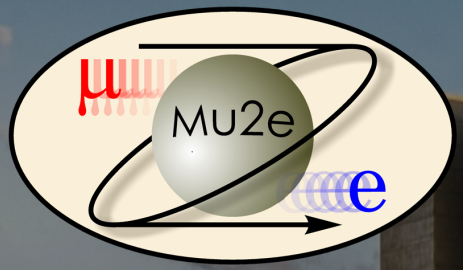

An automated QC station for the characterization of the Mu2e Calorimeter Readout Units

Elisa Sanzani on behalf of the Mu2e Calorimeter group

ICHEP 2022

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INFN

Istituto Nazionale di Fisica Nucleare

Fermilab

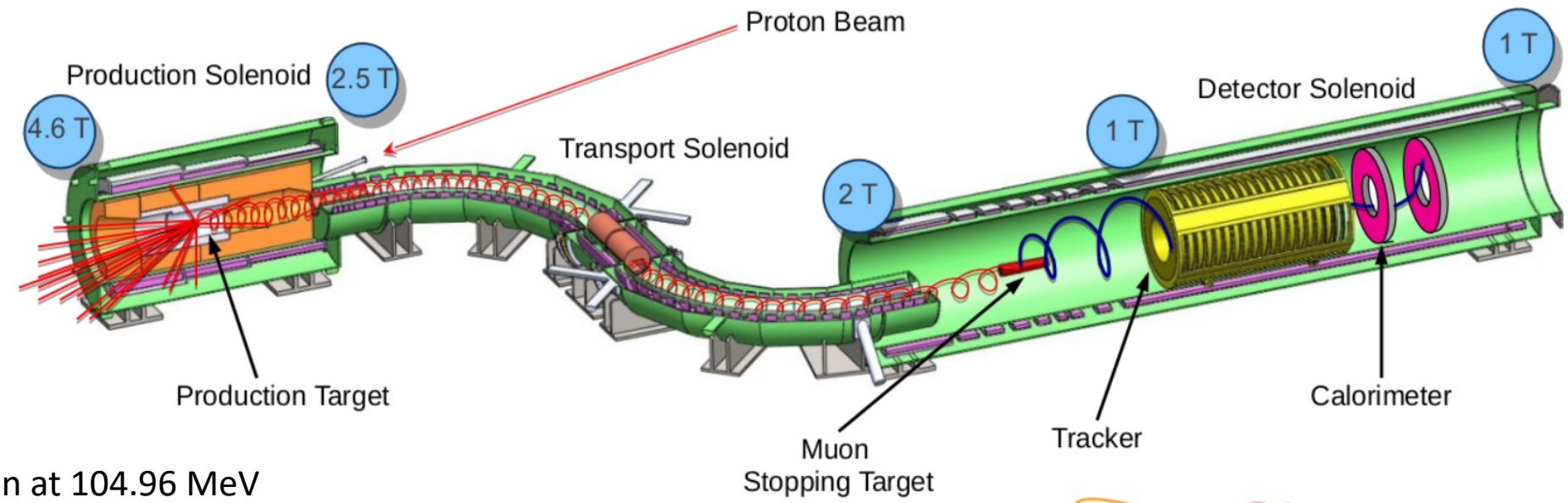
The Mu2e experiment at FNAL

Search for Charged Lepton Flavour Violation (CLFV) via the conversion process:

$$\mu^- N \rightarrow e^- N$$

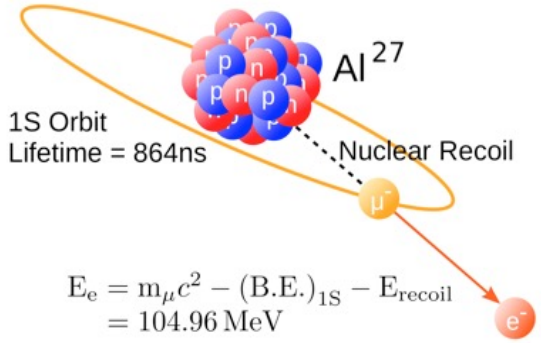
SM BR($\mu \rightarrow e$) ≤ 10^{-54}

⇒ observation of a conversion event implies New Physics!



- Signature: Monoenergetic electron at 104.96 MeV
- Goal: Improve by *four* orders of magnitude the current sensitivity on

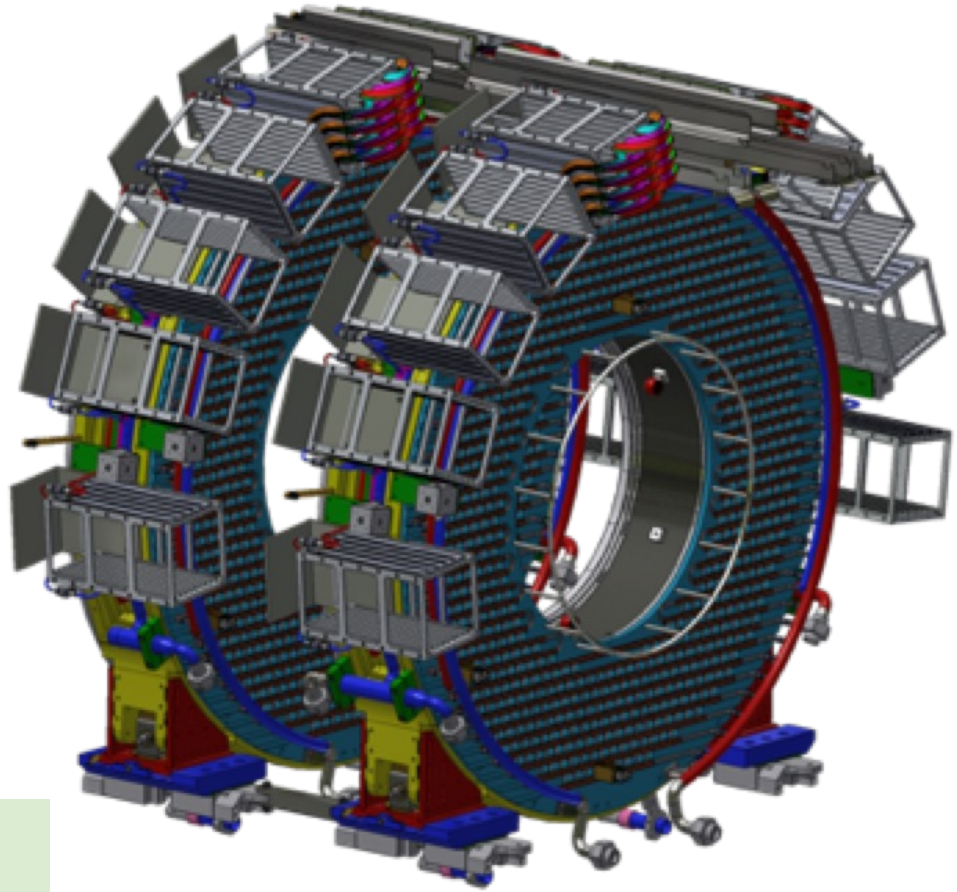
$$R_{\mu e} = \frac{\Gamma(\mu^- + A(Z,N) \rightarrow e^- + A(Z,N))}{\Gamma(\mu^- + A(Z,N) \rightarrow \upsilon_\mu + A(Z-1,N))} < 8 \cdot 10^{-17}$$



- A high intensity pulsed muon beam at 10 GHz is stopped on the Al target.
- The interaction products are analysed by the Mu2e detectors:
  - ✓ A high momentum resolution 3 meter long Straw Tube Tracker, made of ~$2 \cdot 10^4$ straws arranged in 36 planes, suppresses the irreducible decay in orbit background
  - ✓ A pure CsI Crystal Calorimeter complements the tracker information and provides excellent energy and time resolution
  - ✓ A Cosmic Ray Veto surrounds the detector regions to identify incoming cosmic ray muons

The Mu2e Crystal Calorimeter

- The calorimeter adds redundancy and complementary qualities with respect to the tracking system:
  - ✓ Large acceptance for the mono-energetic electron candidate events
  - ✓ Particle Identification capabilities with μ/e rejection factor >200
  - ✓ Cluster-based seeding for track finding at high occupancy
  - ✓ Stand-alone online trigger capability
- Working conditions:
  - ✓ 10^{-4} Torr vacuum
  - ✓ 1T magnetic field
  - ✓ TiD up to 100 krad and neutron fluence 10^{12} $n_{1MeV\text{-}eq}/cm^2$
- Requirements:
  - ✓ $\sigma_E/E < 10\%$ @ 100 MeV
  - ✓ $\sigma_t < 500$ ps @ 100 MeV
  - ✓ $\sigma_x < 1$cm



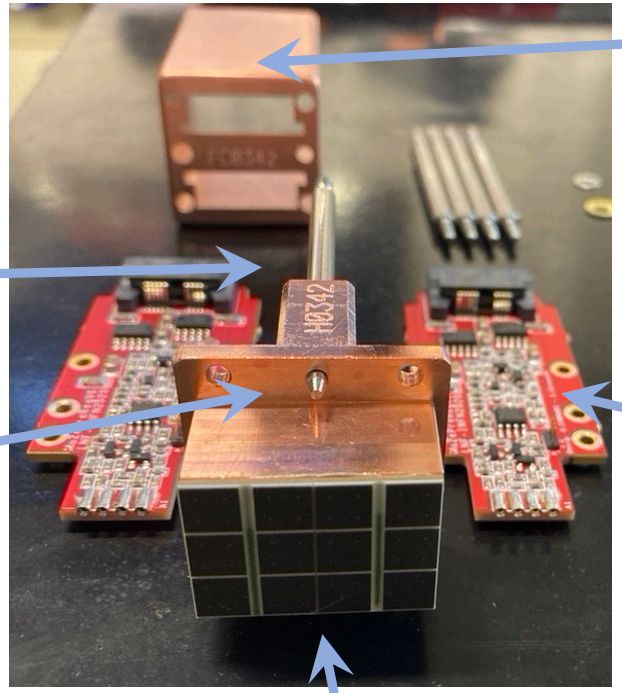
- **Two annular disks, each one filled with 674 pure CsI crystals**
- **$10X_0$ crystal length ($15X_0$ at average arrival angle)**
- **Readout via 2 UV-extended SiPM matrices per crystal**
- **10 crates/disk to host DAQ boards**
- **SiPM + FEE fluid cooling down to –10° C (I_{dark} halves every 10°C reduction)**

See D.Paesani's talk for more details about the Mu2e Calorimeter!

The Calorimeter Readout

Fiber optic coupler for the secondary distribution layer of the laser calibration system

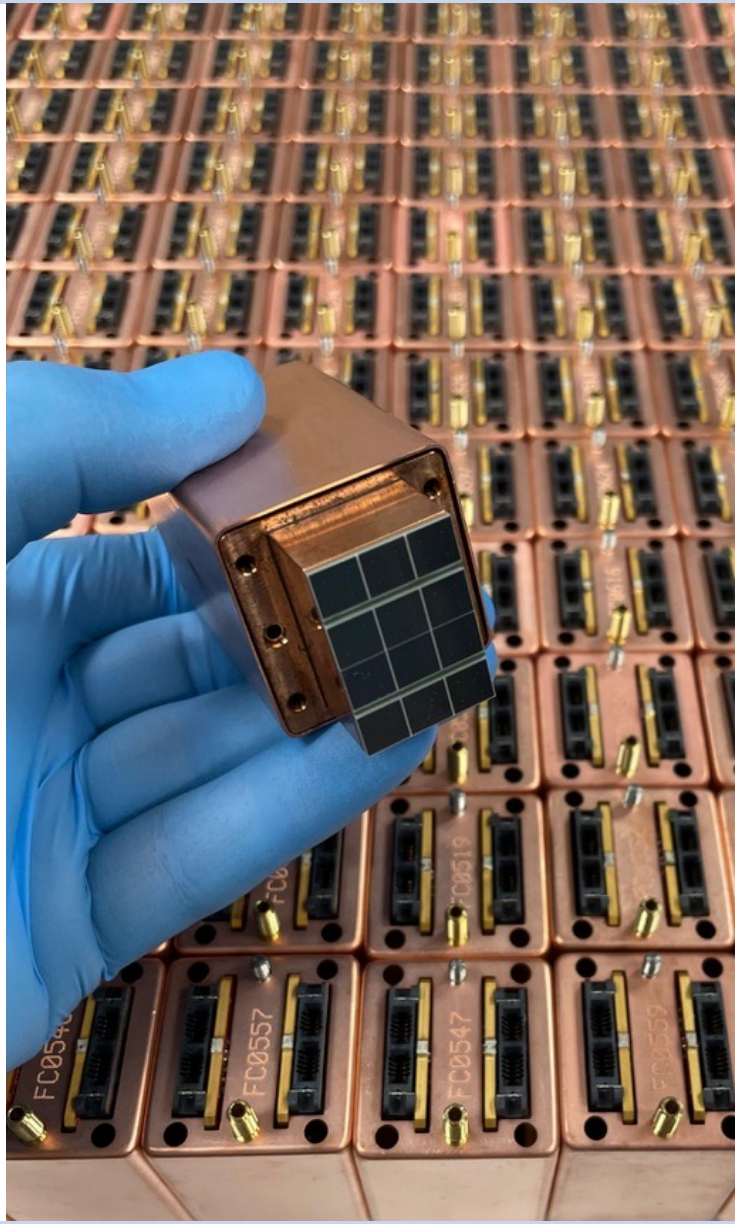
Faraday cage for shielding



Copper thermal block for SiPM cooling and for mechanical support

Two Front End Electronics Boards (FEE)

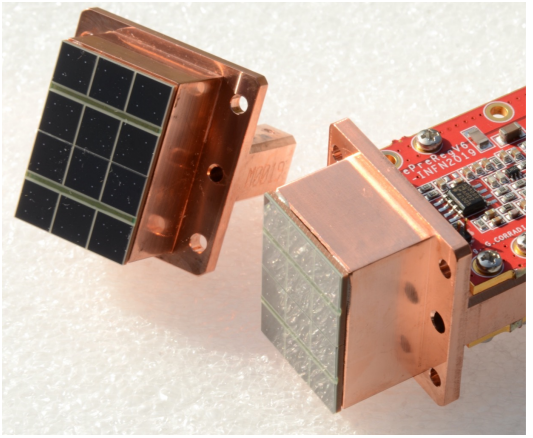
Two Hamamatsu UV-extended 2x3 matrices of SiPMs

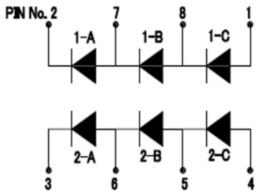


Two independent readout channels per crystal, one per SiPM
→ Redundancy and higher light collection

SiPM: properties and QC

- 1 Mu2e SiPM = two 2x3 matrices of individual MPPCs of 6x6 mm^2
- 14400 50 x 50 μm^2 pixels for each MPPC
- UV-extended (SPL) to match CsI emission peak at 315 nm
- Series/parallel MPPC connection to decrease equivalent capacitance by 1/3

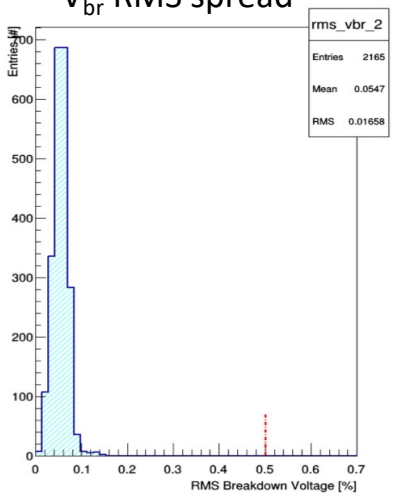




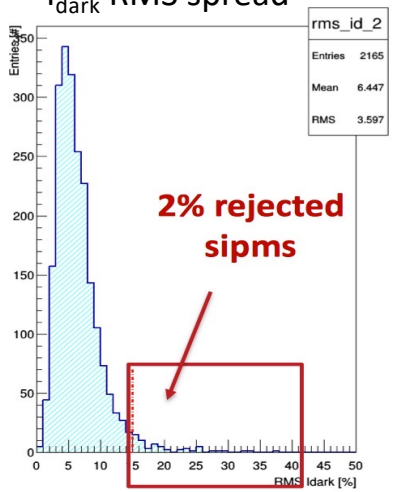
Requirements:

- Gain >10^6 at $V_{op} = V_{bd}$ + 3 V
- 20% PDE at 300 nm
- MTTF > 10^6 hours at 20°C
- Short pulse width

V_{br} RMS spread



I_{dark} RMS spread



QC steps:

- Visual control + mechanical specifications
- V_{br}, I_{dark}, gain x PDE measured for each cell
- MTTF evaluation at 65°C for ~14 days
- 5 SiPM/batch underwent 10^{12} $n_{1\mathrm{MeV}-eq}/cm^2$ irradiation test

- **QC on all production SiPMs completed in late 2019 with < 2 % of out-of-specs components**
- **More than 3000 SiPMs are now glued to their copper holders**

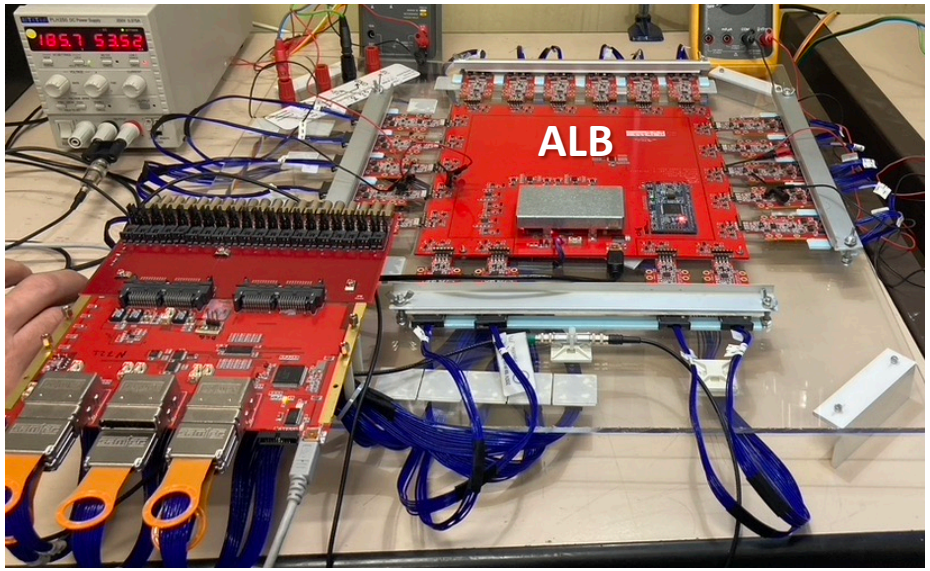
→ Now being assembled in a ROU with the FEE boards

FEE: properties and QC

Properties:

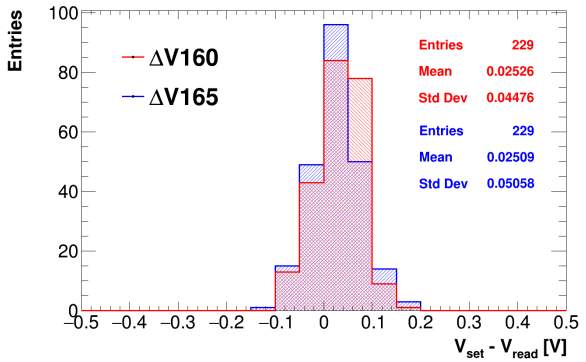
- ✓ Signal rise time > 25 ns for appropriate time reconstruction
- ✓ Rate capability up to 1 MHz, short fall time
- ✓ High stability SiPM management
- ✓ Radiation-hardness (100 krad TiD, 10^{12} $n_{1MeV\text{-}eq}/cm^2$)
- ✓ Programmable bias up to 200V via 12-bit DAC
- ✓ SiPM bias, current and temperature monitor via 12-bit ADC

Quality Controls: 6 hours *burn-in* test at 65°C + *calibration* (JINR + LNF)



Active Load Board to calibrate 20 FEE in one go

- Linear 2-point calibration of ADC and DAC
- Stress test with 2mA current
- Calibration of temperature and current monitors
- FEE pulsing to evaluate signal shape and gain linearity



accuracy on HV setpoint ±50 mV (1 LSB) after calibration

All FEEs have undergone the QC steps → ready to be assembled in a ROU

ROUs Quality Control Station

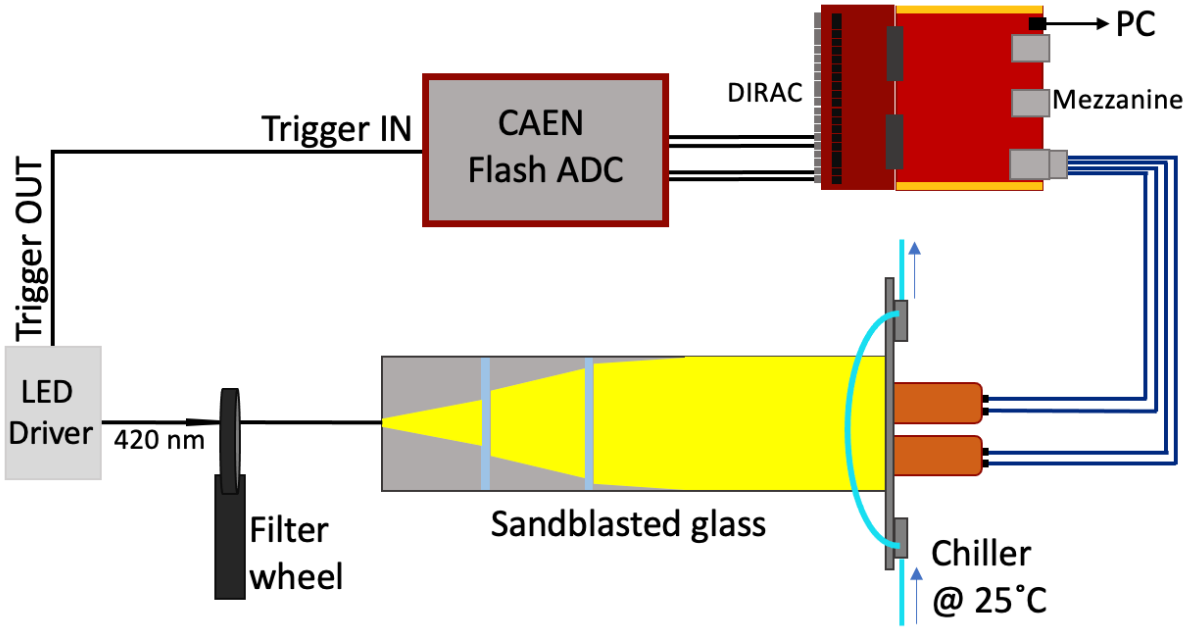
Before ROUs are mounted to the calo disk, the overall chain

SiPM + holder + FEEs + Faraday cage

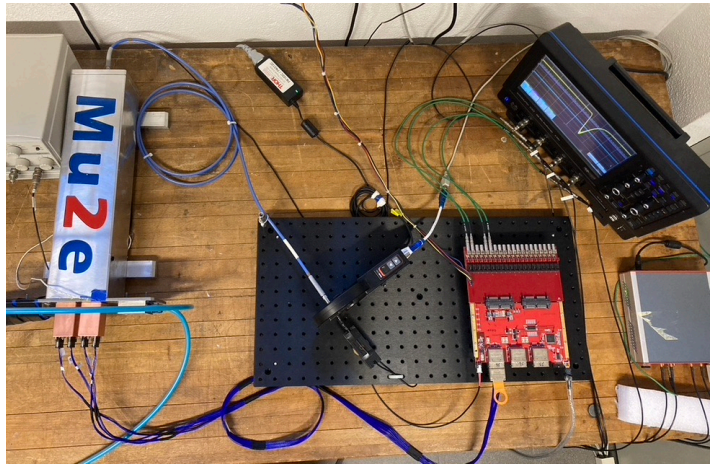
has to be tested and characterized:

- Verify each unit works properly (no broken parts, sparks)
- Characterize to see if gain and PDE meet the specs
- Build database for reference during data-taking

QC Station for the ROUs at LNF

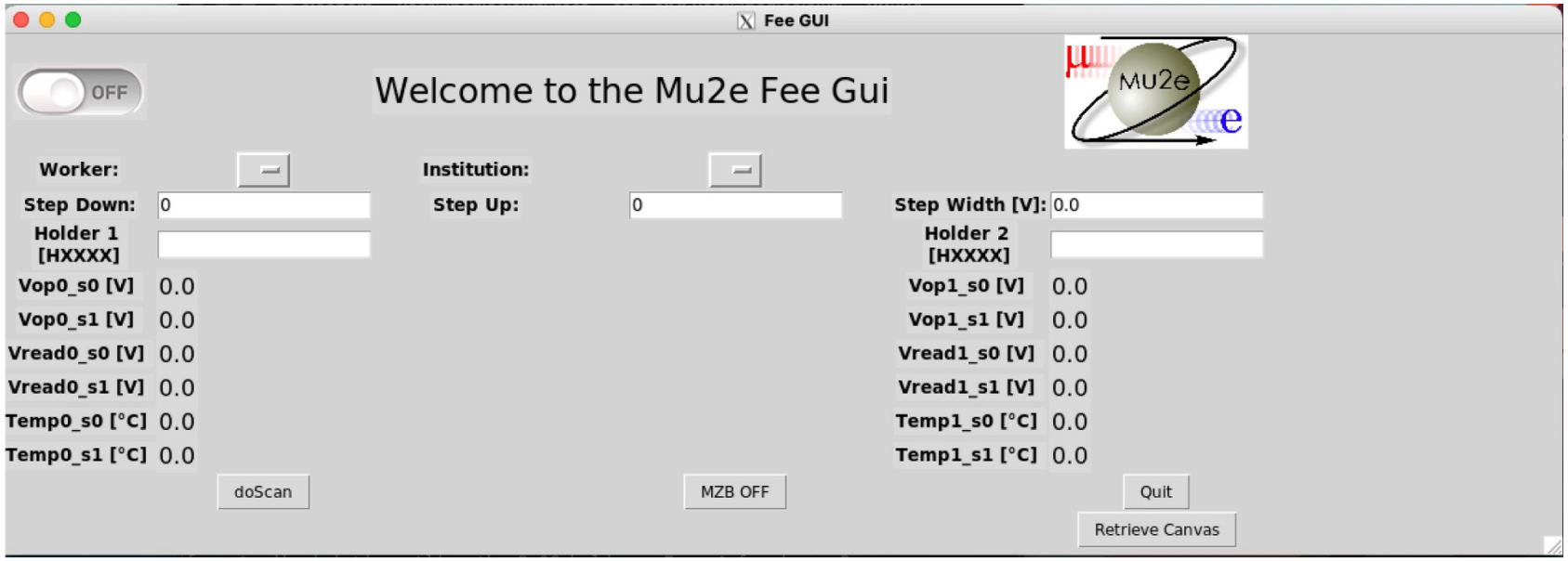


- ✓ 420 nm Blu LED at 10kHz
- ✓ 9 position filter to attenuate the light intensity
- ✓ Sandblasted glass layers ensure uniform light diffusion on the SiPMs faces
- ✓ Metal box for light tightness
- ✓ 2 ROUs mounted on an Al cooling plate and stabilized at 25 °C
- ✓ Mezzanine and DIRAC boards collect the signals from the FEEs
- ✓ The signal is acquired via USB through the Mezzanine board



QC Station software

- ✓ Python and C++ programs for data acquisition and live analysis
- ✓ High parallelization of jobs ⟹ 7 minutes/scan
- ✓ GUI for fast scan setup and to quickly retrieve old results for validation checks



Scan

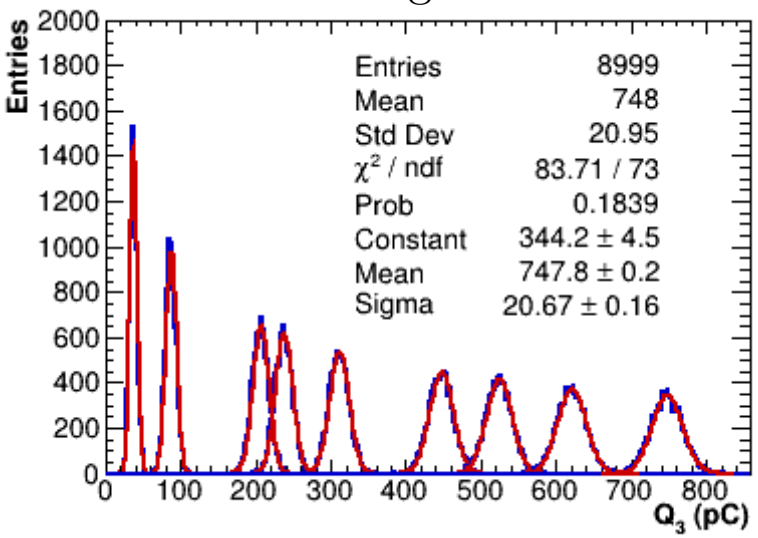
- 9 filters scan per HV value ⟹ 10^4 events acquired/HV point for each filter position
- 7 HV positions ⟹ V_{op} - 4V to V_{op} + 2V in 1V intervals. Best compromise between scan time and #points

→ Study of SiPM Gain, Photon Detection Efficiency and total charge for every light intensity and bias voltage

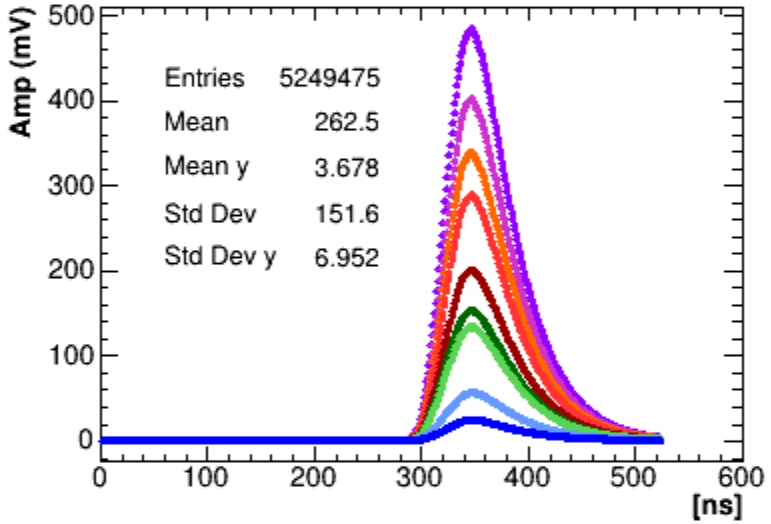
Gain measurement

- $V_{bias} = V_{op}$
- Scan over the 9 filters

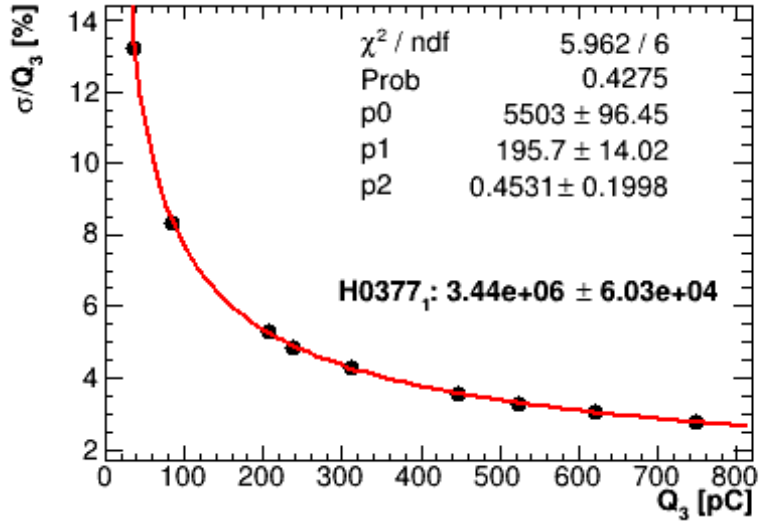
Charge



Waves profile



σ_Q/Q vs Q

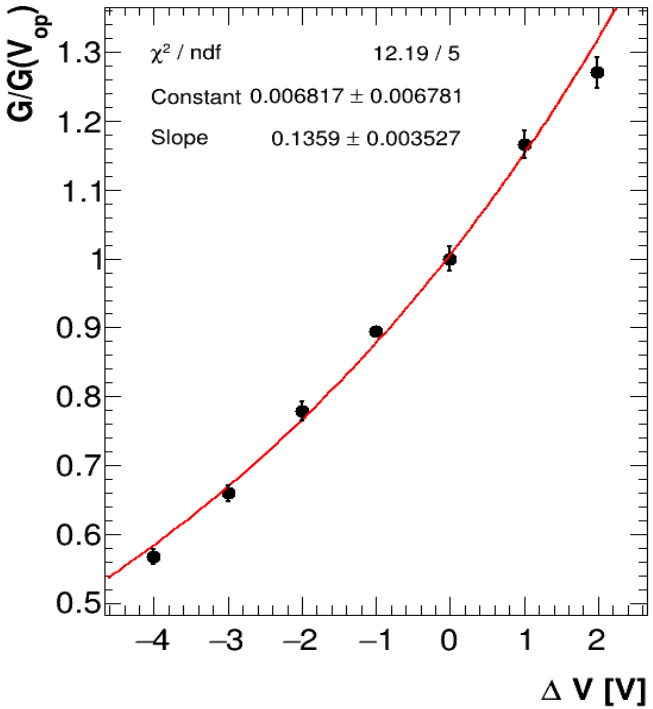


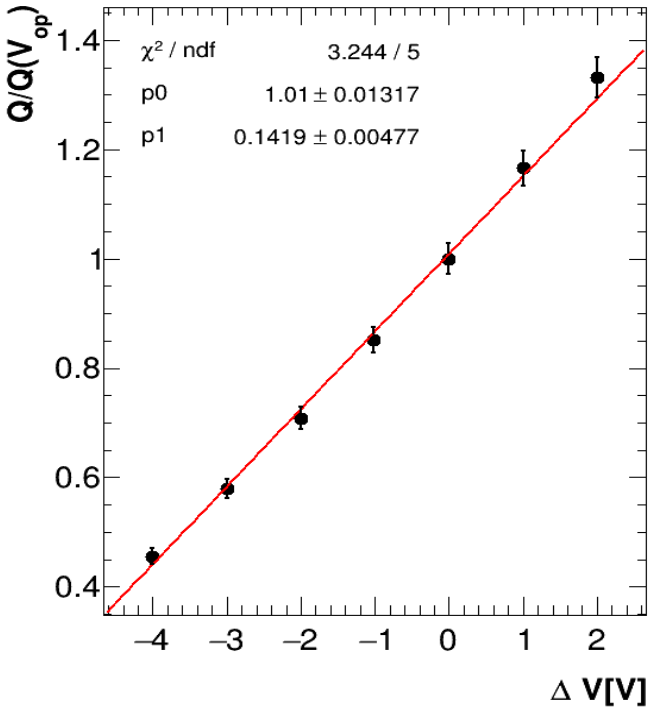
Gain from fit: $\frac{\sigma_Q}{Q}(Q) = \sqrt{\frac{p_0}{Q} + \frac{p_1^2}{Q^2} + p_2^2} \Rightarrow G = {}^{p_0}/_{q_{e[\,pC]}}$

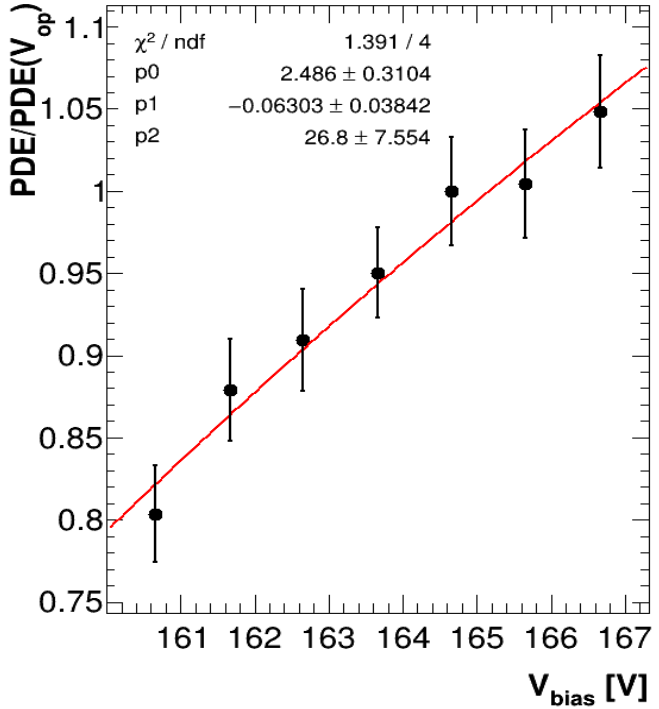
→ Study of the ROU response at V_{op} and verify signals are as expected

HV scan

- Dependence of G, Q, PDE on V_{bias} ⇨ 7 HV points scan
- Important when V_{bias} will be changed after radiation damage (I_{dark} increase)







$$G(V) = \exp[slope \cdot V + const]$$

$$Q(V) = p_0 \cdot V + p_1$$

$$PDE(V) = p_0 \cdot \left[1 - \left(p_1 \cdot V \cdot exp\left(-p_2/\sqrt{V}\right)\right)^{-2}\right]$$

arXiv:1904.05977

Scan quality parameters: $\chi^2/d.o.f. < 5$ && $\Delta G/G < 2.5\%$ → If not met, flag raised

Gain temperature dependence

Temperature sensor in the FEE → Study of Gain vs T

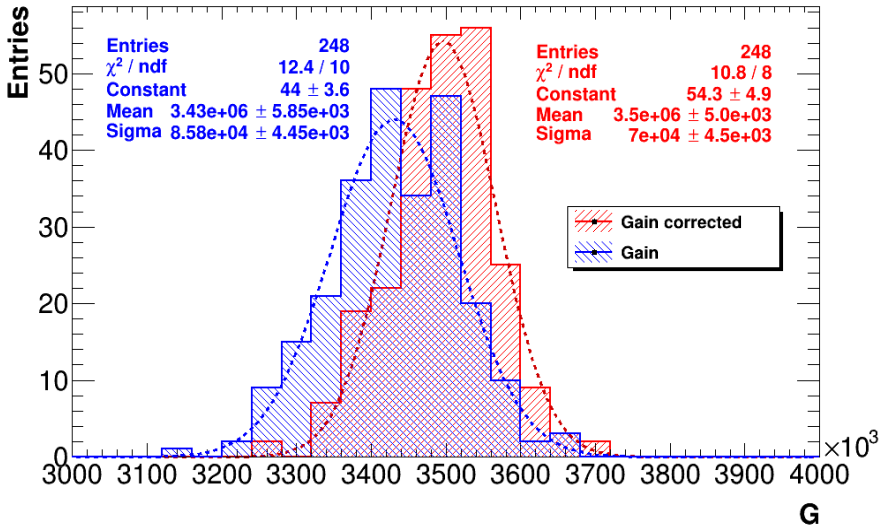
- Found gain decrease of 1.6%/°C

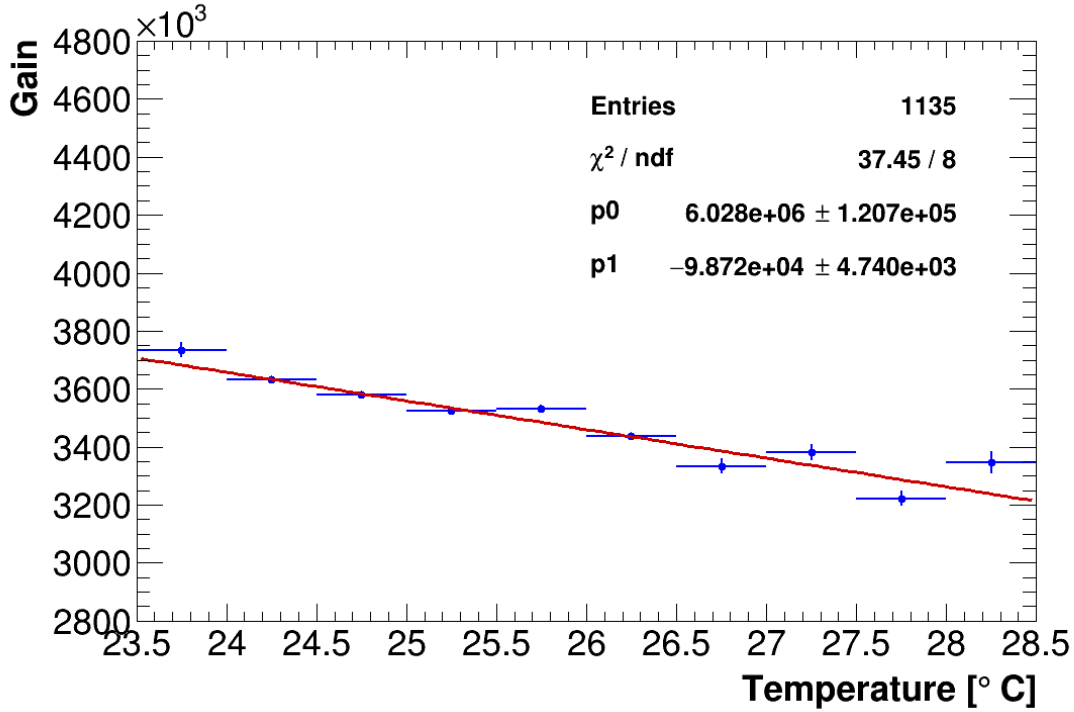
→ As expected from previous studies of the SiPMs

- Observed temperature variations in the QC station of ±2.5°C

→Correction of the saved gain data to 25°C

$$G_{corr} = G\,(1 + 0.016 \cdot (T - 25))$$

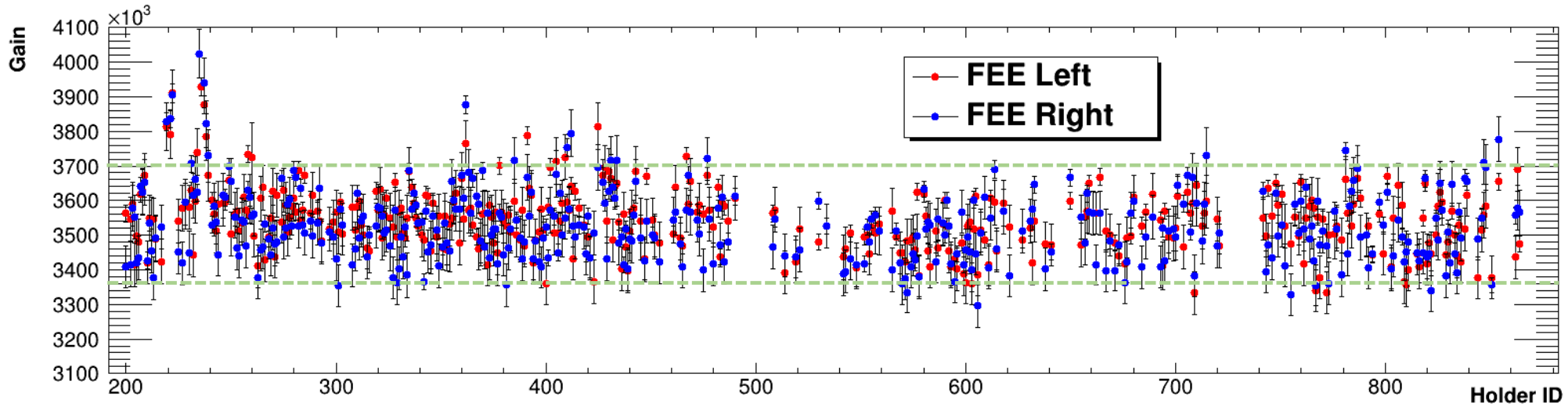




Temperature correction tested on repeated measurements:

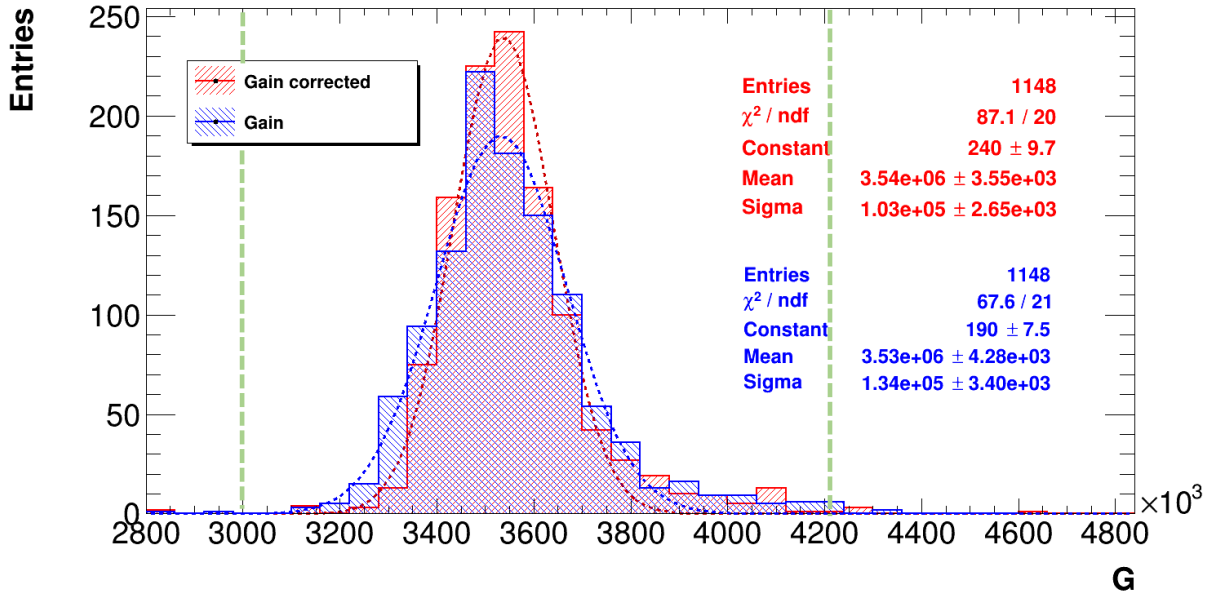
→ Measurement reproducibility better than 2%

ROUs consistency study



Evaluation of ROUs consistency

- ✓ No significant variation along production
- ✓ No left/right FEE dependence
- ✓ Gain spread of O(3%)
- ✓ Average gain $(3.54 \pm 0.35) \cdot 10^6$



Control unit if gain: $< 3.0 \cdot 10^6$ or $> 4.2 \cdot 10^6$

→ verify that all components are working properly and that FEE-HV calibration is properly set

Conclusions

- The Mu2e Calorimeter is ready for assembly → first crystals have been stacked!
- ROUs scan continuing at the station: ~600/1400 done
- First 100 ROUs shipped to Fermilab, ready to be mounted on the first disk in the fall

- ROUs uniformity along production is of O(3%)
- Creation of a database with relevant info from this test underway
  - Gain + fit parameters
  - PDE + fit parameters
  - Temperature information
- All the parts of the readout, and the ROUs as a whole, met specifications and requirements

→Ready to keep assembling the Mu2e Calorimeter and the Readout Units are also ready to go!