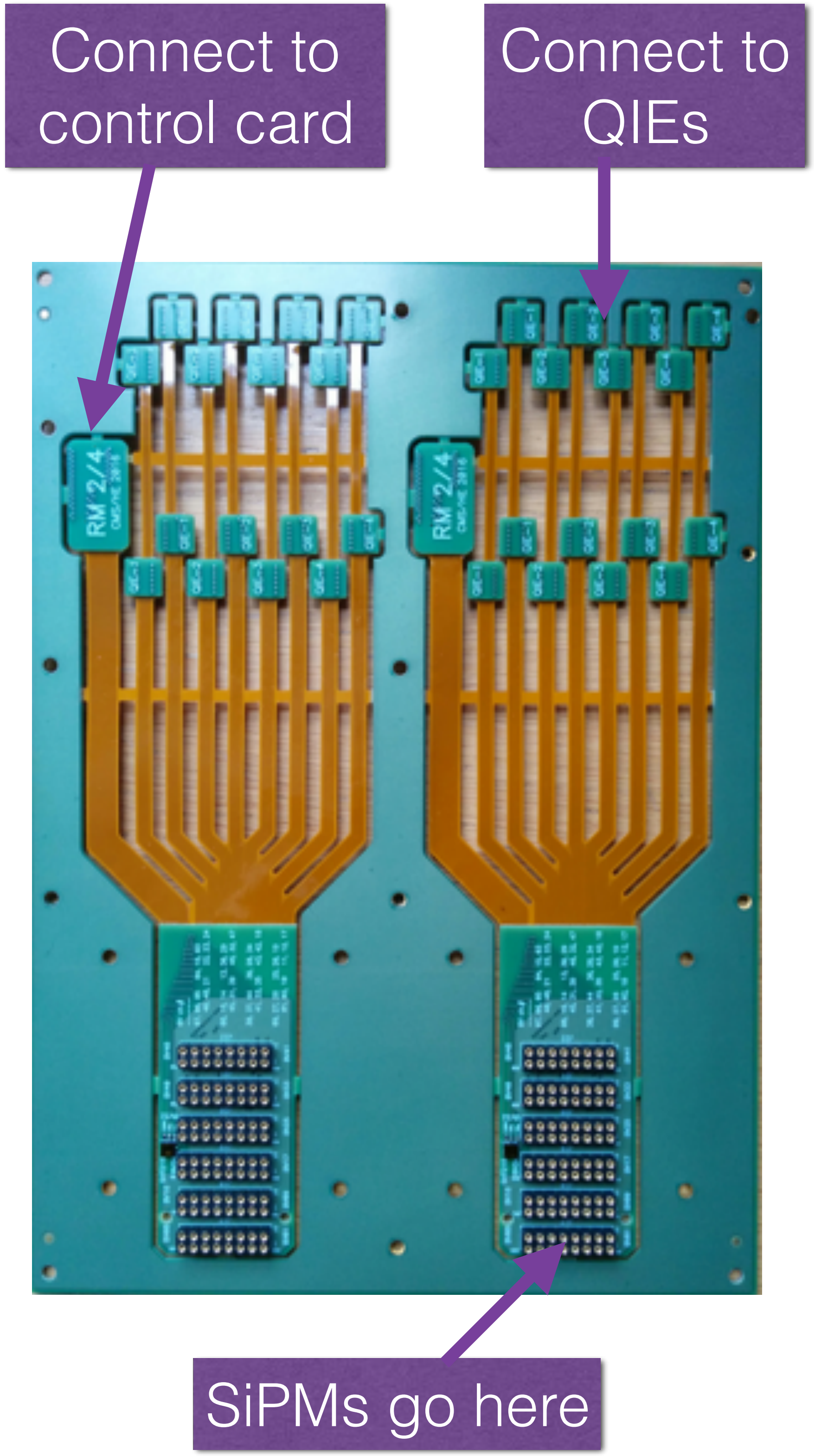
Quality control of all produced cards

- Checked response of all BV channels to the set DAC value
- Very uniform out of the box: RMS of 0.3%
- Small variations will be further leveled to achieve uniform SiPM gain across all channels



SiPM mounting board

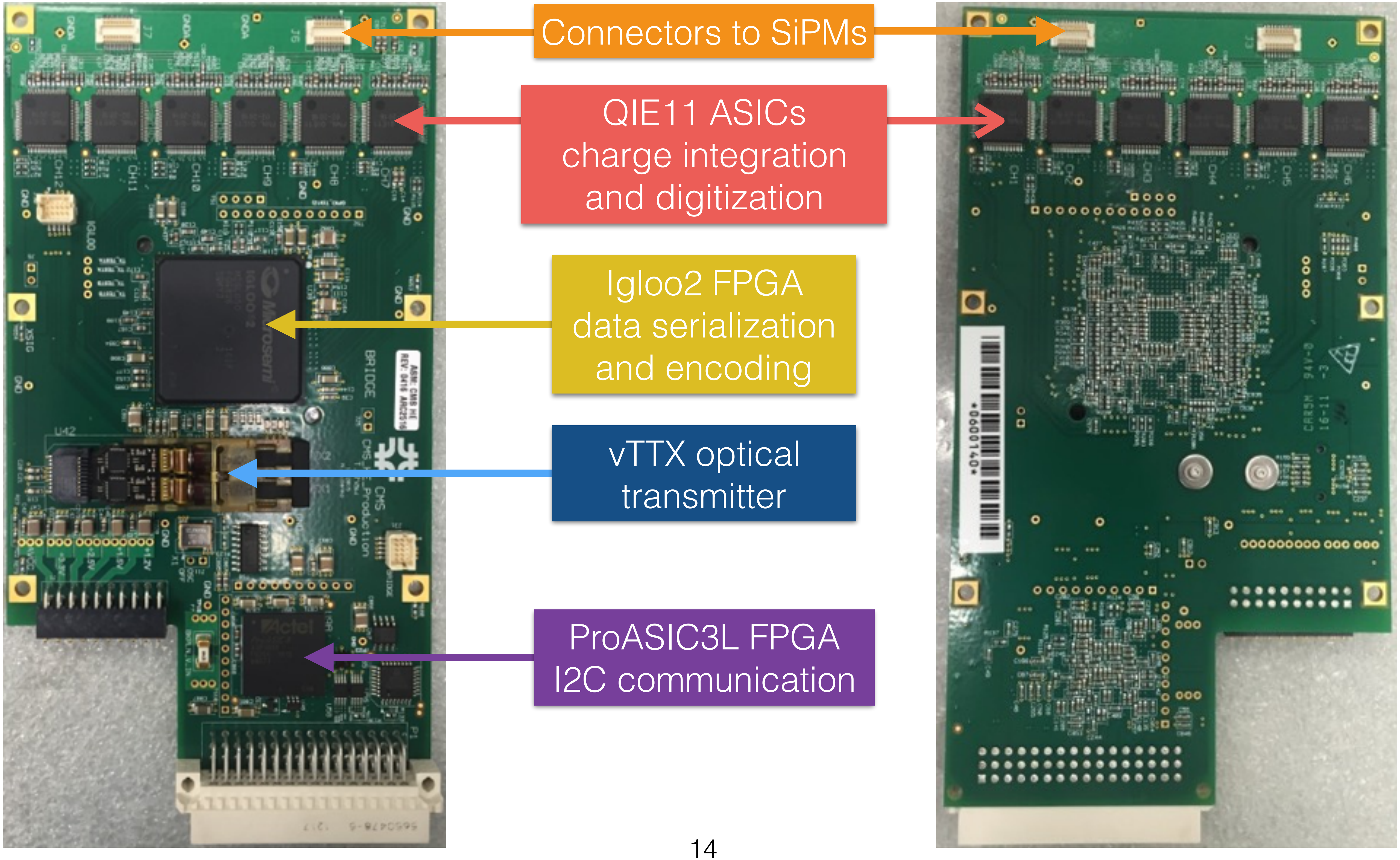
- Rigid-flex construction
  - Rigid part holds the SiPMs inside cooling assembly
  - Flex cables interface with QIE chips for charge integration
  - Flex cable to transfer BV to each SiPM
- Temperature and humidity sensors installed next to SiPMs
- Worked with vendor
  - Optimize fabrication process
  - Design adjusted to allow more reliable production


Connect to control card

Connect to QIEs

SiPMs go here

QIE cards



Connectors to SiPMs

QIE11 ASICs
charge integration
and digitization

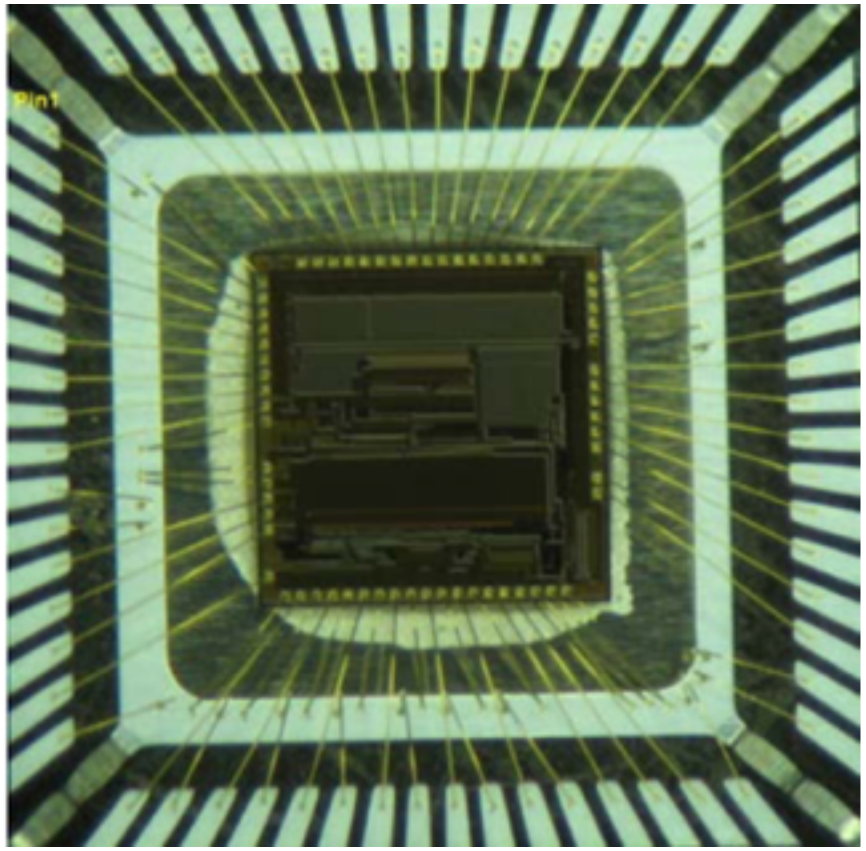
Igloo2 FPGA
data serialization
and encoding

vTTX optical
transmitter

ProASIC3L FPGA
I2C communication

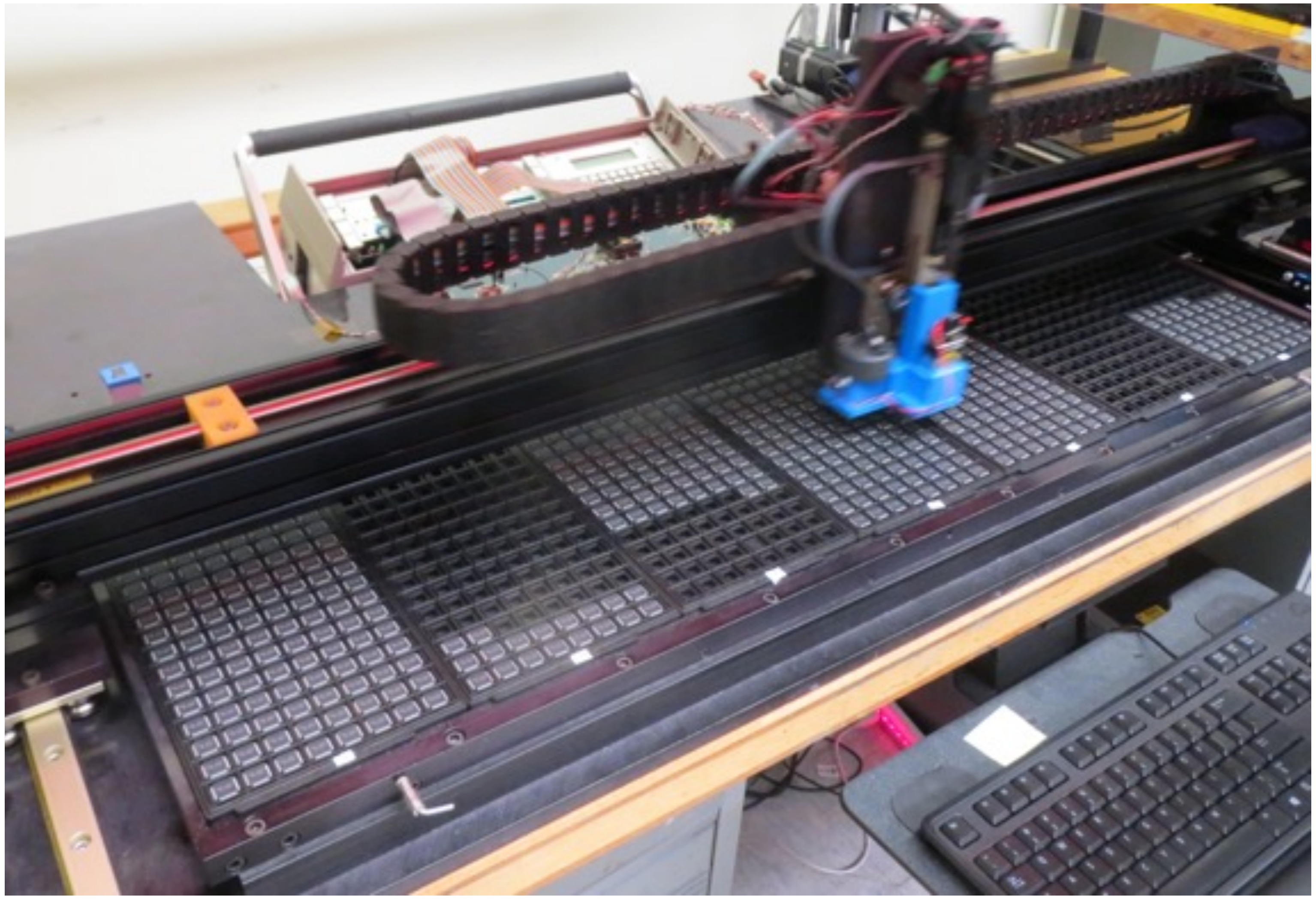
QIE11 ASIC

- Integrate charge in 25ns intervals without dead time
- 17-bit dynamic range with 8-bit readout, previous generation (QIE8) had 14-bit dynamic range with 7-bit readout.
- Extended dynamic range (350 pC with 3 fC LSB) with extra bit of precision to match the larger SiPM gain
- Achieves ~1% resolution over full dynamic range by using 4 integration ranges (scaled by factors of 8) with a 6-bit pseudo-logarithmic ADC in each range
- Programmable current shunt (between 1 and 1/11.5) for tuning SiPM gain independently of SiPM PDE



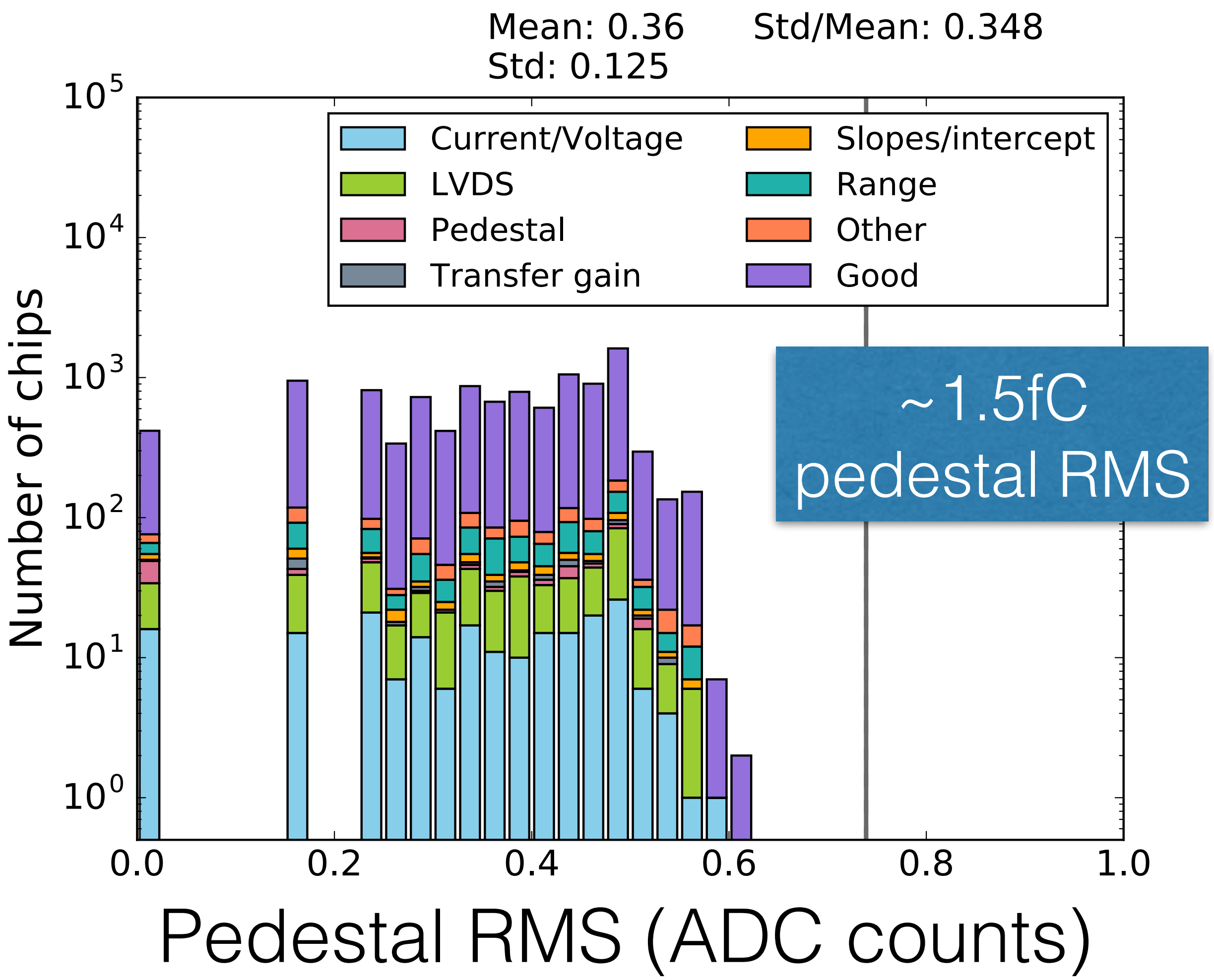
QIE11 testing

- O(40k) chips have been thoroughly tested before mounting on QIE cards
- Custom test setup
  - Robot system for moving QIE chips onto test board
  - Can load 1120 chips per cycle
  - Test suite covers all aspects of the chips, and takes about 2.5 minutes per chip.

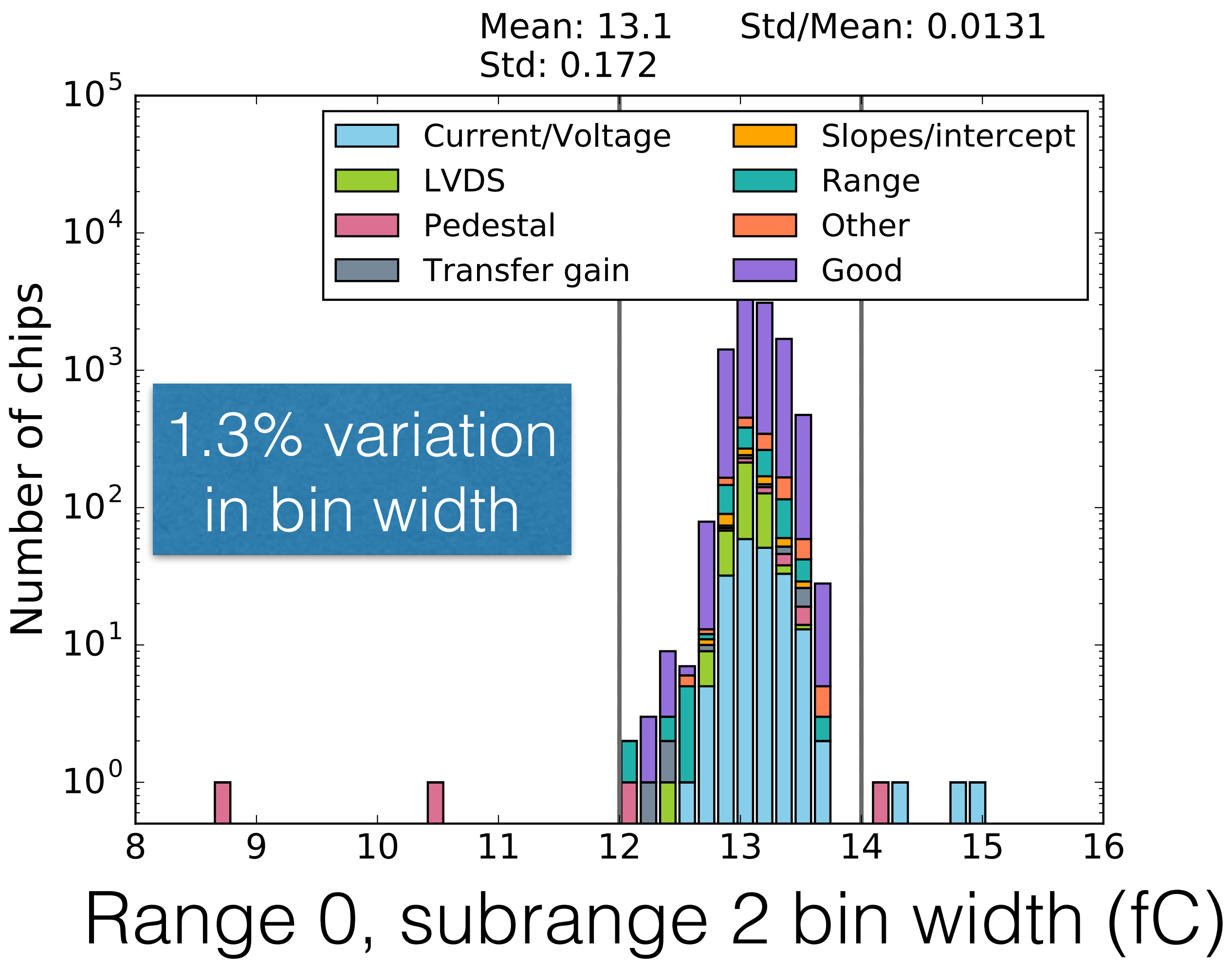


QIE11 testing

- Very good acceptance:
  - 98% for basic functionality
  - 86% for final selection, including uniformity selections



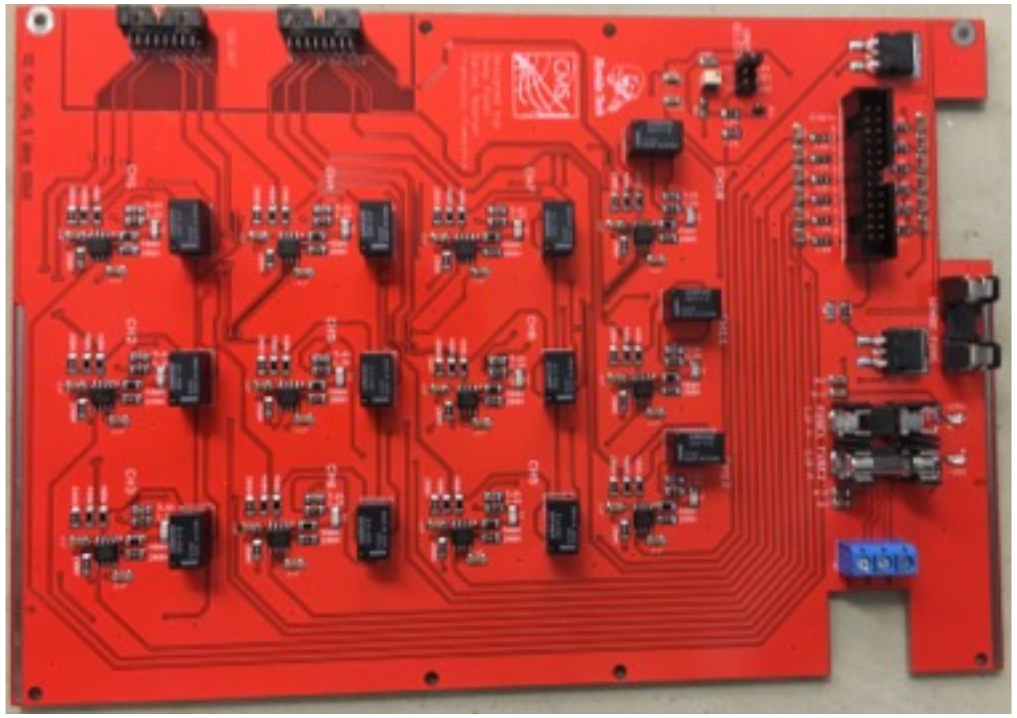
~1.5fC pedestal RMS



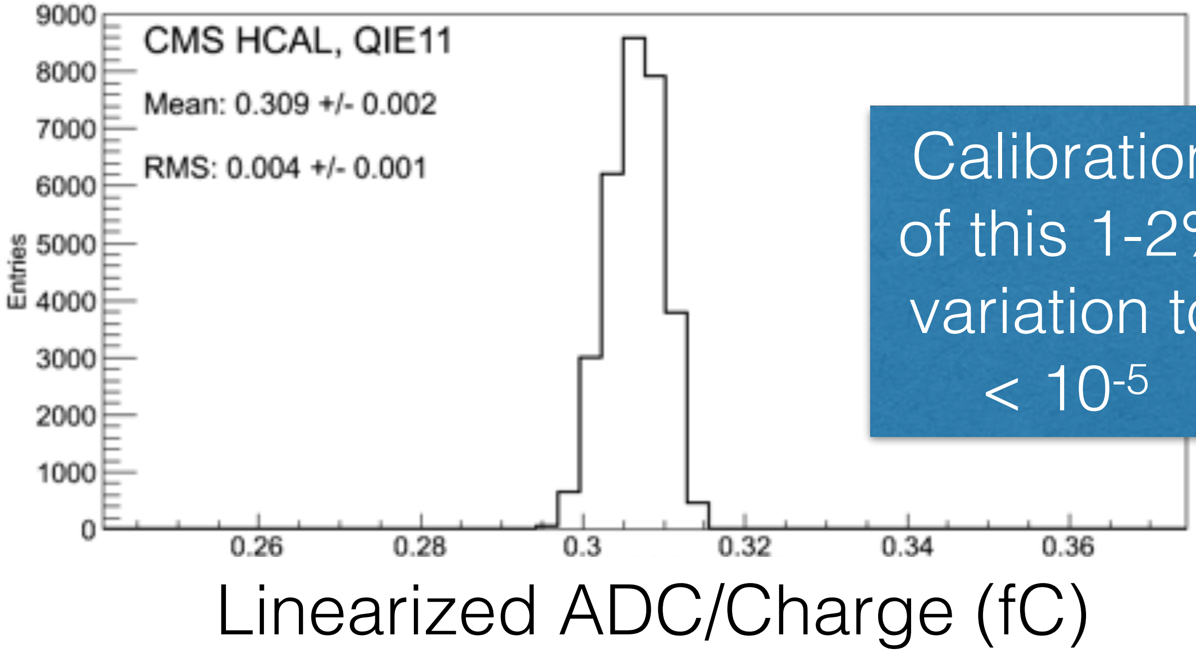
1.3% variation in bin width

QIE card testing

- All cards went through quality control (94% yield)
- Each QIE on each card has been calibrated for all shunt values using a custom charge injector board

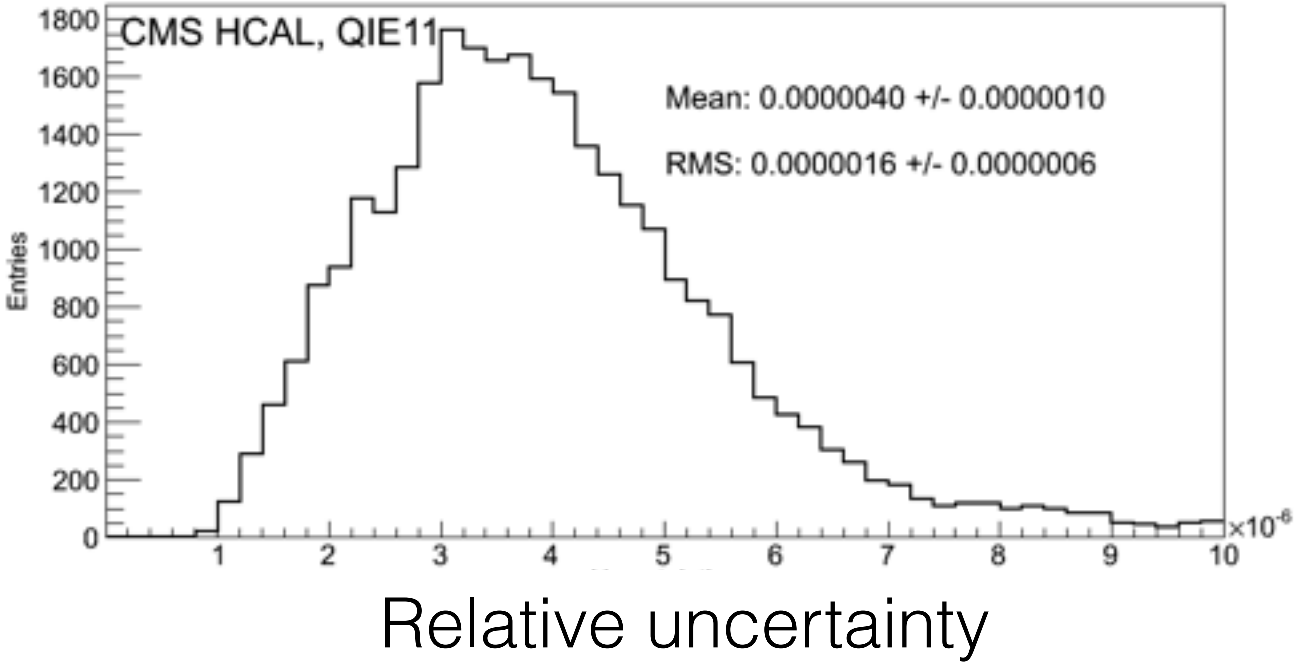


Range 0 bin width (gain 1)



Calibration of this 1-2% variation to $< 10^{-5}$

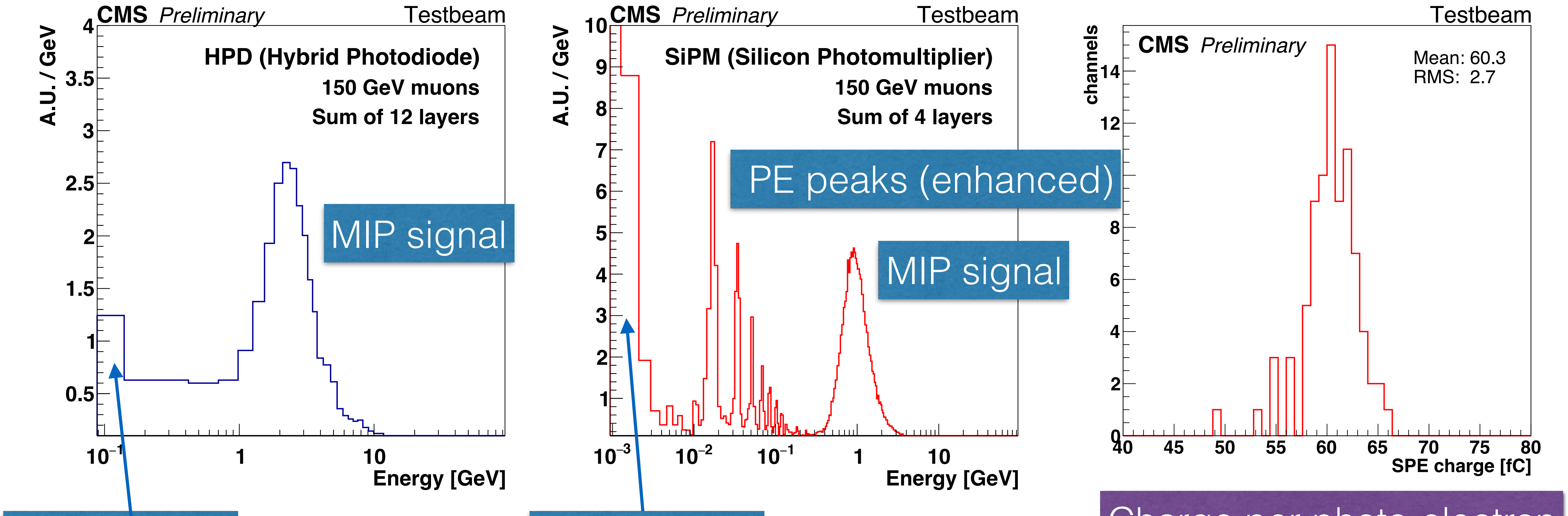
Range 0 bin width (gain 1)



doi:10.1088/1748-0221/11/03/C03020

Testbeam

- Preproduction system was tested at the CERN H2 beamline (muon and pion beam)
- Shows excellent performance of SiPMs vs HPDs in terms of signal to noise ratio
- 4% RMS on SPE charge using uniform bias voltage setting, at constant over-voltage this becomes 1%



QIE Pedestal

QIE Pedestal

Charge per photo-electron

Summary

- CMS HCAL will upgrade the frontend with SiPMs and associated readout and control electronics
- Upgrade for endcap HCAL is planned for early 2017 and final testing and burn-in of the new system is well underway
- Upgrade of barrel HCAL will be done during LS2