Design and status of the Mu2e crystal calorimeter

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On behalf of the Mu2e calorimeter group

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New Perspectives 2019
Fermi National Accelerator Laboratory

ROMA TRE UNIVERSITÀ DEGLI STUDI

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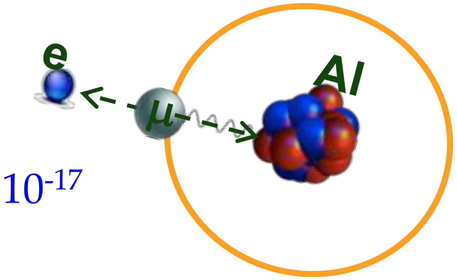
INFN Istituto Nazionale di Fisica Nucleare

CLFV @ Mu2e

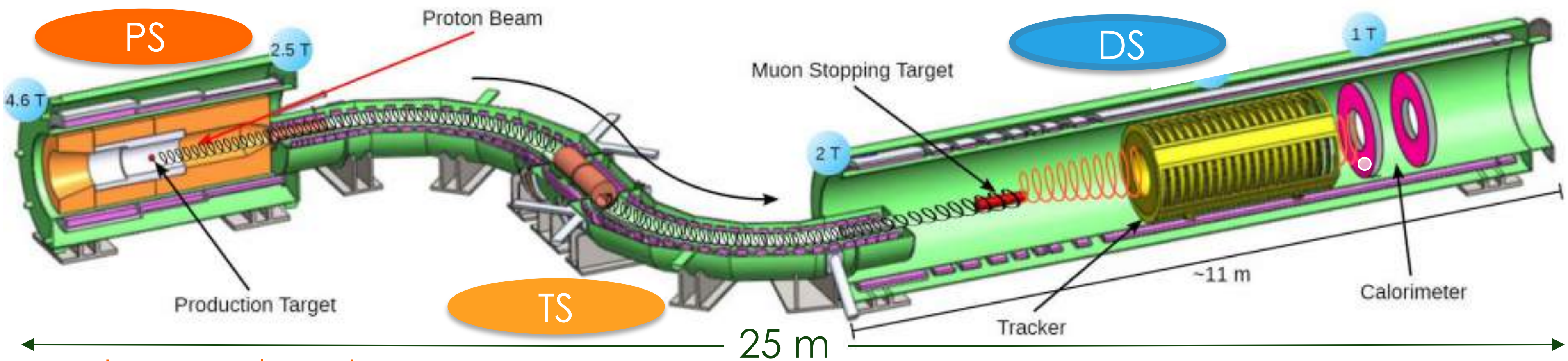
- CLFV strongly suppressed in SM: Branching Ratio $\leq 10^{-54}$
  → Observation would indicate New Physics
- CLFV @ Mu2e: μ- e conversion in the field of a nucleus
  → discovery sensitivity to many NP models

$E_{CE} = m_\mu c^2 - E_b - E_{recoil} =$
$= \mathbf{104.97\ MeV}$



More information in Yujing talk

$$R_{\mu e} = \frac{\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)}{\mu^- + N(A,Z) \rightarrow \nu_\mu + N(A,Z-1)} < 8.4 \times 10^{-17}$$



Production Solenoid / Target

- Protons hitting target and producing mostly π

Transport Solenoid

- Selects and transports low momentum μ^-

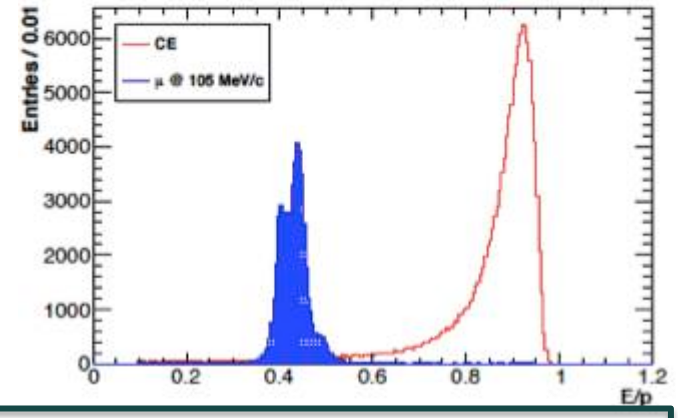
Detector Solenoid: stopping target & detectors

- Stops μ^- on Al foils
- Events reconstructed by detectors optimized for 105 MeV/c momentum

Calorimeter requirements

The electromagnetic calorimeter (EMC) should provide high acceptance for reconstructing energy, time and position of conversion electrons (CE) and provide:

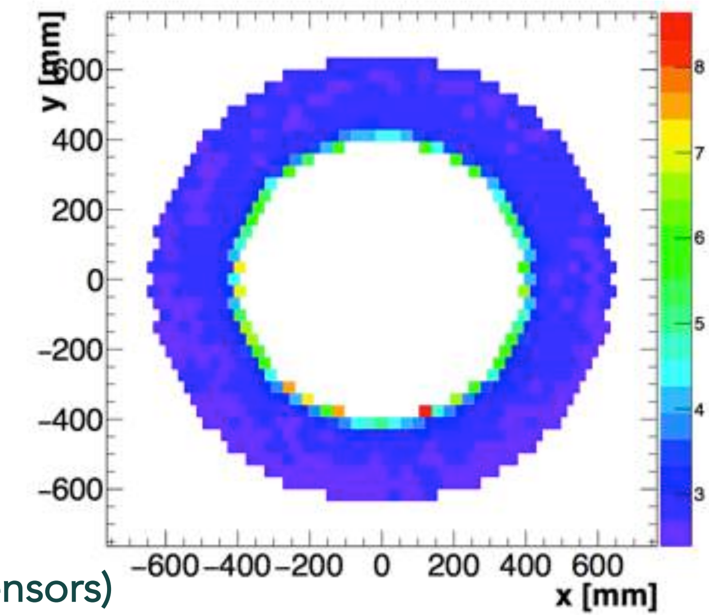
1) PID: e/μ separation
2) EMC seeded track finder
3) Fast and track-independent trigger



Requirements @ 105 MeV/c

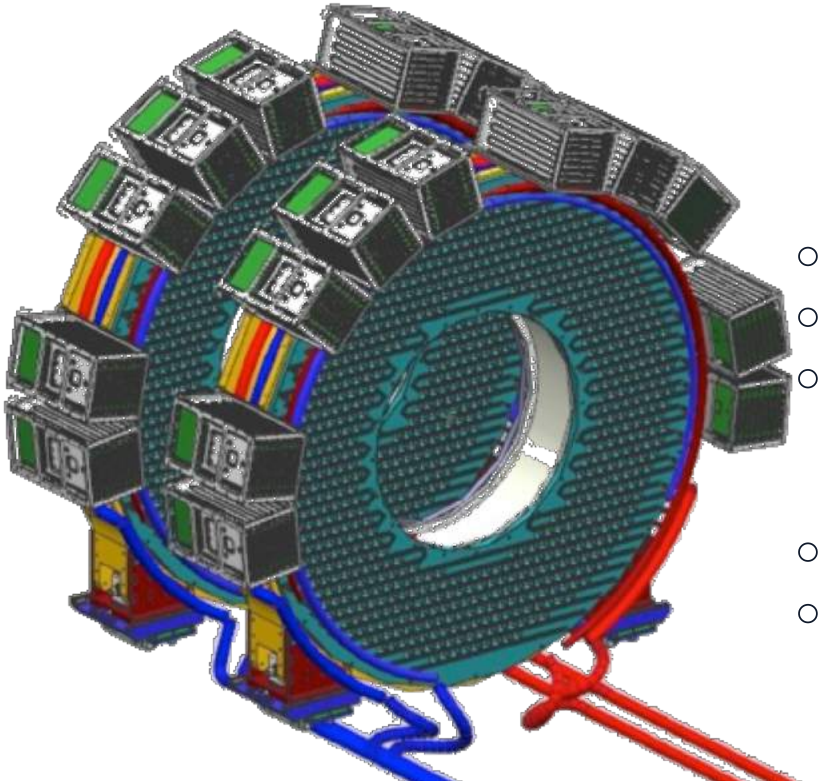
- $\sigma_E/E = \mathcal{O}(10\%)$ **for CE**
- $\sigma_T < 500$ **ps for CE**
- $\sigma_{X,Y} \leq 1$ **cm**

- Fast signals, τ<40 ns
- Operate in 1 T and in vacuum at 10^{-4} Torr
- Redundancy in readout (2 sensors+FEE /crystal)
- Radiation hardness (safety factor of 3):
  - 100 krad (45 krad) dose for crystals (sensors)
  - $3\text{x}10^{12}\ n_{1MeV}/cm^2$ ($1.2\text{x}10^{12}\ n_{1MeV}/cm^2$) for crystals (sensors)
- Low radiation induced readout noise < 0.6 MeV



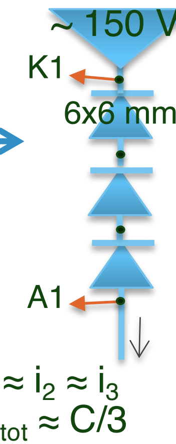
Front Disk Dose – 1 year [krad]

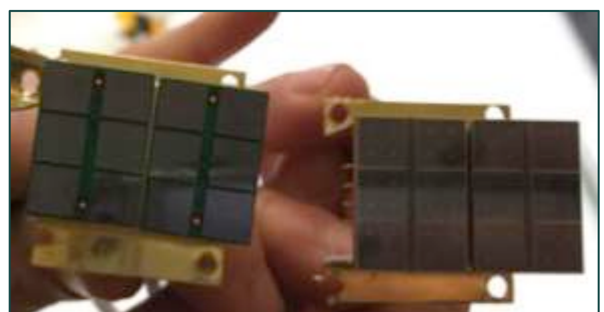
Calorimeter Design

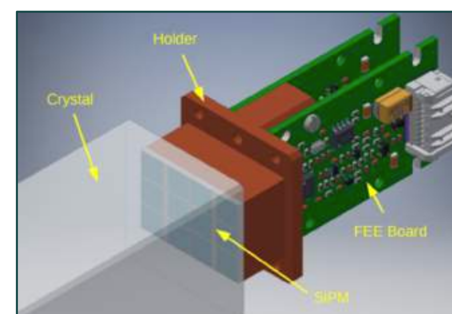


Two annular disks with 674 undoped CsI (34 x 34 x 200) mm^3 square crystals each

- R_{IN} = 374 mm, R_{OUT} = 660 mm
- Depth = 10 X_0 (200 mm); Distance = 70 cm
- Redundant readout:
  2 UV-extended SiPMs/crystal (Mu2e SiPMs)
  → 50 um pixel, 12x18 mm^2 active area
- 1 FEE / SiPM, digital readout on crates
- Long R&D phase to select final producer





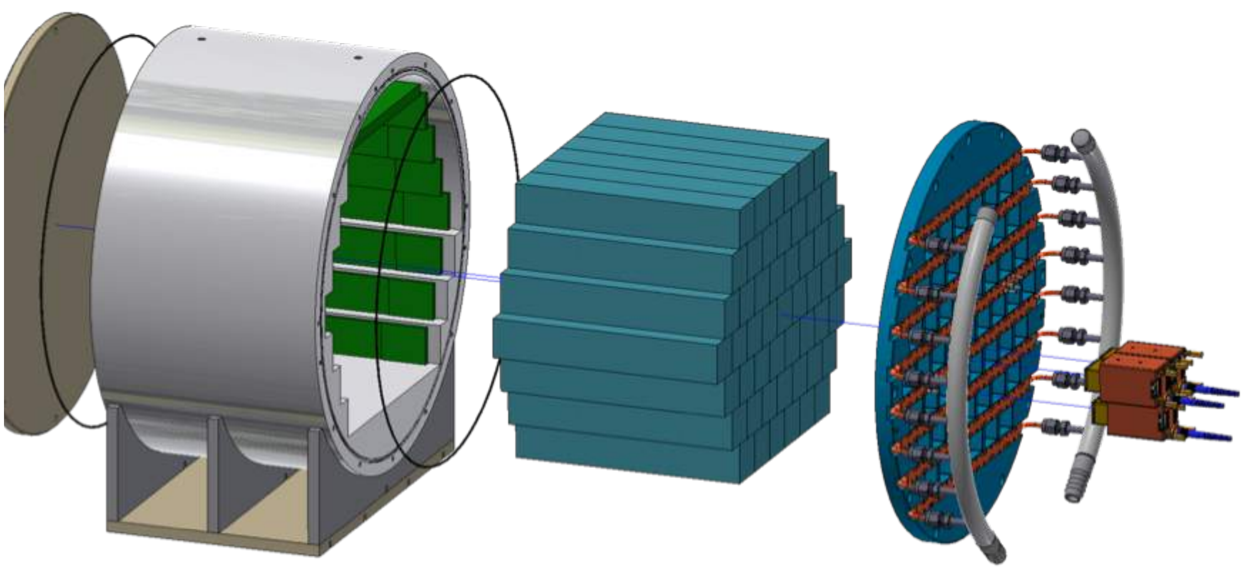


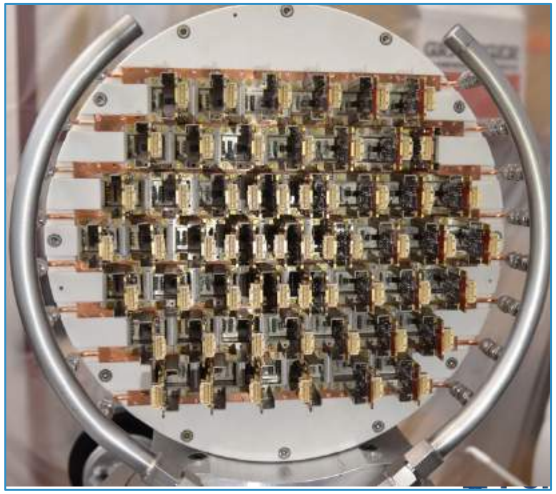
Module 0

Large EMC prototype: **51 crystals, 102 SiPMs, 102 FEE boards**

Mechanics and cooling system similar to the final ones but smaller scale → Main goals:

- Integration and assembly procedures
- Test beam May 2017, **60-120 MeV e$^-$** (**@ 0° and @ 50°**)
- Work under vacuum, low temperature, irradiation test





Readout: 1 GHz CAEN digitizers (DRS4 chip), 2 boards x 32 channels

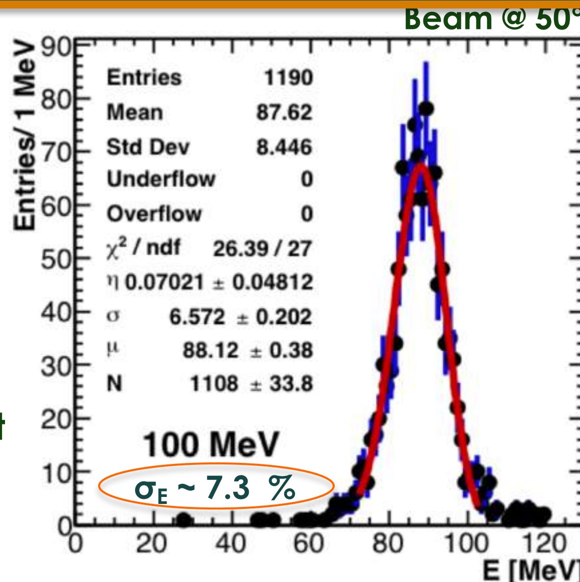
Module 0 TB results

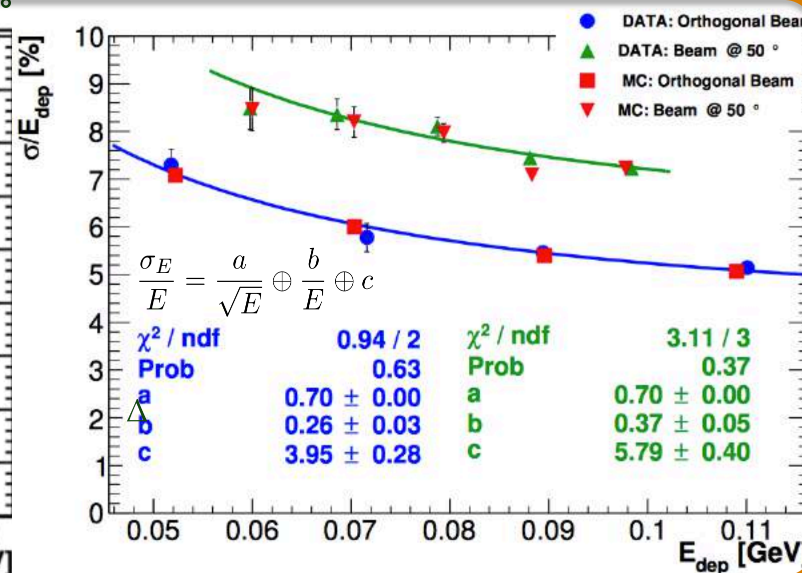
Energy response

- Single particle selection
- MIPs Equalization & E-scale

- LY/SiPM = 30 pe/MeV

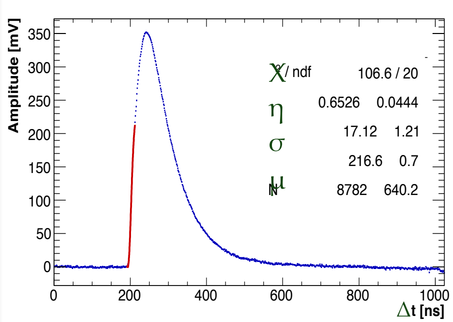
- **Great Data-MC agreement**

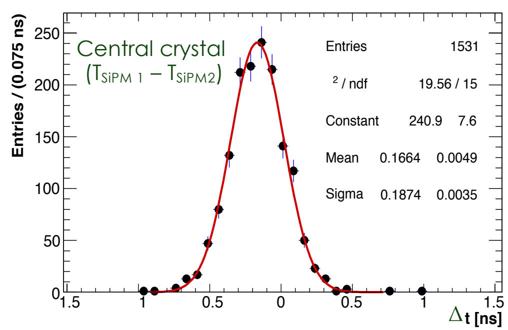


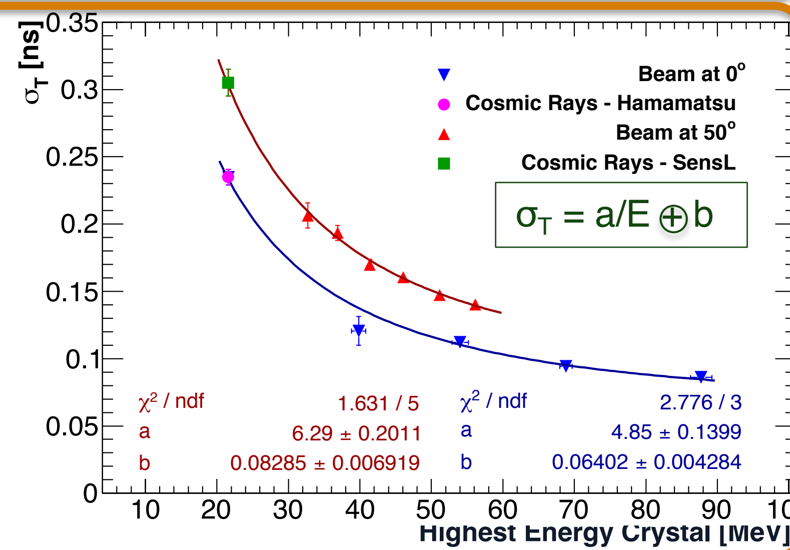


Time response

- Log-normal fit on leading edge
- Constant Fraction method used → CF = 5%







QA of components for production (2018-2019)

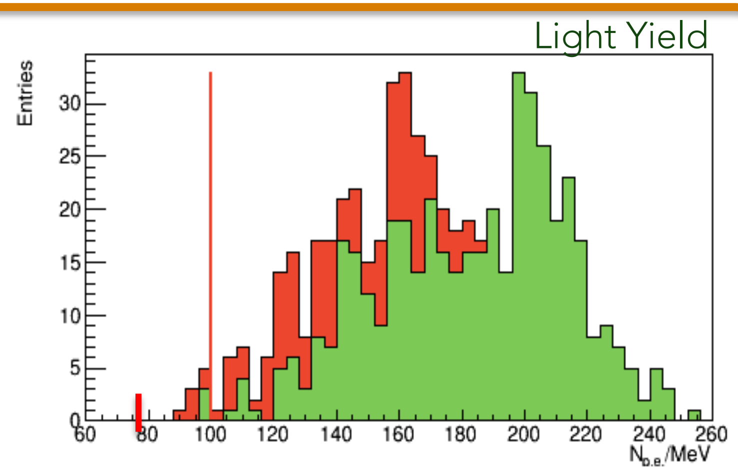
Dedicated QA laboratory at SiDet (FNAL) → production started on March 2018
Additional laboratories for crystals and irradiation testing at Caltech and HZDR

Crystals

More than 1000 crystals already tested from **SICCAS** (rate: 60 crystals/month), **SG** almost same rate

- Optical properties measurements: LY, LRU, resolution, slow component, RIN

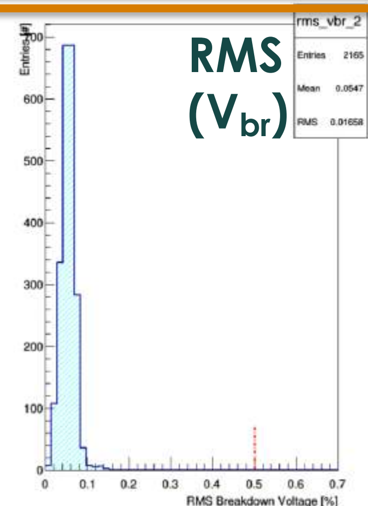
More details on E.Diociaiuti poster

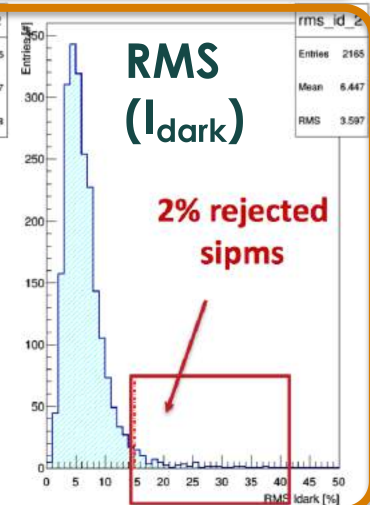


SiPMs

About 3200/4000 Mu2e SiPMs already characterized
Producer: **HAMAMATSU**

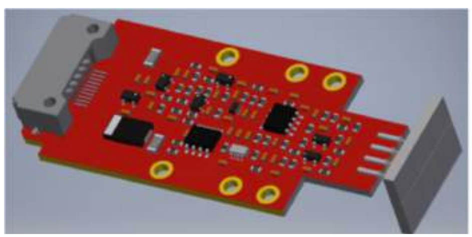
- 280 pieces/month
- All 6 cells tested, measuring $\mathbf{V_{br}}$, $\mathbf{I_{dark}}$, **Gain x PDE**
- **Irradiation with ~1x10^{12} neutrons/cm^2 (MTTF)** test on 5 (15) SiPMs/batch

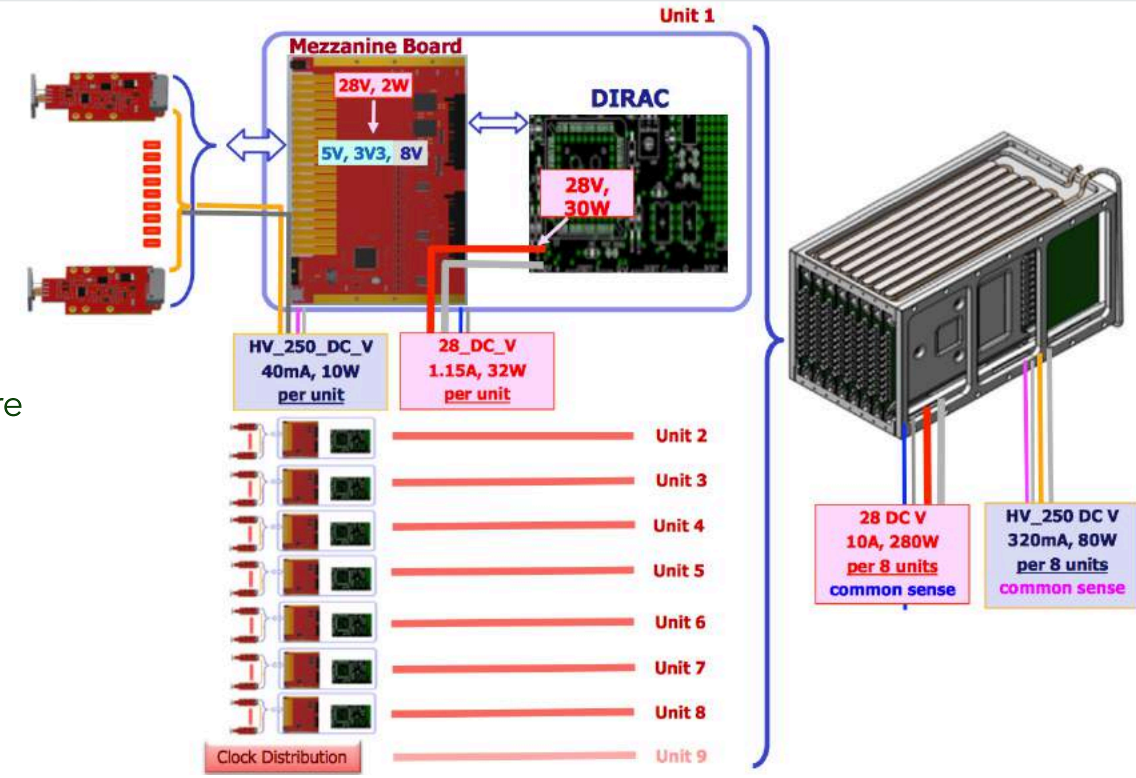




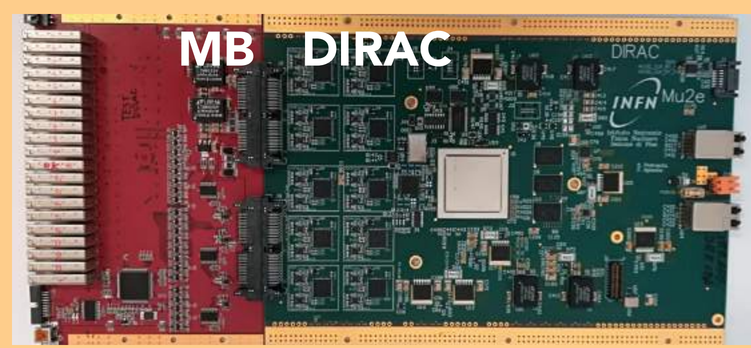
FEE & Digital readout

Dedicated FEE board on each SiPM:
- 2 amplification stages (x 2, x4)
- Linear regulation of bias voltage
- Shaping:
  - → Rise time 50 ns
  - → Full width 200 ns
- 1 V dynamic range
- Monitoring of SiPM currents/temperature
- **rad-hard up to 100 krad**





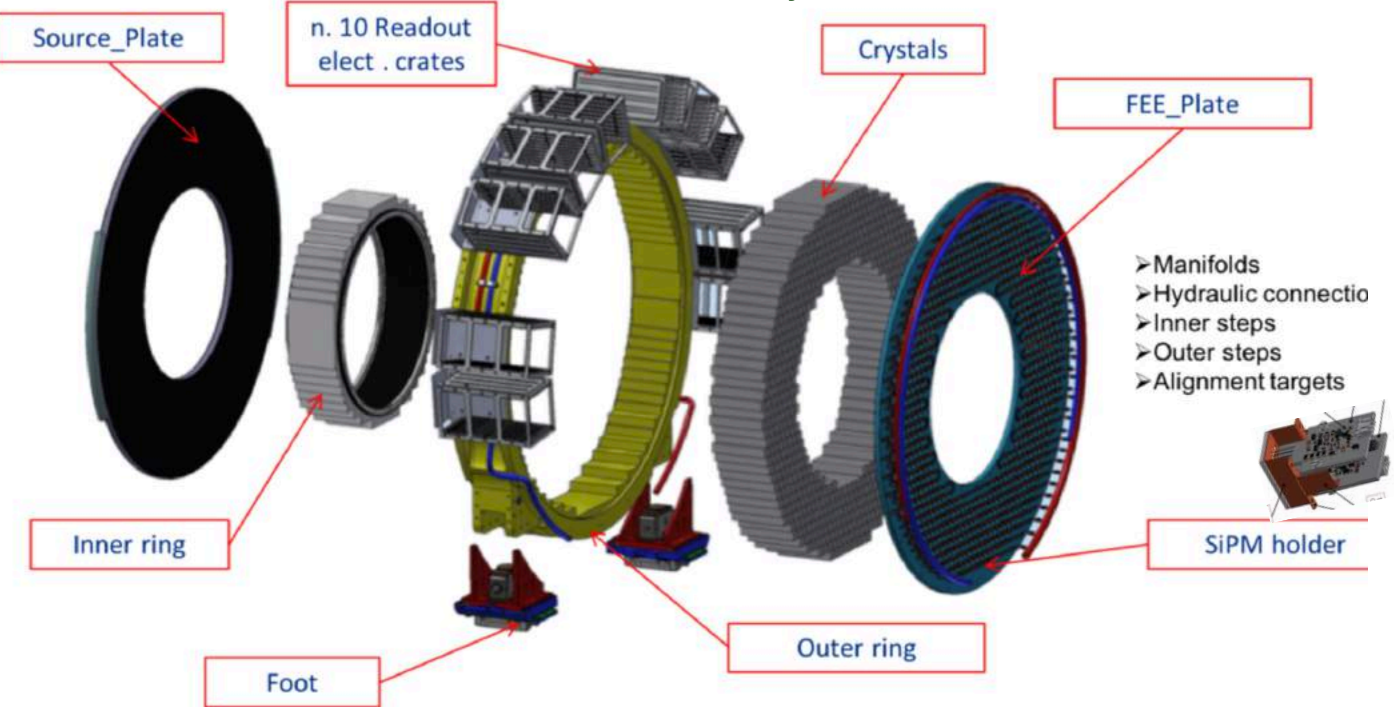
<u>10 crates per disk with 6-8 digital boards/crate</u>
- 20 SiPM+FEE channels per board
- Mezzanine (MB): input FEE signals, HV to SiPMs
- DIRAC board provides digitization at 200 Msps, 12 bit ADC
- DC-DC converter
- VTRX optical readout
- Final Rad-Hard FPGA PF300T→Rad-hard up to **15 krad**



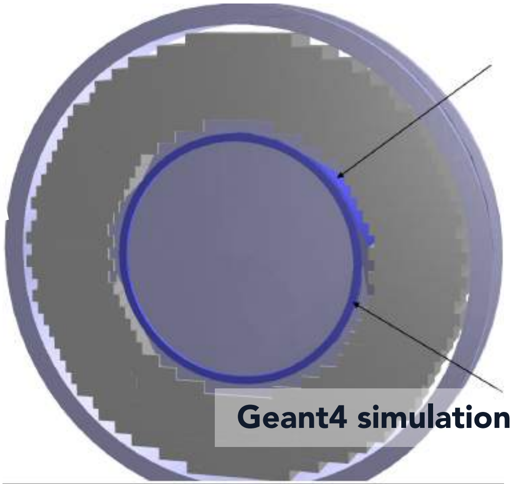
Final Mechanical design

Crystals stacked from the bottom to the top inside an external stainless steel cylindrical support

- FEA completed: good stability, small stress on support legs
- Inner cylinder: composite material
- FEE plate: PEEK
- CF front face with source tubing integrated
- FEE crates mounted on the external cylinder



mockup with fake iron crystals



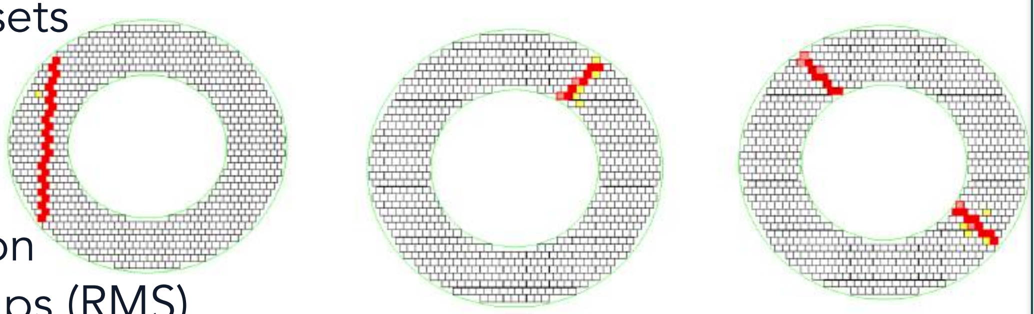
Geant4 simulation

- 2 calibration systems integrated: radioactive source and laser system

Additional IN-SITU calibrations

Cosmic Rays

- dE/dX → equalize and calibrate the energy response;
- Time of flight → to align the time offsets
- Energy scale at O(1%)

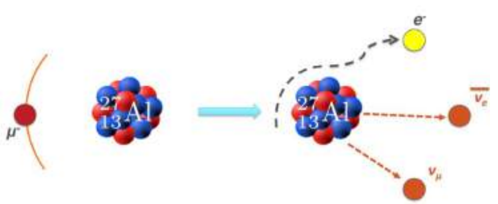


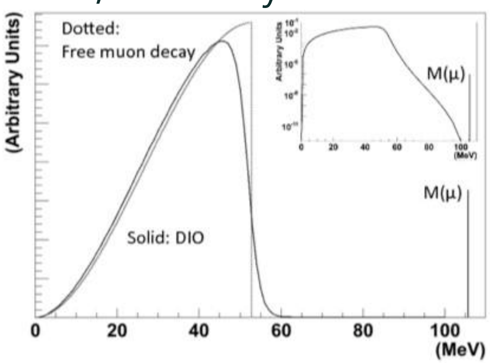
- Estimated time 6 hours
  - Continuous monitor E-T resolution
  - calibrate T_0s @ a level below 30 ps (RMS)

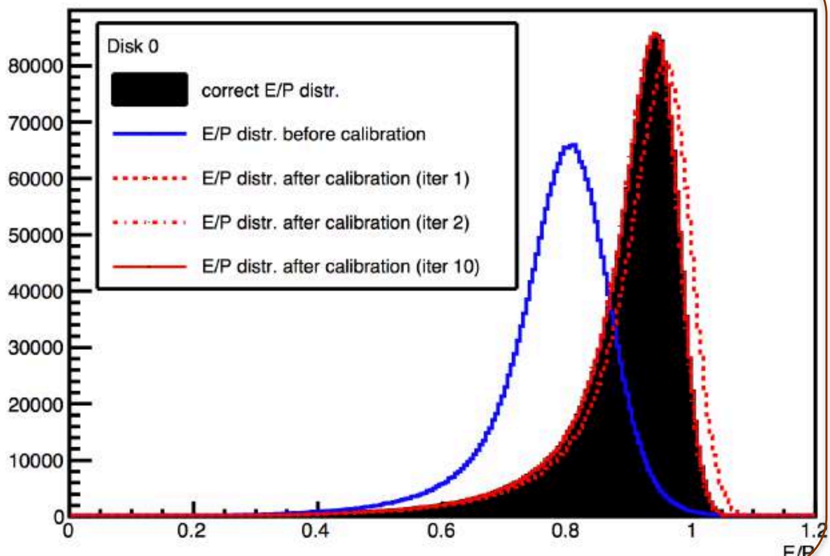
DIO electrons

Calibration relative to tracker measurements

- High energy tracks from DIO electrons
- Absolute calibration at 0.5 T
- Calibration extrapolation to 1 T, accuracy ~ 0.2%

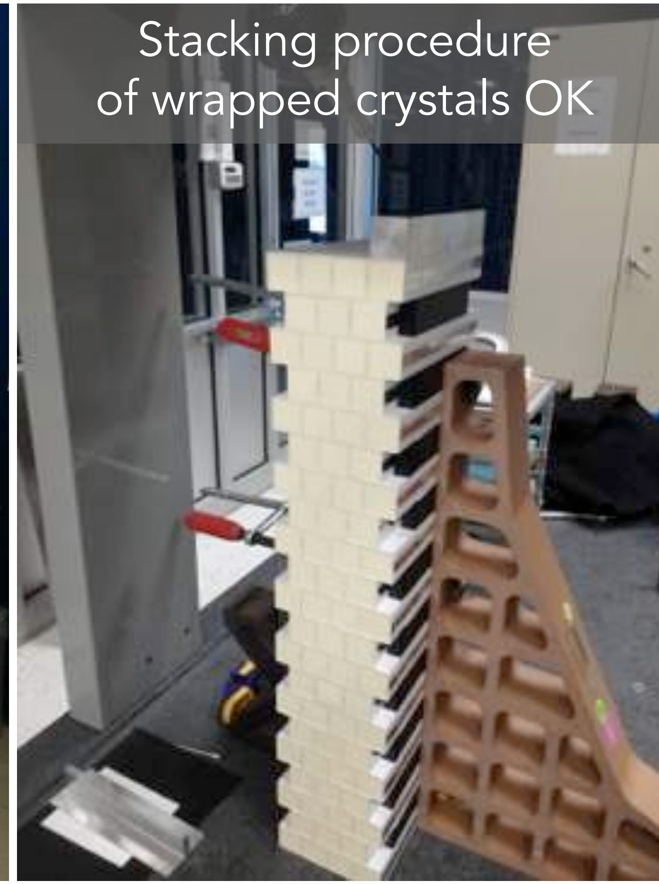






Calorimeter Assembly room

- Assembly Room under construction at FNAL in SiDet
  - Completion scheduled for March 2019



Getting ready to start assembly in November 2019!

Summary and Conclusions

- The Mu2e calorimeter concluded its prototyping phase satisfying the Mu2e requirements:
  - **Un-doped CsI crystals perform well**
    - **Excellent LRU and LY** > 100 pe/MeV (PMT+Tyvek wrapping)
    - τ of 30 ns, negligible slow component
    - **Radiation hardness OK**: 40% LY loss at 100 krad
  - **Mu2e SiPMs quality OK**
    - High gain, high PDE, low I_{dark}, low RMS spread in array
    - SiPMs performance after **irradiation OK → require 0 ° C cooling**
  - **Calorimeter prototypes** tested with e^- beam
    - **Good time and energy resolution achieved @ 100 MeV**

- Calorimeter production phase started March 2018
- Production will end in October 2019, FEE production on summer 2019
- Calorimeter assembly expected by the end of 2019
- **Calorimeter installation in Mu2e experimental hall planned for 2020**

Thanks for listening

Raffaella Donghia

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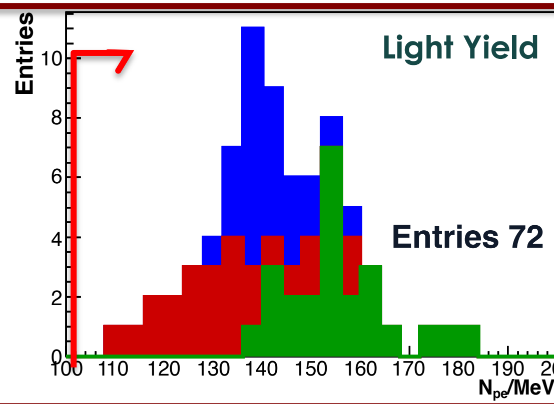
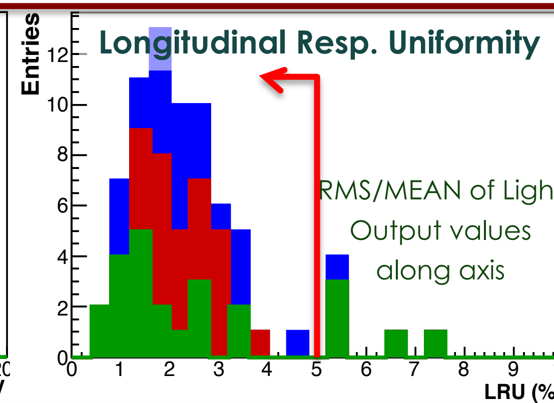
Intense R&D (2016-2017)

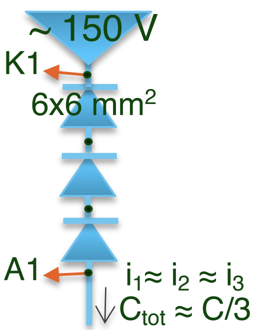
Crystals

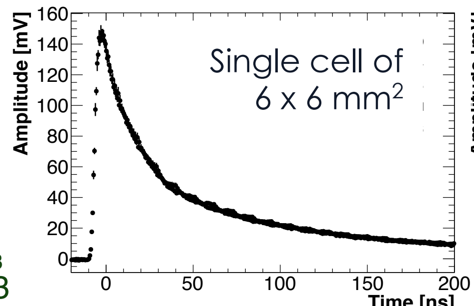
- 24 crystals from SICCAS, Amcrys, Saint Gobain
- Optical properties tested with **511 keV γ's**
- 150 μm **Tyvek**+UV-extended **PMT** readout
- Amcrys discarded for RIN properties

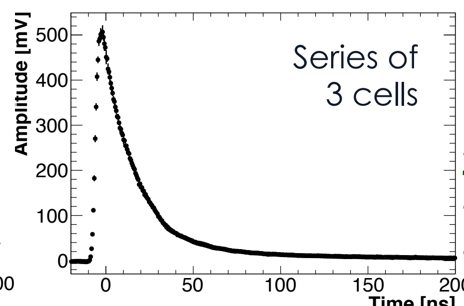




Mu2e-SiPM







Mu2e custom photosensors:

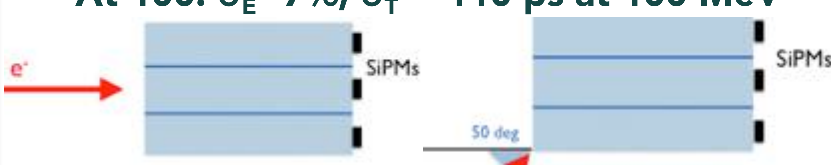
2 arrays of 3 6x6 mm² UV-extended SiPMs

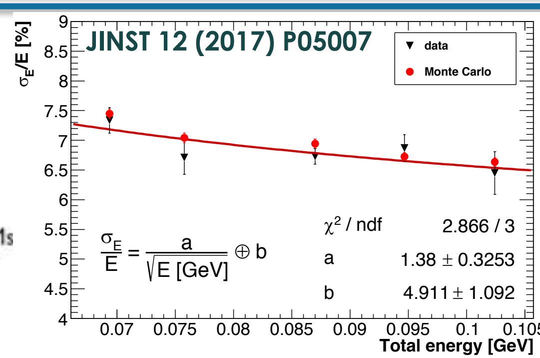
- reduction of the overall capacitance
- faster signals

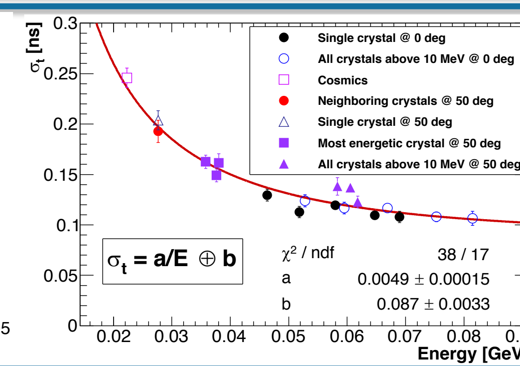
Prototype TB

Small prototype 3x3 tested @ BTF (LNF, 2015)

- **80-120 MeV e⁻**
- **At 100: σ_E~7%, σ_T ~ 110 ps at 100 MeV**







Straw tubes

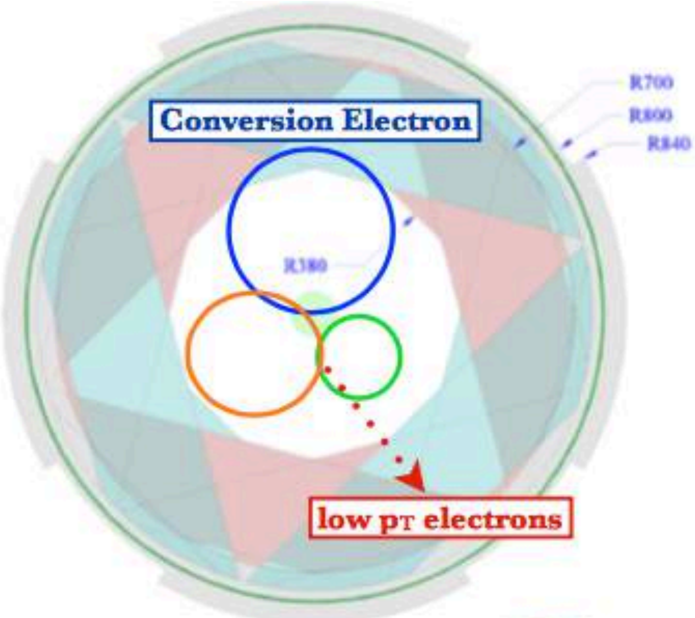
- ~ 20k straws employed in the tracker
- Multiple scattering is the major contributor to dp
  - ✓ straw material budget is comparable to the gas
- Straw specs:
  - ✓ 5 mm diameter, 2x6.25 µm Mylar walls Au and Al coated
  - ✓ 25 µm Au-plated W sense wire
  - ✓ 80/20 Ar/CO_2 with HV ~ 1500 V
- Straw length varies from 44 to 114 cm

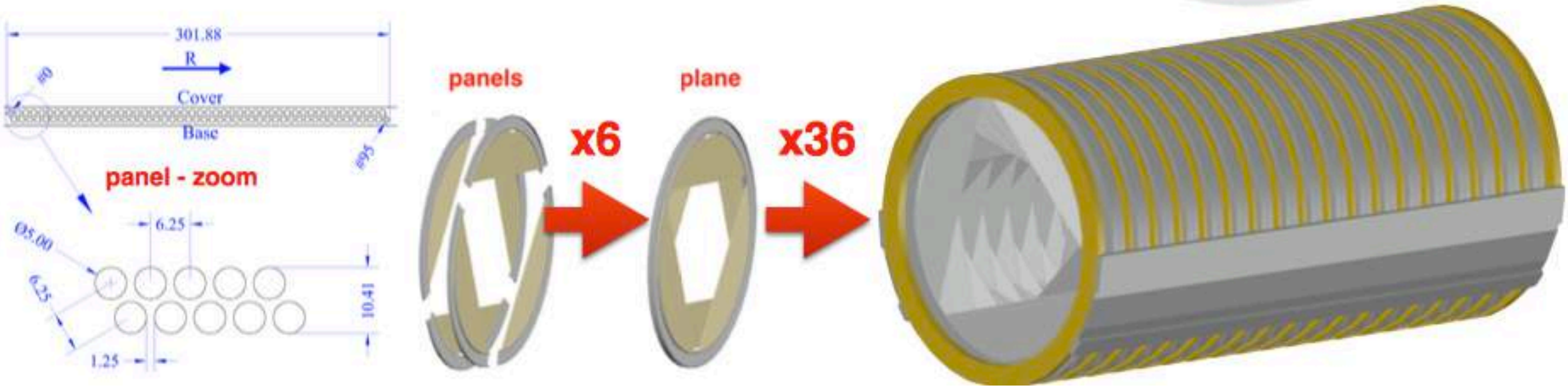
Mylar roll

straw tube

Straw tube tracker

- 36 double-layer planes equally spaced with straws transverse to the beam
- Inner 38 cm un-instrumented:
  - ✓ blind to beam flash
  - ✓ blind to >99% of the DIO spectrum
- Expected resolution:
  - ✓ ~ 200 keV/c @ 105 MeV

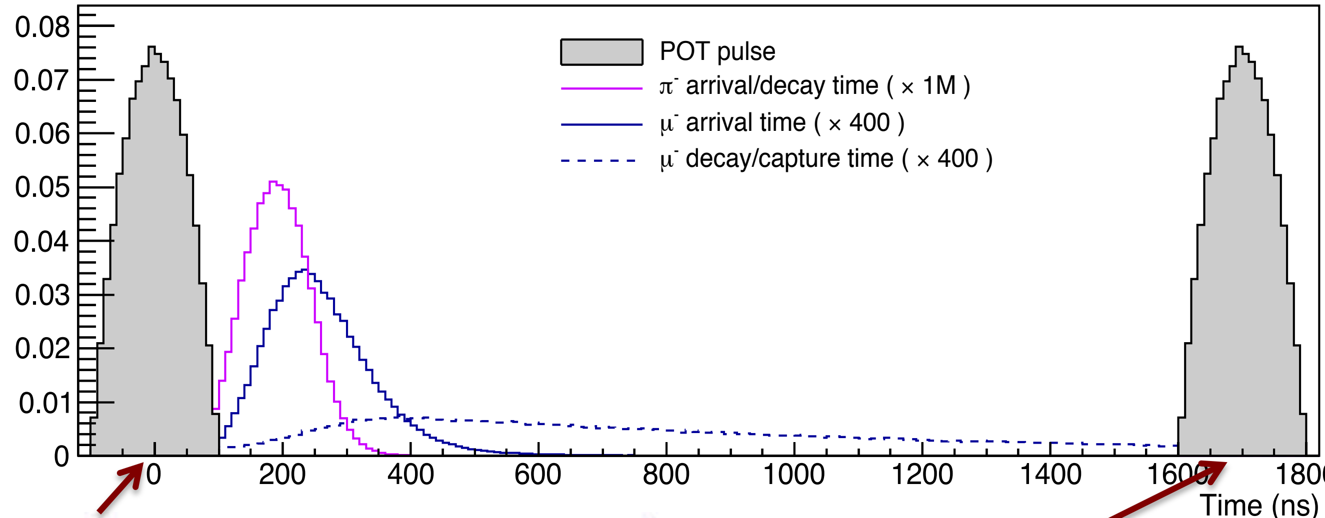


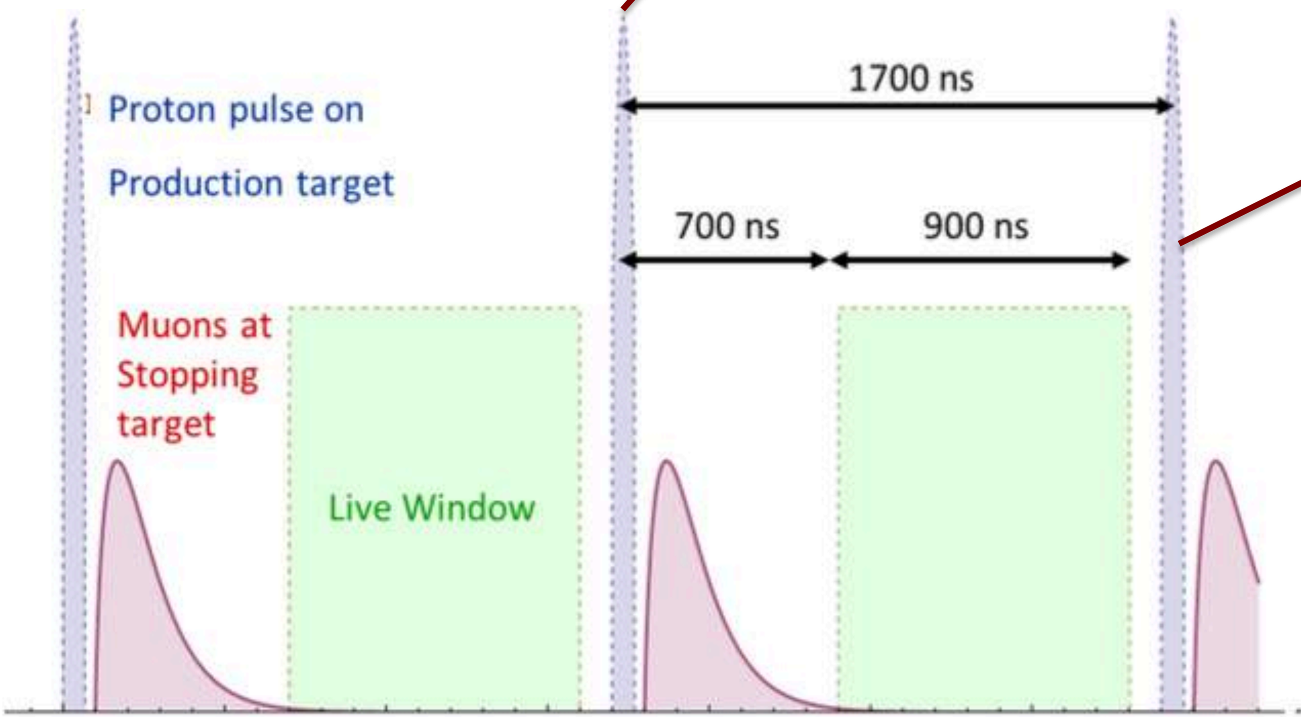


Background

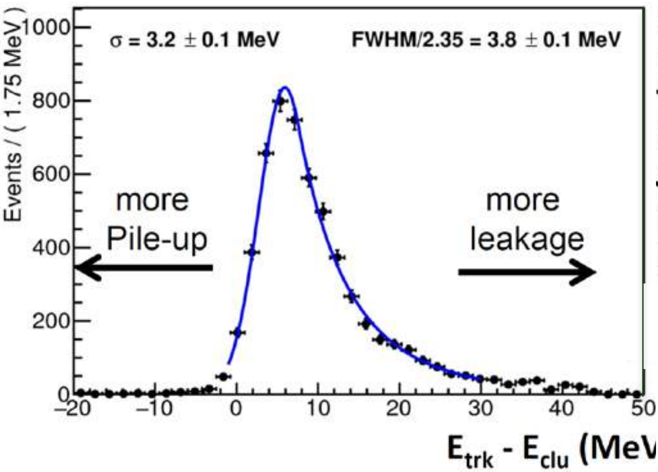
	Source	Scale with	Solution
Intrinsic	**decay-in-orbit**	**# of stopped-μ**	**Tracker resolution**
Beam	radiative π capture	closeness to beam pulse	pulsed beam
Running time	Cosmic ray	live time	veto system & PID

Beam structure

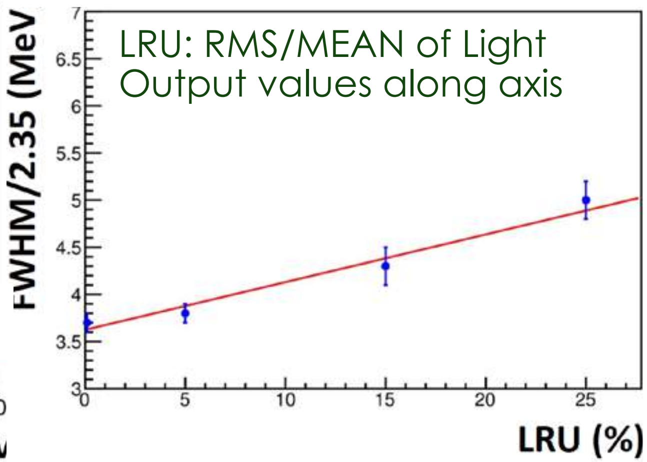


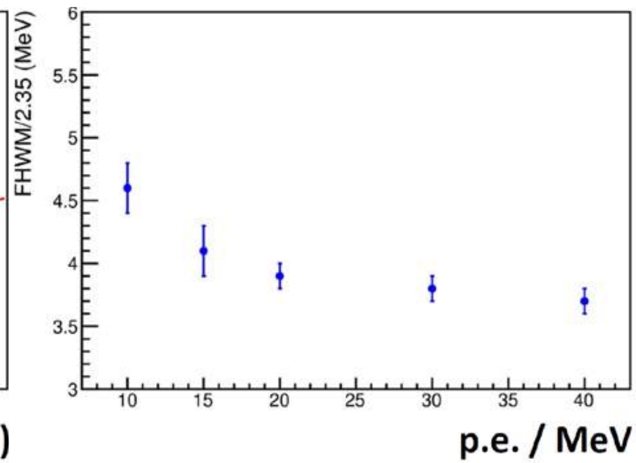


Simulated performance



FWHM / 2.35 = 3.8 ± 0.1 MeV





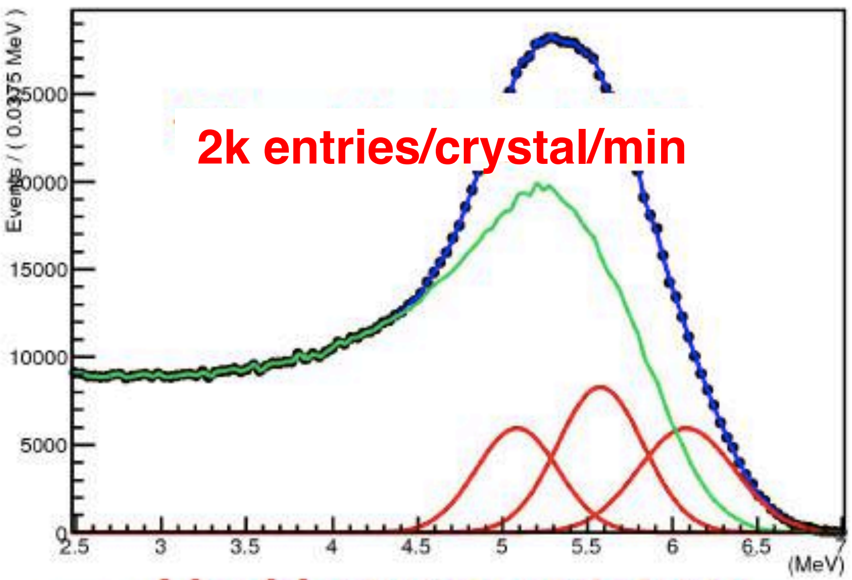
	LYSO	BaF2	CsI
Radiation Length X_0 [cm]	1.14	2.03	1.86
Light Yield [% NaI(Tl)]	75	**4**/36	3.6
Decay Time[ns]	40	**0.9**/650	20
Photosensor	APD	**RMD APD**	SiPM
Wavelength [nm]	402	**220**/300	310

Simulation includes full background

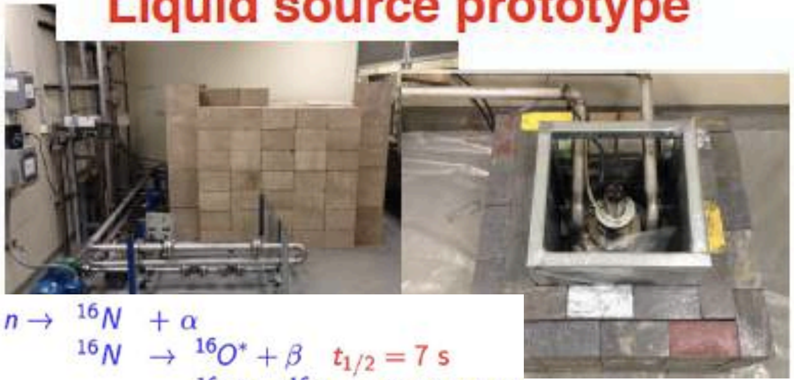
- The overall resolution depends on properties of the crystals
- Several crystals considered

Calibration source and laser

Liquid source FC 770 + DT generator: 6 MeV + 2 escape peaks → **E-scale**

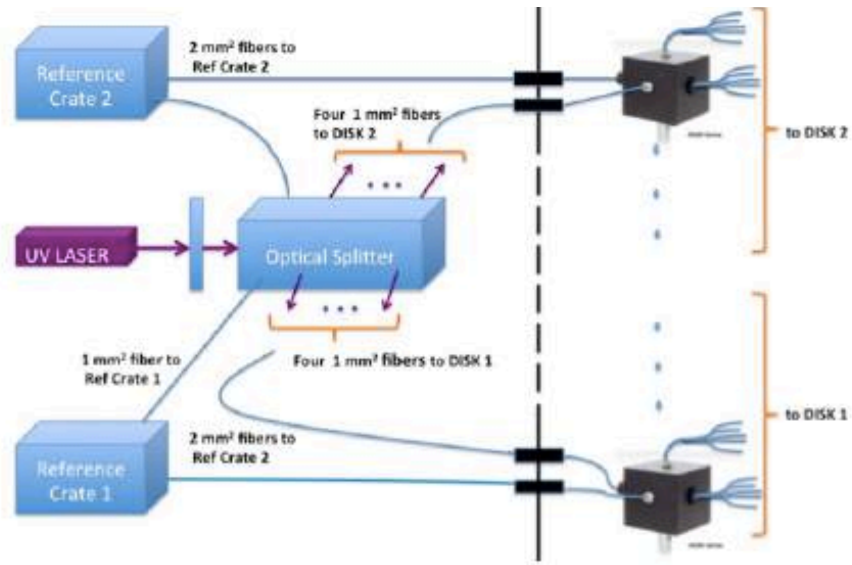


Liquid source prototype



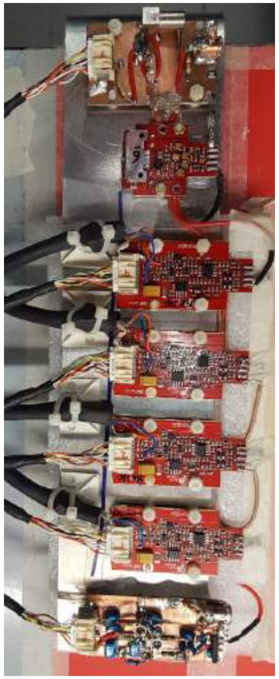
$$^{19}F + n \rightarrow {}^{16}N + \alpha$$
$$^{16}N \rightarrow {}^{16}O^{*} + \beta \quad t_{1/2} = 7\ s$$
$$^{16}O^{*} \rightarrow {}^{16}O + \gamma(6.13\ \text{MeV})$$

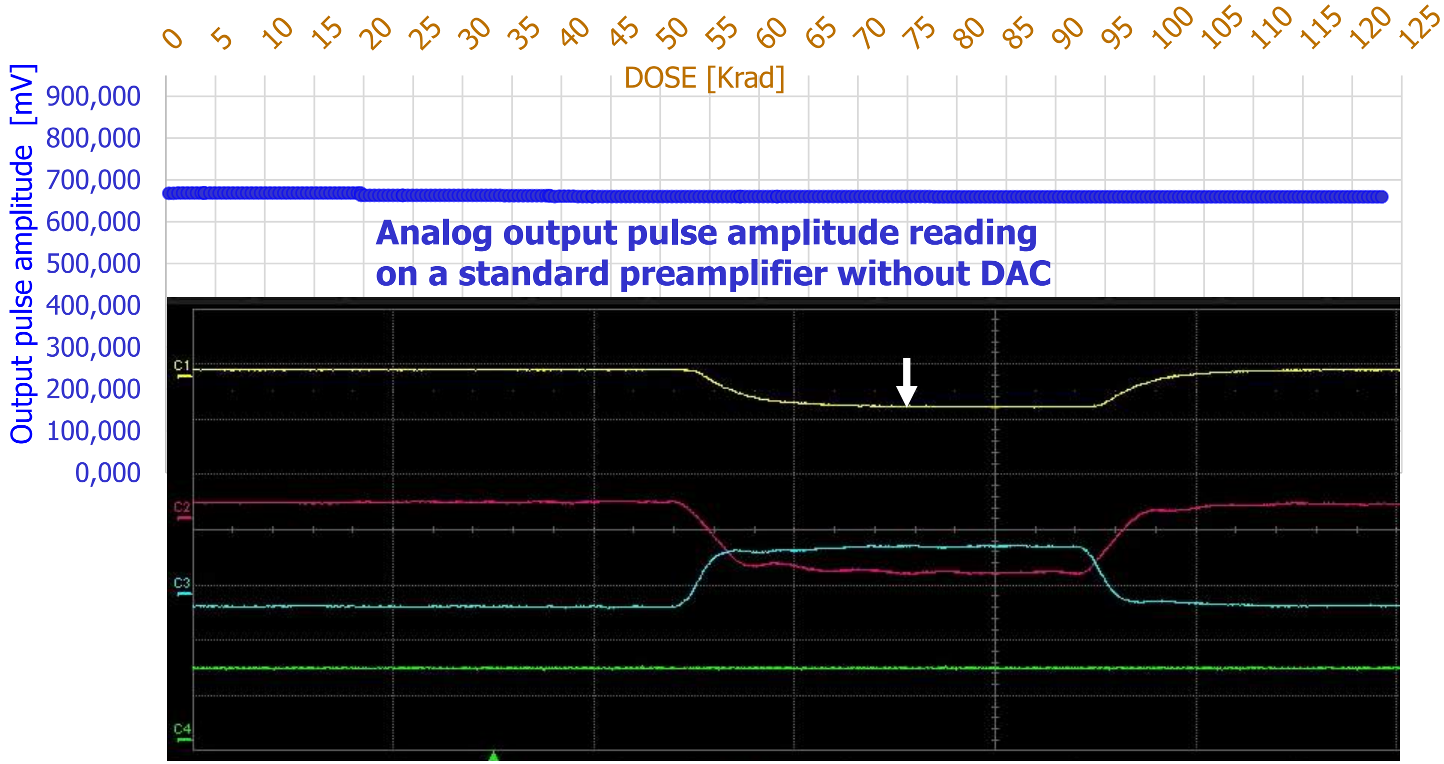
Laser system to **monitor SiPMs gain** and timing performance



Laser system - test station

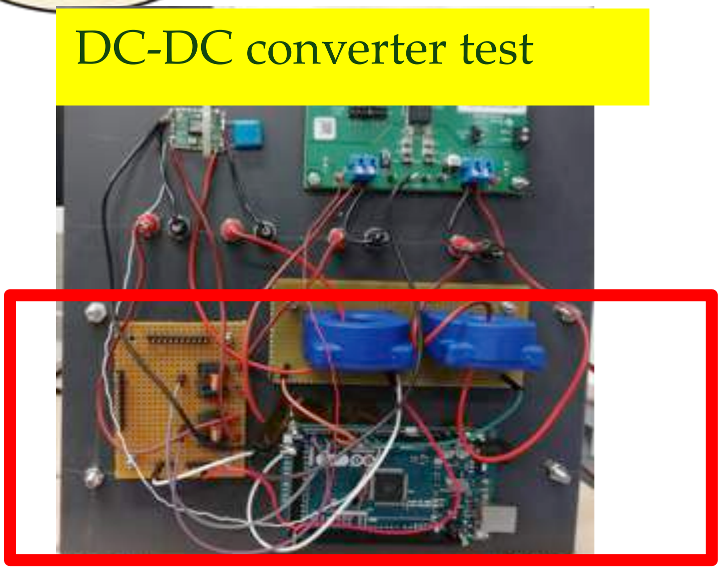
Electronics: FEE test up to 120 krad

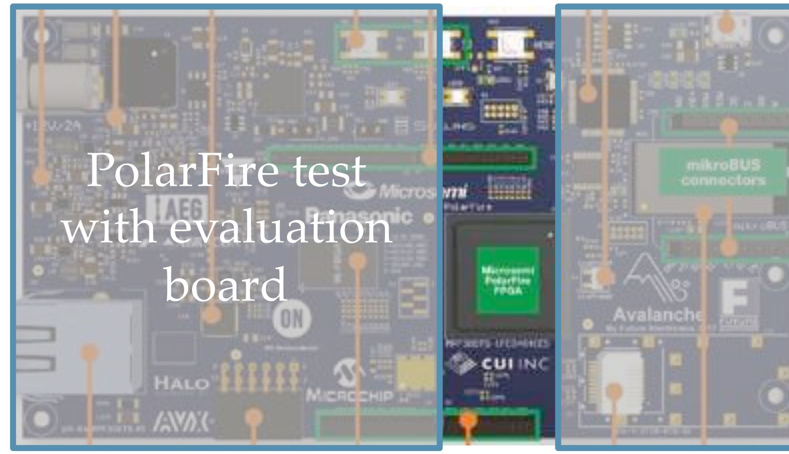




- ❑ all analog parts of Amplifier and HV regulator OK
- ❑ LT ADC/DAC of digital session suffering from 10-15 krad up
- ❑ new rad-hard ADC/DAC identified from Texas Instrument
- ❑ PCB with TI ADC/DAC ready for new irradiation test ➔ 28 January

Electronics: DIRAC test up to 80 krad





- ADC and jitter cleaner tested up to 40 Krad. OK
- Polarfire: routing and logic delays measured. No changes up to 77 Krad. Reprogrammability checked at 53 Krad still ok. Problems > 77 looks due to DC DC converter
- DCDC converters: LTM8053 OK up to 50 Krad, LMZ31710 broke at 32 Krad two times. **Both still ok for ECAL.** Test in B field to be repeated

Summary CsI production

SICCAS

- 622 crystals received /725 = 86%
- **Rejection factor 3%**

End of SICCAS production: Apr 2019

→ StGb getting stabilized

→ October 2018: 25 crystals received with high rejection factor: 41%

→ Dec 18: 63=25+38 crystals received

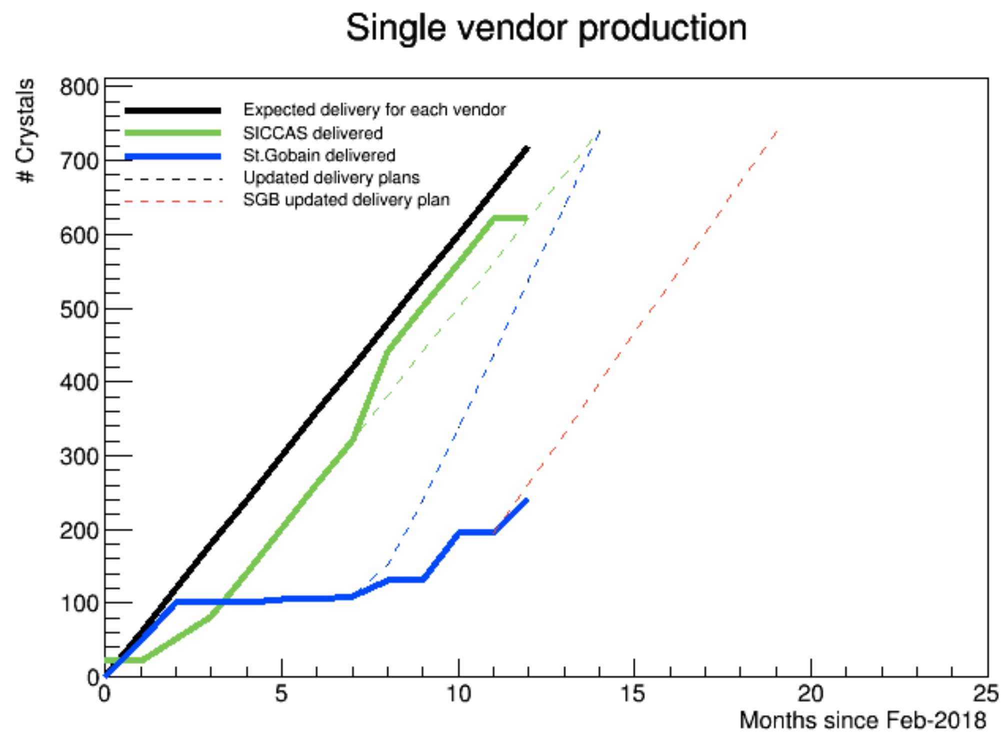
Rejection factor = 10/63 = 16%

⇒ End of January +48 crystals

⇒ Very good quality + 30 arrive this week

Bi-weekly phone call established

End of SgB production ➔ Oct 2019



	Siccas	St.Gobain	Total
Shipped	**622/725**	**242/725**	**864/1450**
Arrived	622	242	864
CMM + inspection	622	242	864
Sent to Caltech	184	16	210
Back to Vendor	**13**	44+20	73
Irradiation at Caltech	8	-	8

SiPM production

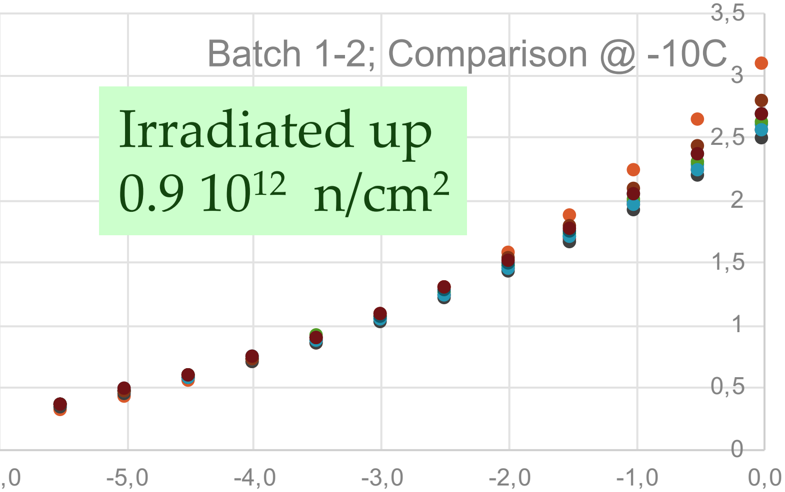
- ❑ All 12 shipments of the standard production (3360) received
- ❑ Schedule is to complete QA production test for end of March.
- ❑ Two additional shipments expected with the schedule of of completing their QA in May 2019 and reach 4000 sensors

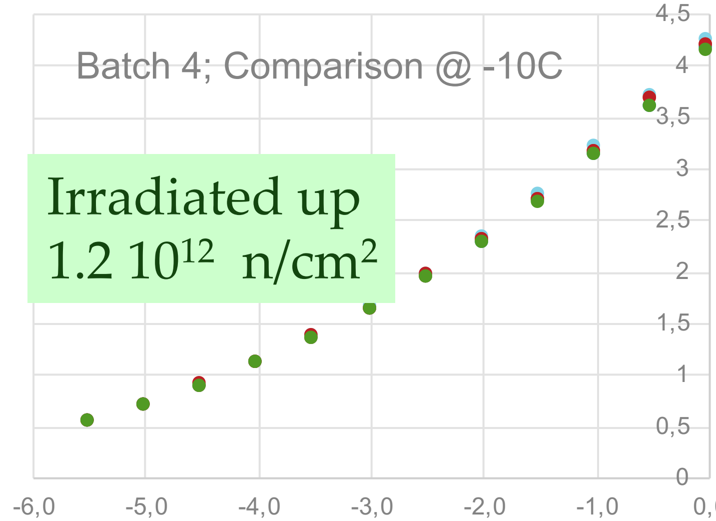
Up to yesterday:

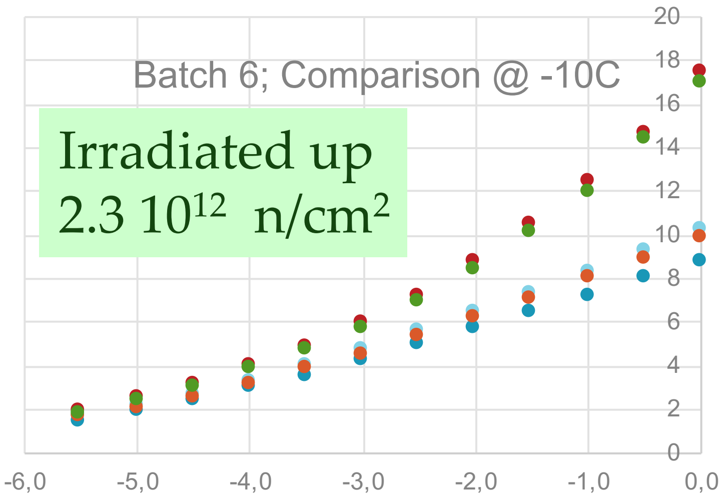
- ➔ Geometry checked: Batch # 12 (3360)
- ➔ QA station (Idark, I-V and Gain) checked: Batch # 10 (2750)
- ➔ Irradiation test up to batch #7 (see next page)
- ➔ MTTF test keep working w.o. deads ..

→ MTTF > 10 million hours

SiPM irradiation with neutron





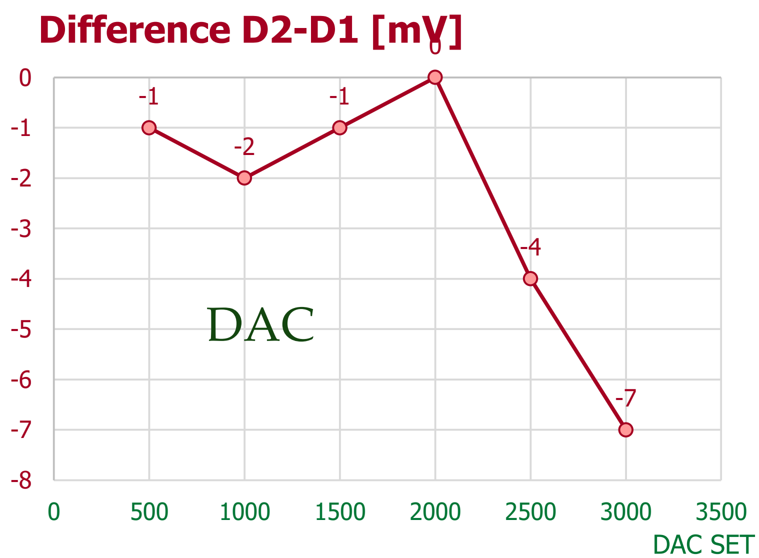


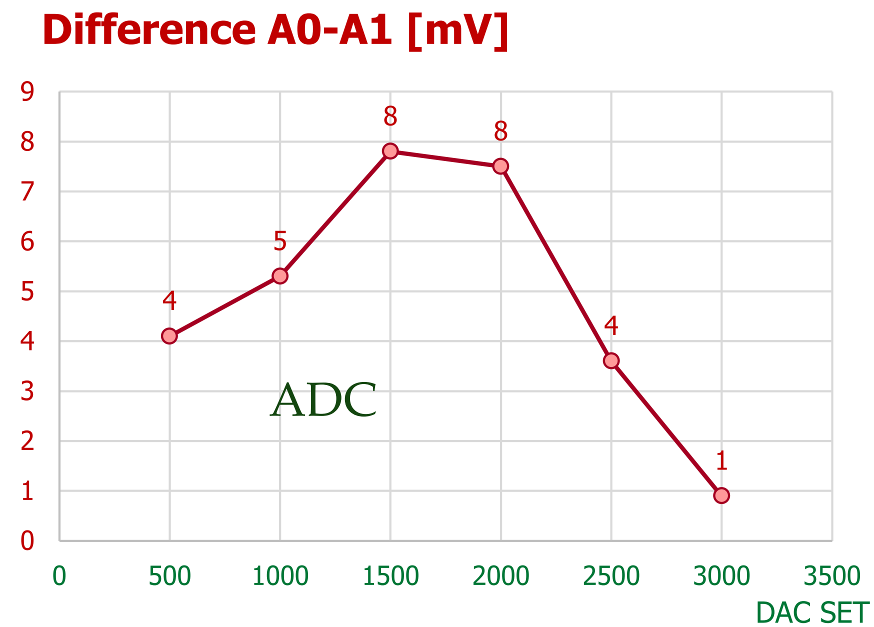
- 5 SiPMs/batch "passively" neutron irradiated @ Dresden
- For Mu2e, the max n-flux in SiPM area is of around (4)x10^10 n/cm^2
- Safety Factor 3(MC)x5(Years)x2(Prod) = 1.2 10^12n/cm^2
- Max Idark current for operation of 2 mA

➔ Requires cooling of -10 C, Lower operation overvoltage to Vop-3V (for the MU2E serie) , 20% of PDE relative loss

FEE ADC/DAC test up to 120 krad

- all analog parts of Amplifier and HV regulator are rad-hard but LT ADC/DAC of digital sector suffering from 10-15 krad up → new rad-hard TI ADC/DAC identified
- PCB with TI ADC/DAC completed
- **1 week of gamma irradiation done @ end of January up to 110 krad**



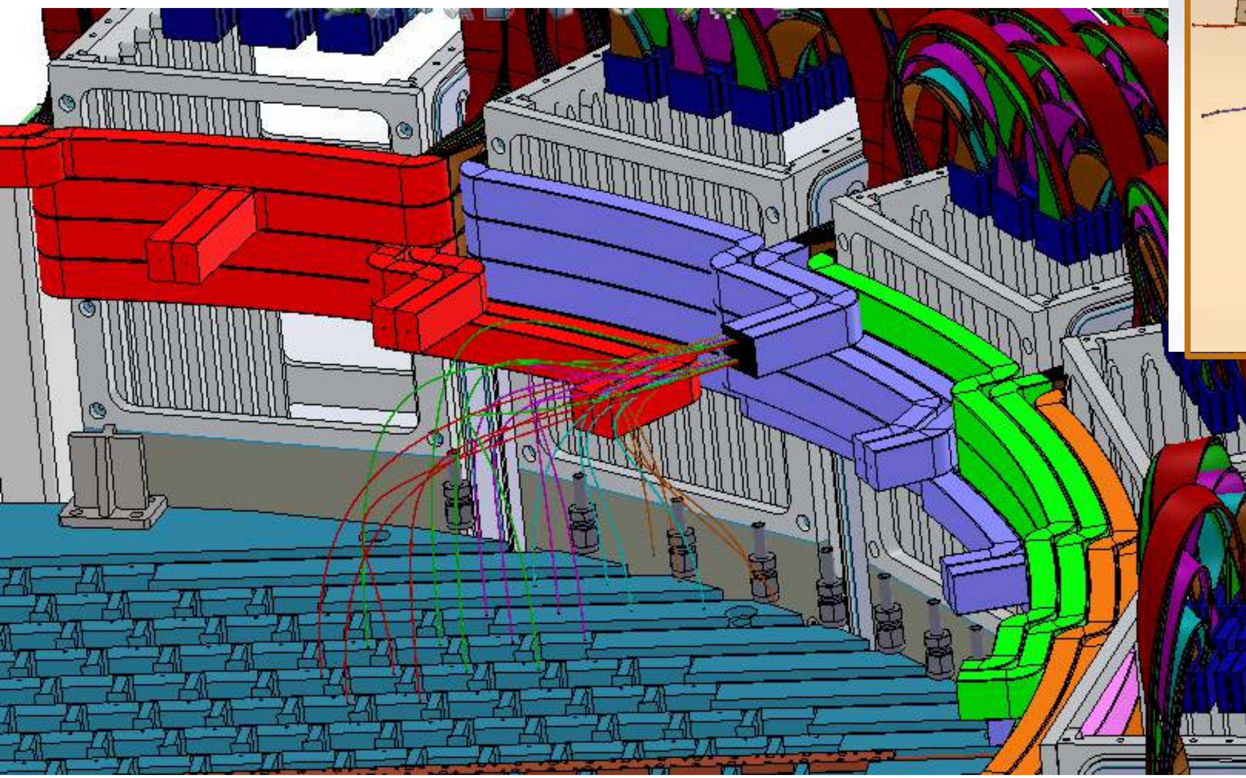


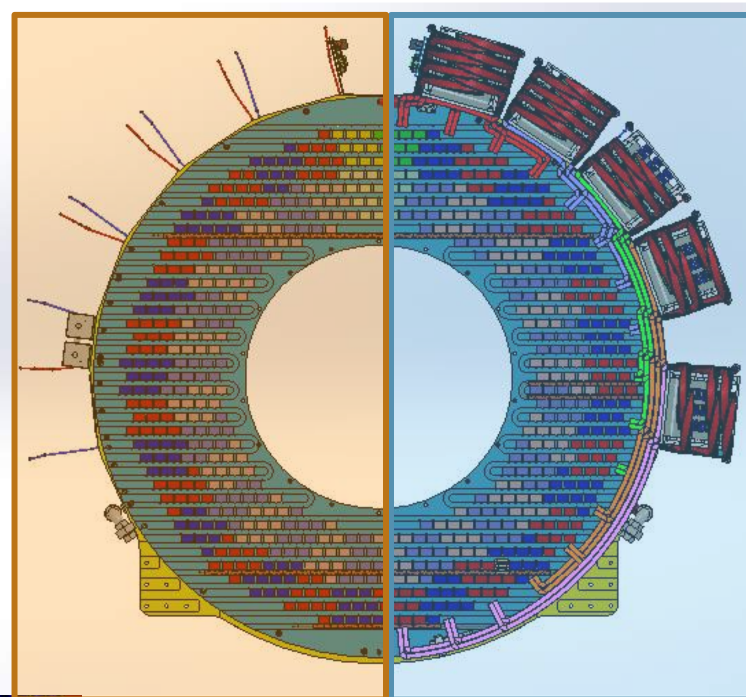
- Maximum deviation of ADC and DAC before and after irradiation
- Consistent with TI specifications

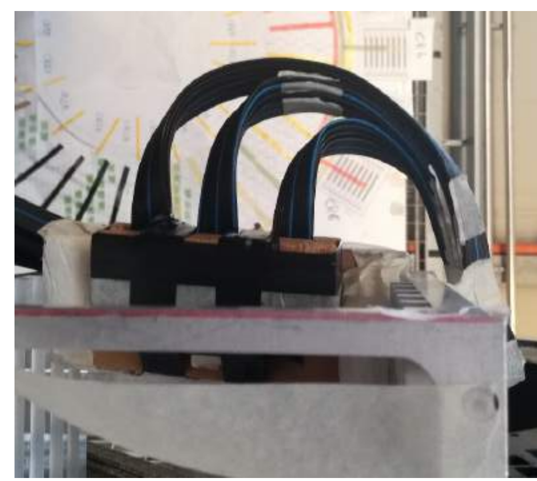
Mechanical integration:FEE+MB cabling

- → FEE rad-hard chip format frozen
- → New cable selected to handle rad-hard ADC/DAC
- → Routing of FEE-MB cables in CAD model
- → First realistic estimate of cable lengths, weights

  4 km cables , 55 kg/disk
- → Final mockup in progress



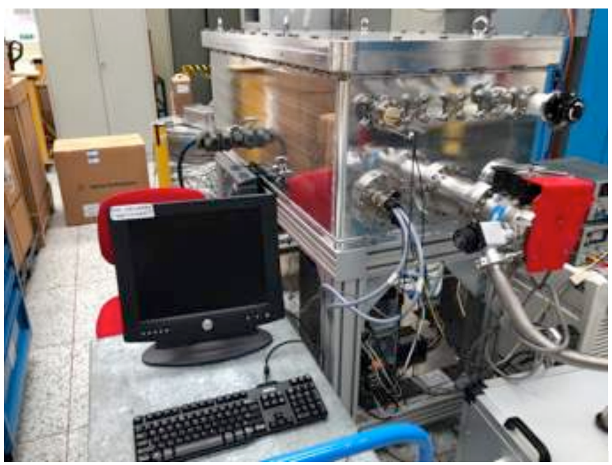


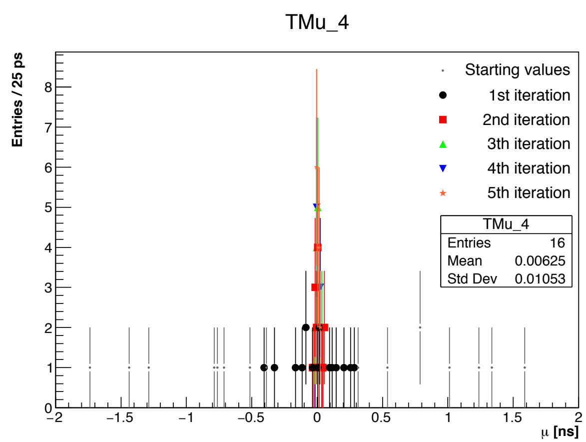


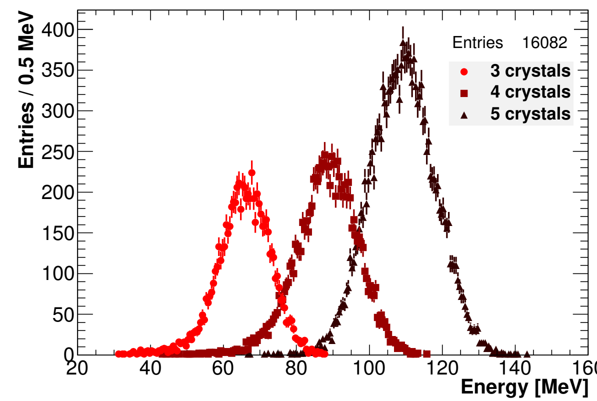
Electronics – Slice test

- Next round of measurement with TID for FEE planned for end of November in Italy. Also FPGA polar fire for digital board will be tested
- Version v3 of FEE and V2 of DIRAC are under way to get them much radiation dose harder
- Aiming for CRR for electronics in spring 2019
- Vertical slice test planned with FEE-v2 and Dirac-V1 in December with 20 channels of Module-0

SLICE test with FEE-V1 and CAEN digitizer



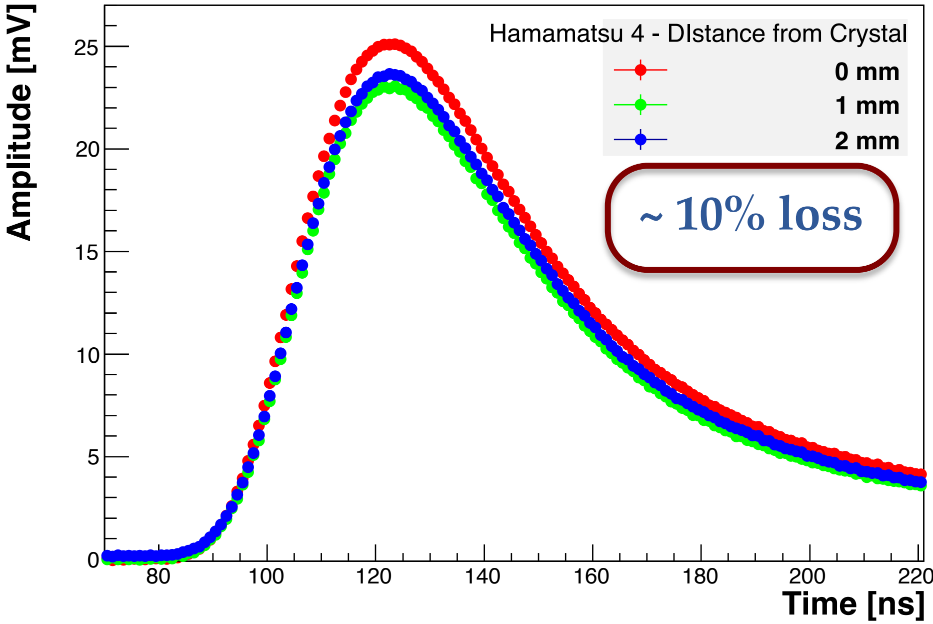




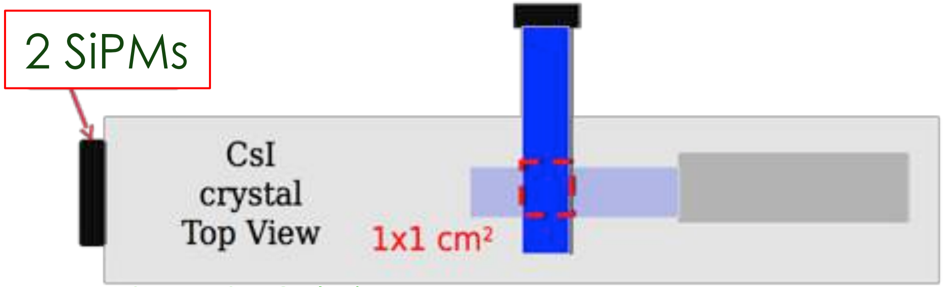
Single channel slice test

SG crystal + Hamamatsu SiPM + FEE
Optical coupling in air.

- **^{22}Na source**
  - TRG: small scintillator readout by a PMT
  - Study distance effect for air-coupling



- **Cosmic ray test** → 2 SiPMs readout
  - TRG: crystal between 2 small scintillators



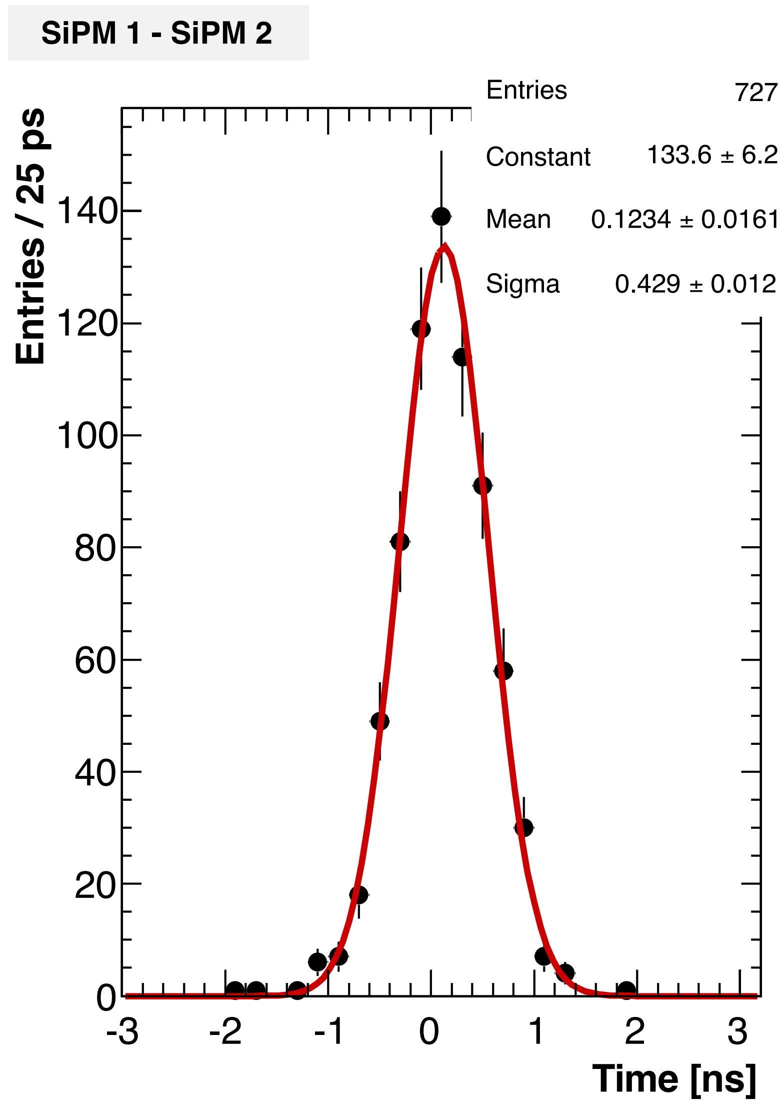
Single channel Cosmic Rays Test

- TRG time resolution ~ 170 ps
- Constant fraction method used
- Pulse height correction applied (slewing)

After jitter subtraction:
SiPM 1 – σ_T ~ 330 ps
SiPM 2 – σ_T ~ 340 ps

T(SiPM1 - SiPM2)/2 → ~ 215 ps
@ ~ 23 MeV energy deposition
(MIP energy scale from Na^{22} source peak)

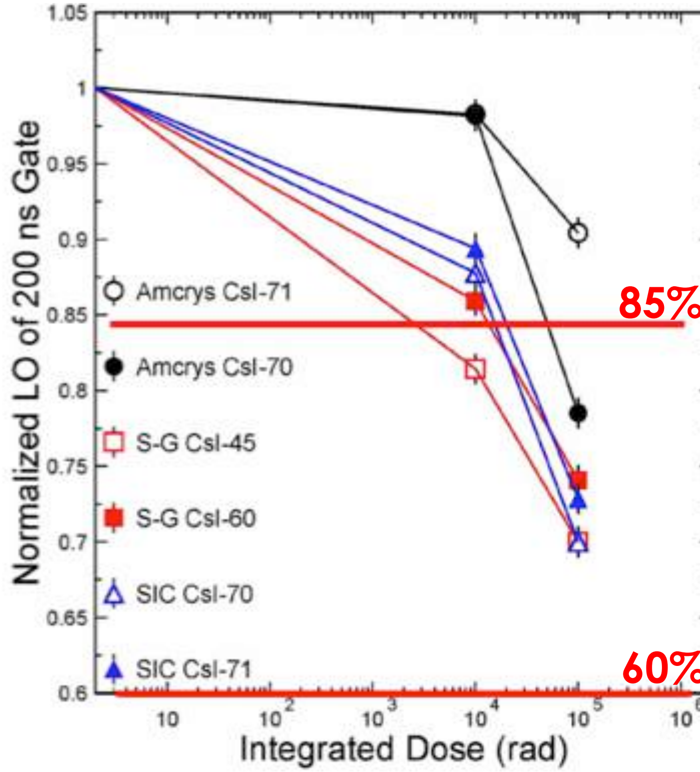
Timing result well compares with old tests:
→ Reduced light output/SiPM (22 vs 30 pe/MeV)
→ 2 SiPMs/crystal
→ LY of 44 vs 30 → 215 ps (now) vs 250 ps (old).



Pre-production test: Crystals (2)

Few samples per vendor have been exposed both to **ionizing dose** and **neutrons**

- Irradiation test up to 100 krad
- Requirement:
  normalized LY **after 10/100 krad > 85/60%**

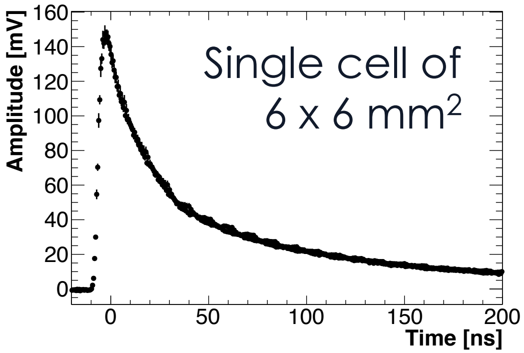


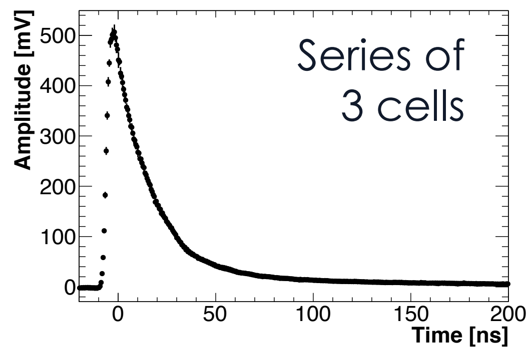
Most crystals have LY larger than 100 p.e./MeV after 100 krad (40% max. loss), promising a robust CsI calorimeter

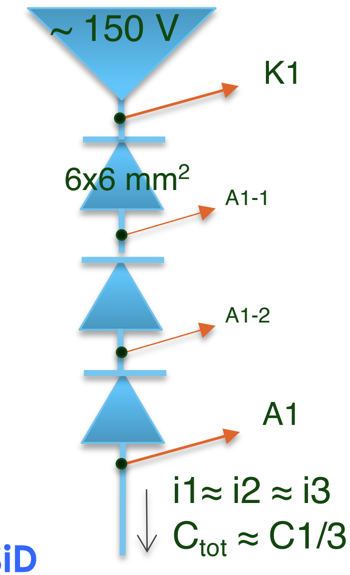
- **Radiation Induced Noise** (RIN) @ 1.8 rad/h required is **< 0.6 MeV**
  - All 72 samples tested. All OK apart some Amcrys crystals that do not satisfy the required limit
- Negligible LY and LRU variation after **1.6 x 10^{12} n_{1MeV}/cm^2 integrared flux**
- Neutron RIN is also smaller than the one from dose

Pre-production SiPMs

Mu2e custom silicon photosensors:
→ 2 arrays of 3 6 x 6 mm² UV-extended SiPMs: total area (12x18) mm²
The readout series configuration reduces the overall capacitance→faster signals

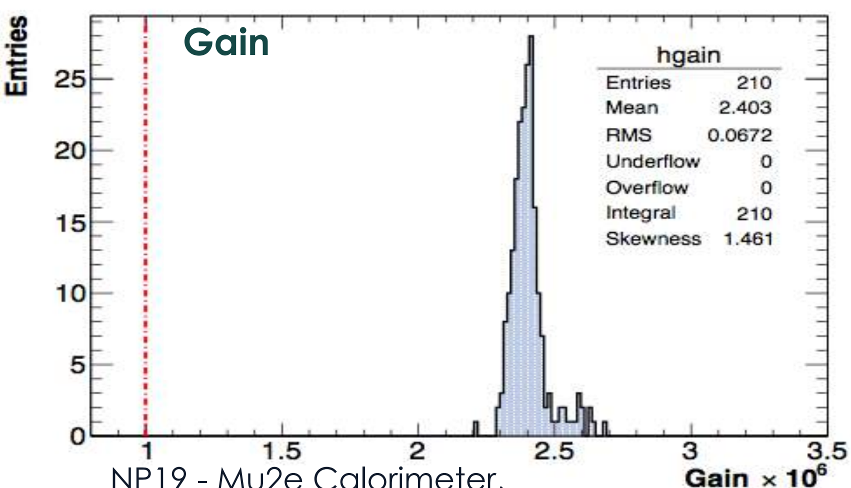


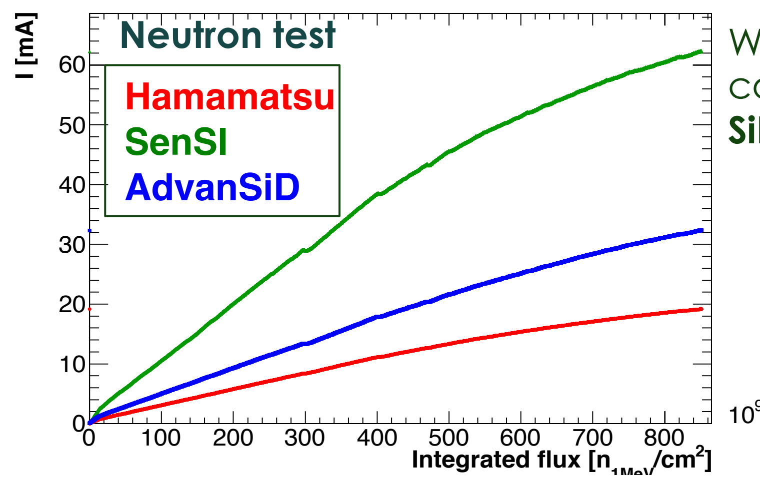




150 sensors: 3×50 Mu2e pre-production SiPMs from **Hamamatsu**, **SenSl** and **AdvanSiD**

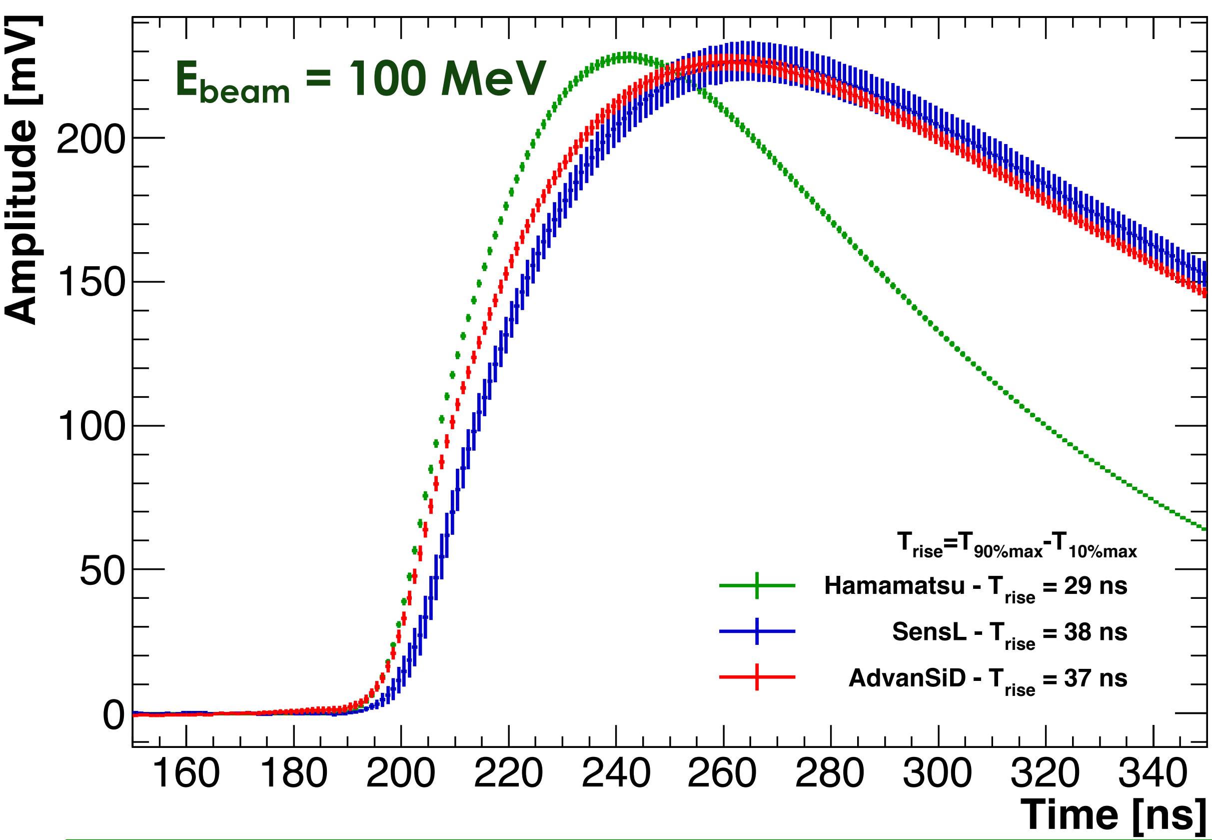
- 3×35 were fully characterized for all six cells in the array

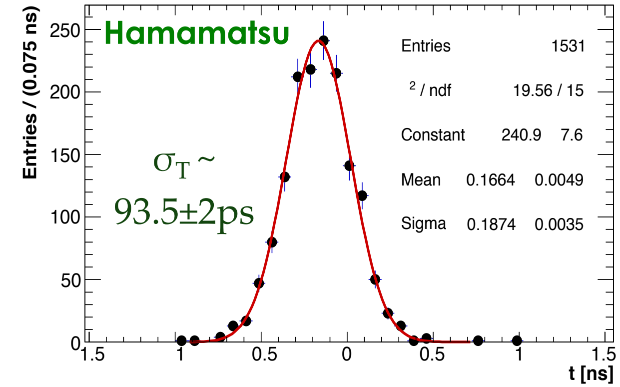


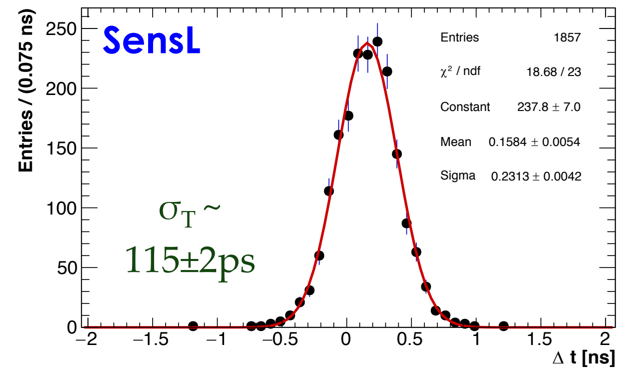


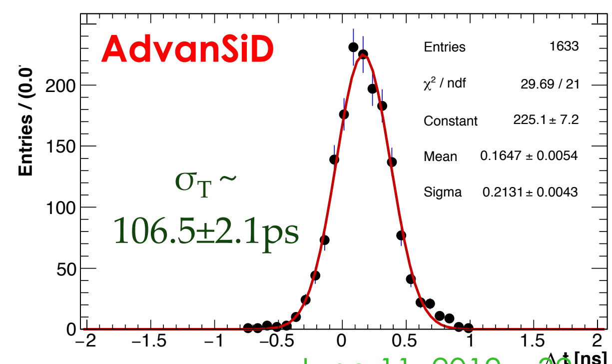
We need to cool down **SiPMs at 0 °**

Module 0 SiPM-vendors comparison









$$\sigma^2_{tot} = \sigma^2_{Landau} + \left(\frac{t_{rise}}{S/N}\right)^2 + \left(\left[\frac{V_{thr}}{S/t_{rise}}\right]_{RMS}\right)^2$$

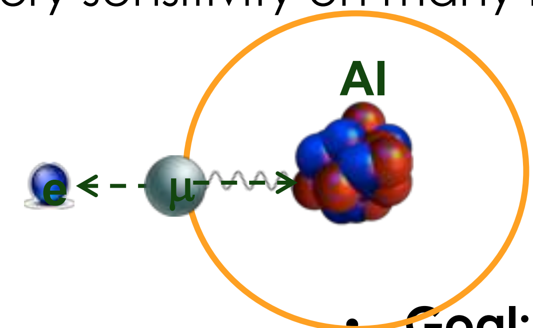
Energy fluctuation

CF discriminator

Charged Lepton Flavor Violation

- CLFV strongly suppressed in SM: BR ≤10^{-54}
  → Observation indicates New Physics

- CLFV@Mu2e:μ- e conversion in a nucleus field
  → discovery sensitivity on many NP models



- **Goal:**

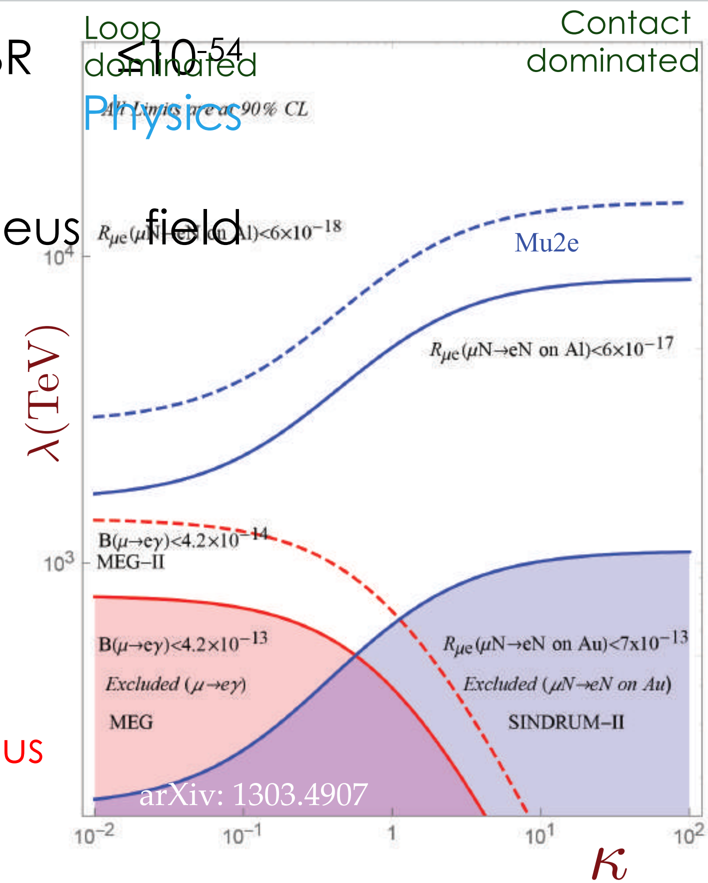
10^4 improvement w.r.t. current limit (SINDRUM II)

μ-e conversion in the presence of a nucleus

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

Nuclear captures of muonic Al atoms

(@ 90% CL, with ~ 10^{18} stopped muons in 3 years of running)

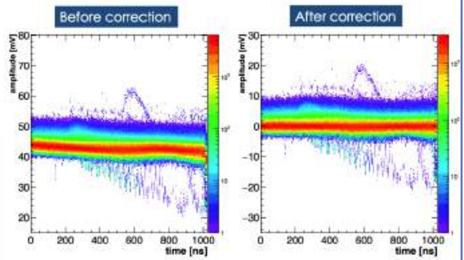


Module 0
Event selection

Pedestal correction: Results

- The integration range reduced to(150,400) ns
- Pedestal distribution reduction **better than a factor 2**

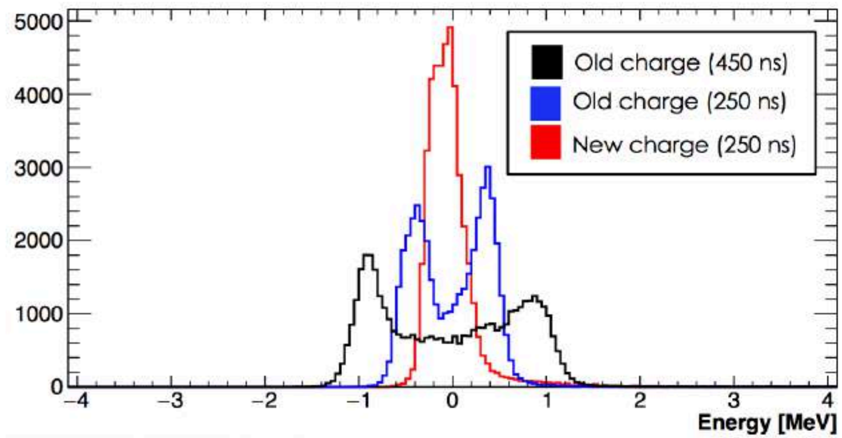
Example of pedestal correction



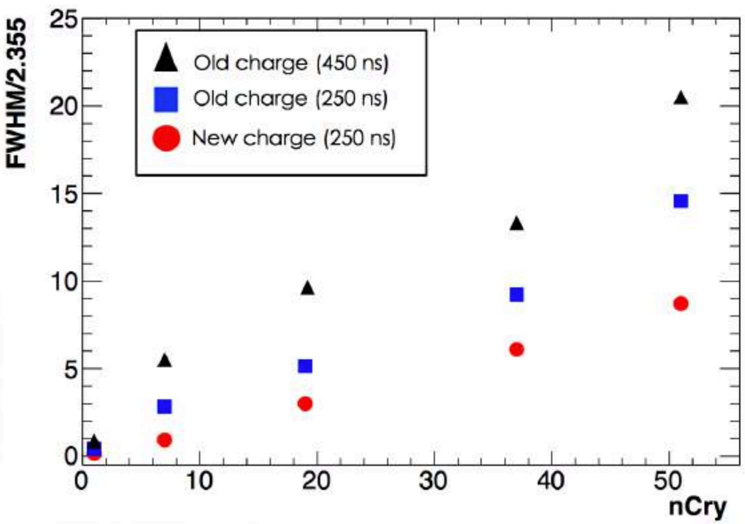
FWHM/2.355 = 0.870 MeV

FWHM/2.355 = 0.148 MeV

FWHM/2.355 = 0.424 MeV



Pedestal energy vs Crystal number

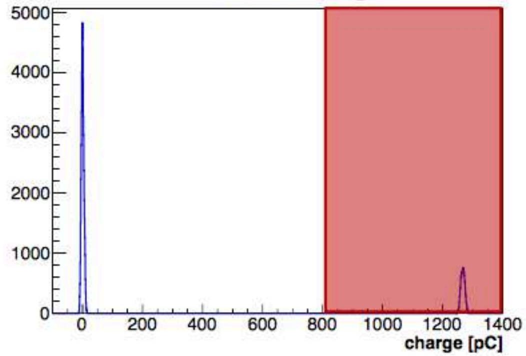


Noise width in the new charge increase linearly with the number of crystals added

Module 0
Event selection

1)We reject events with laser trigger

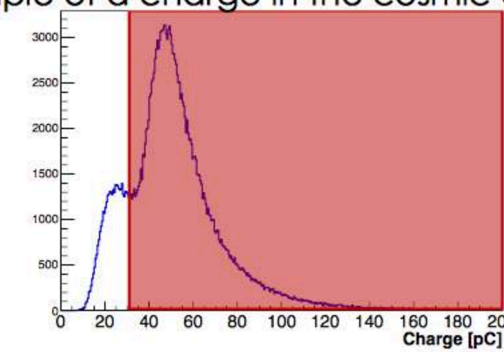
Laser charge



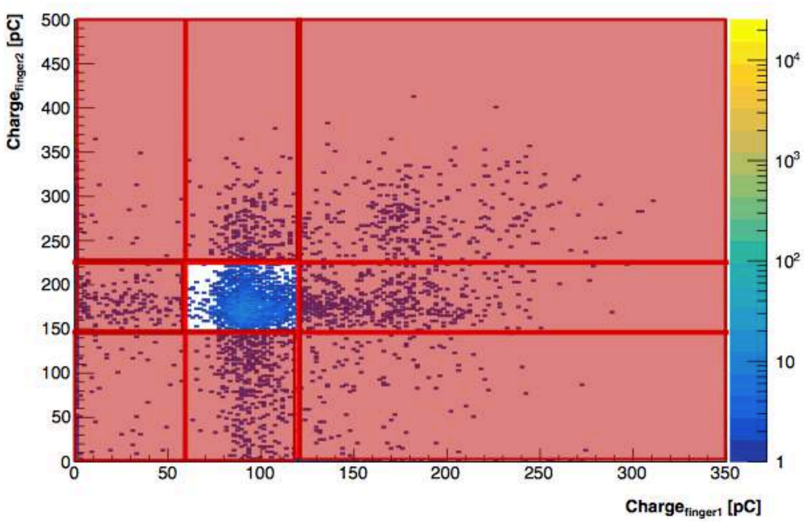
Events~50000

2)We reject events with cosmic trigger

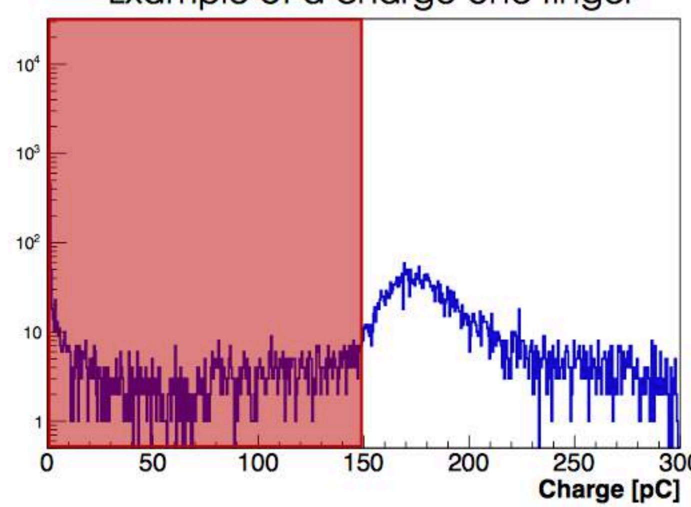
Example of a charge in the cosmic counters



3)We ask for a single particle in the beam counters

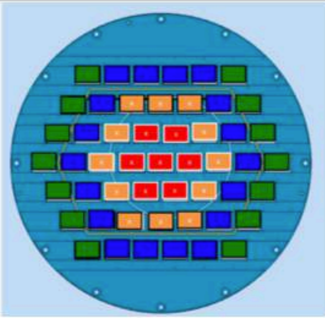


Example of a charge one finger

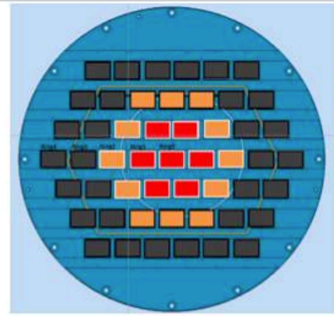


Events after selections~1600

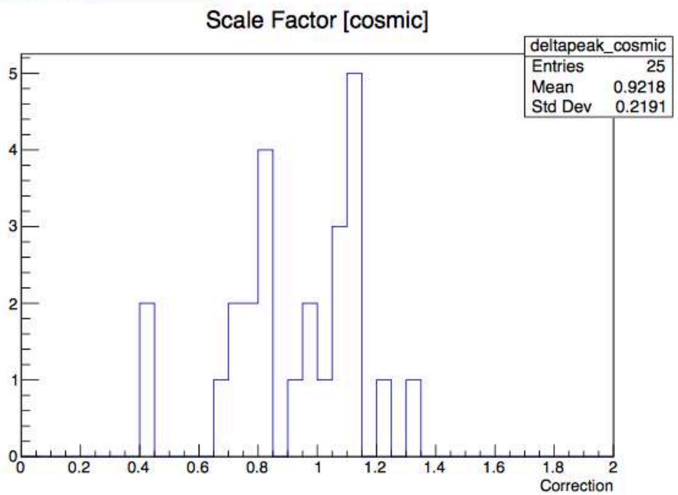
Module 0
Event selection

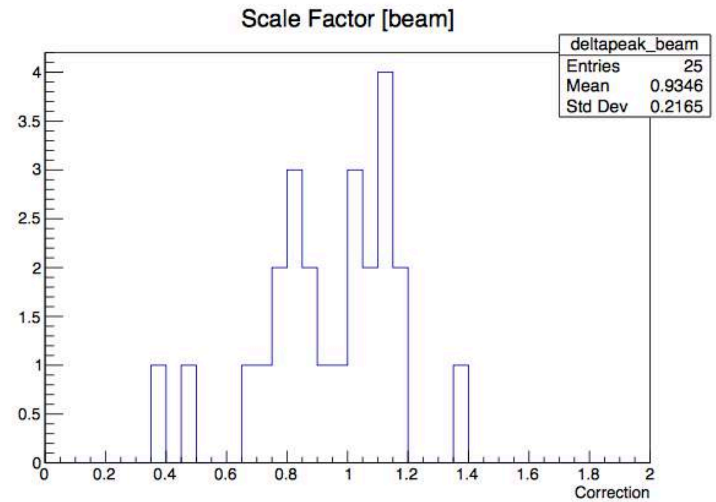


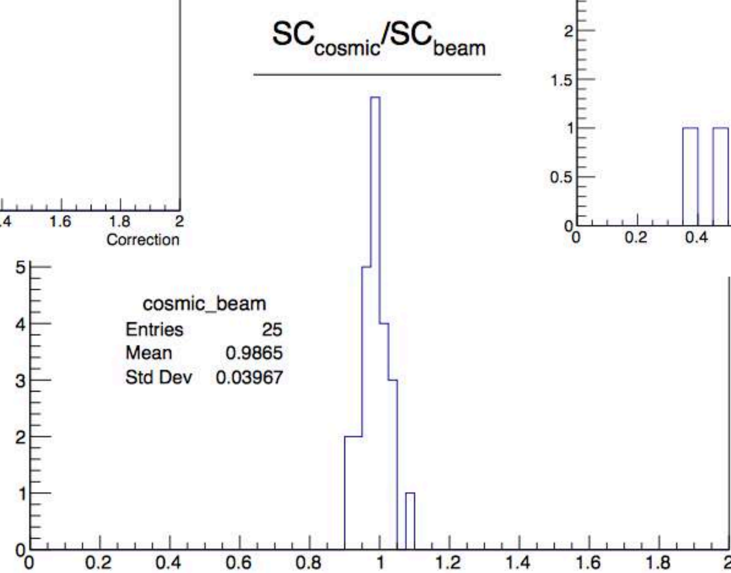
Cosmic trigger used to provide the equalization of all channels



Dedicated runs with beam centered on each crystal of the inner part of the matrix (up to second ring included)

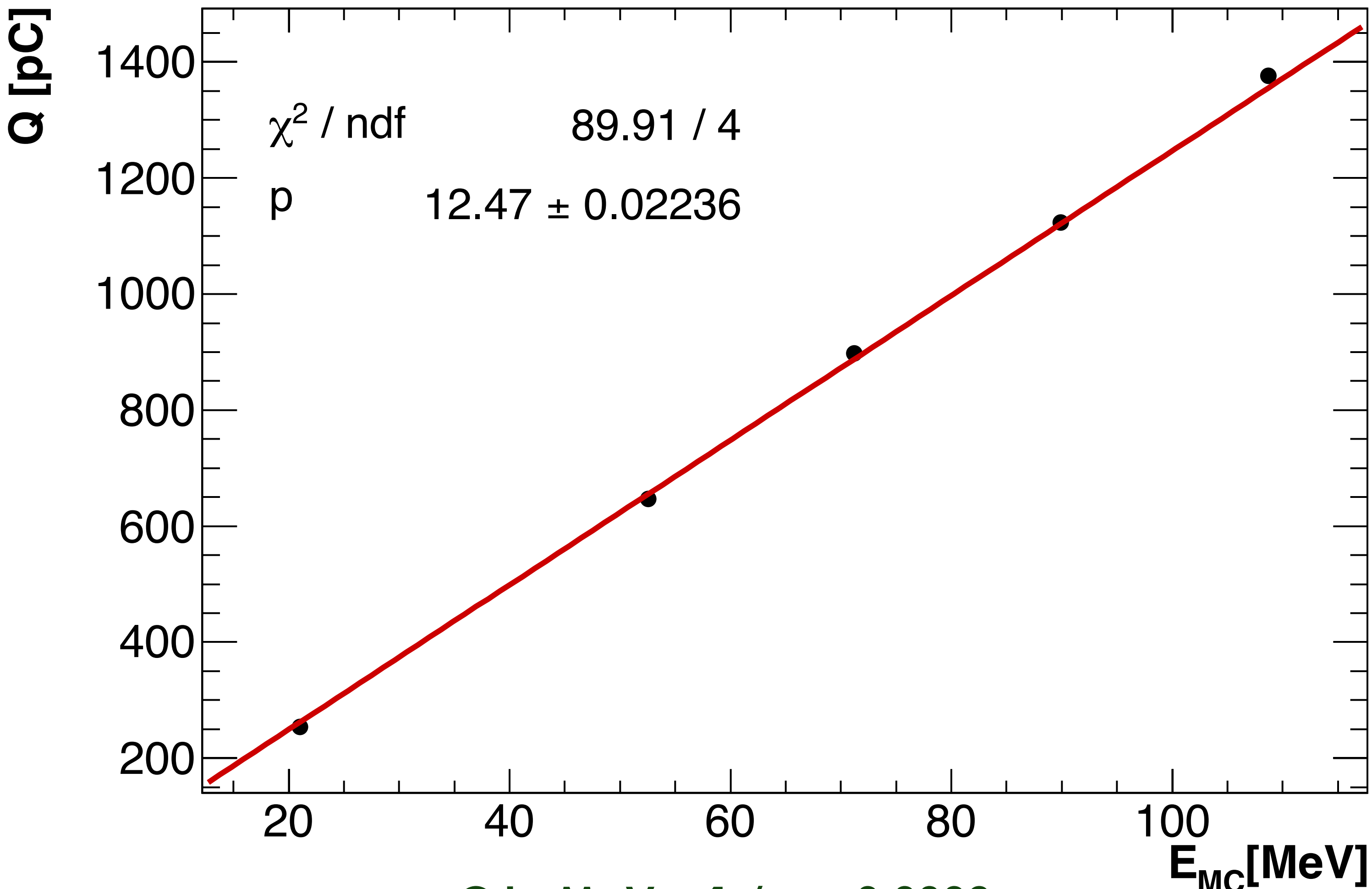






In all the analysis cosmic equalization is used

Module 0
Event selection



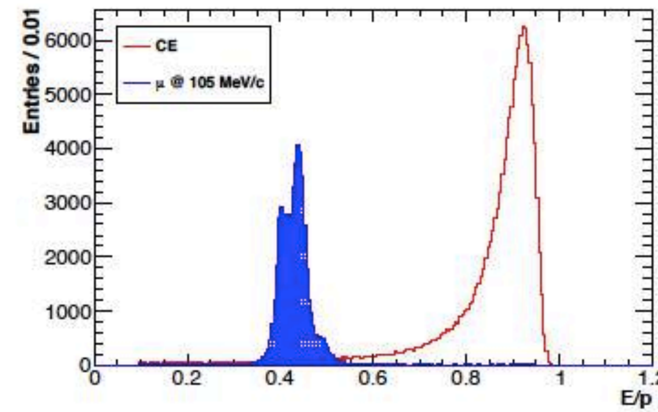
pC to MeV = 1 / p = 0.0802

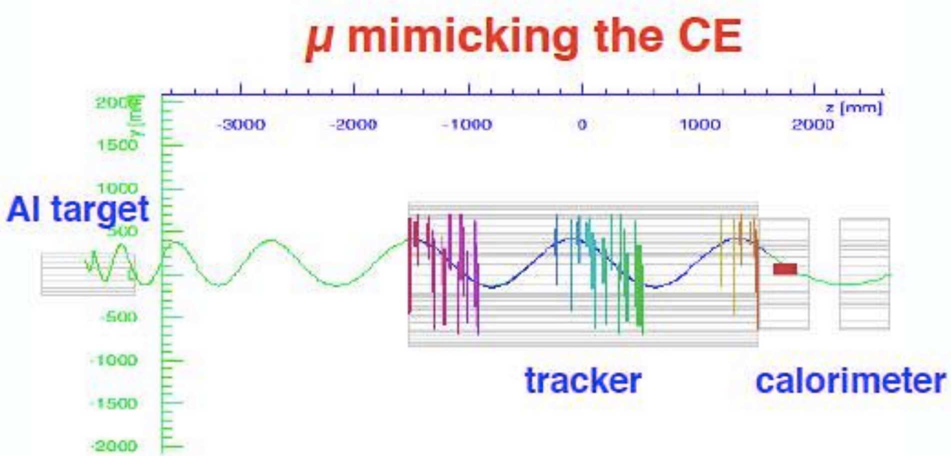
PId

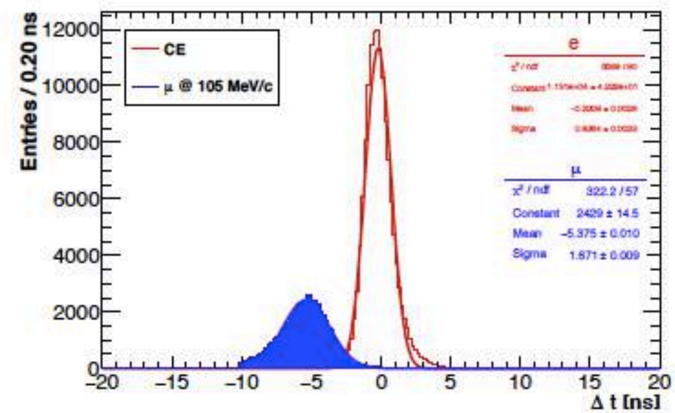
With a CRV inefficiency of 10^{-4} an additional rejection factor of ~ 200 is needed to have < 0.1 fake events from cosmics in the signal window

- 105 MeV/c e^- are ultra-relativistic, while 105 MeV/c μ have β~ 0.7 and a kinetic energy of ~ 40 MeV
- Likelihood rejection combines $\Delta t = t_{track} - t_{cluster}$ and E/p:

$$\ln L_{e,\mu} = \ln P_{e,\mu}(\Delta t) + \ln P_{e,\mu}(E/p)$$



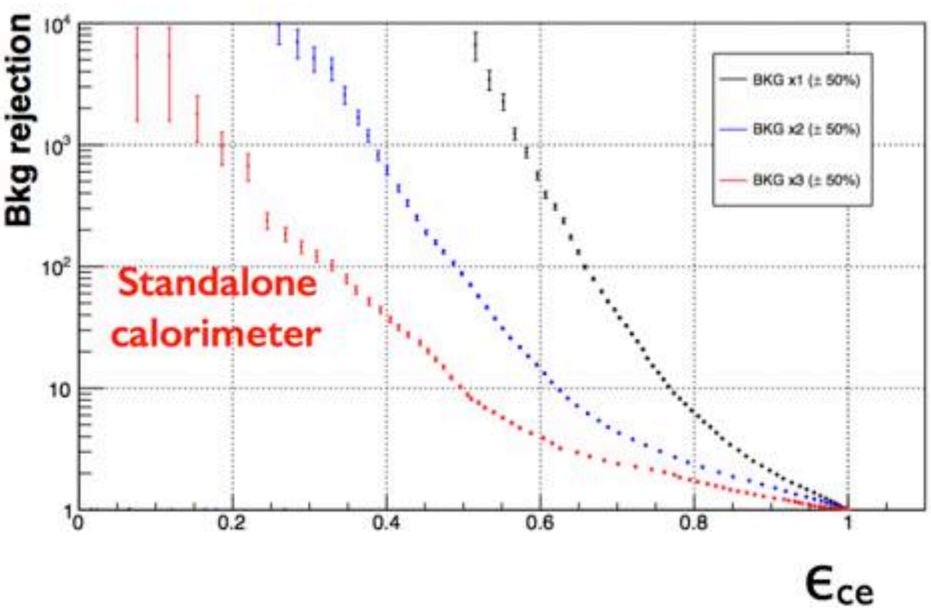


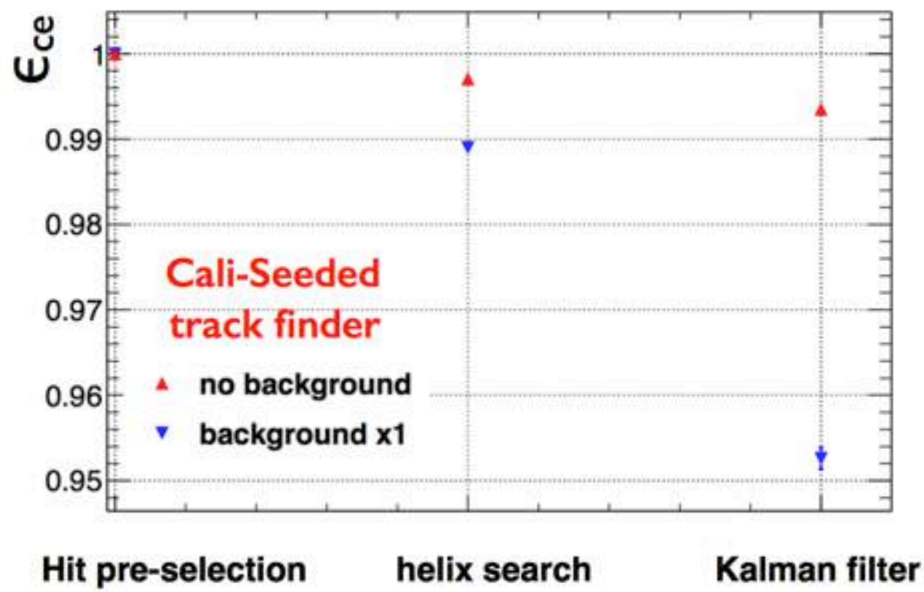


A rejection factor of 200 can be achieved with ~ 95% efficiency for CE

Calorimeter Trigger

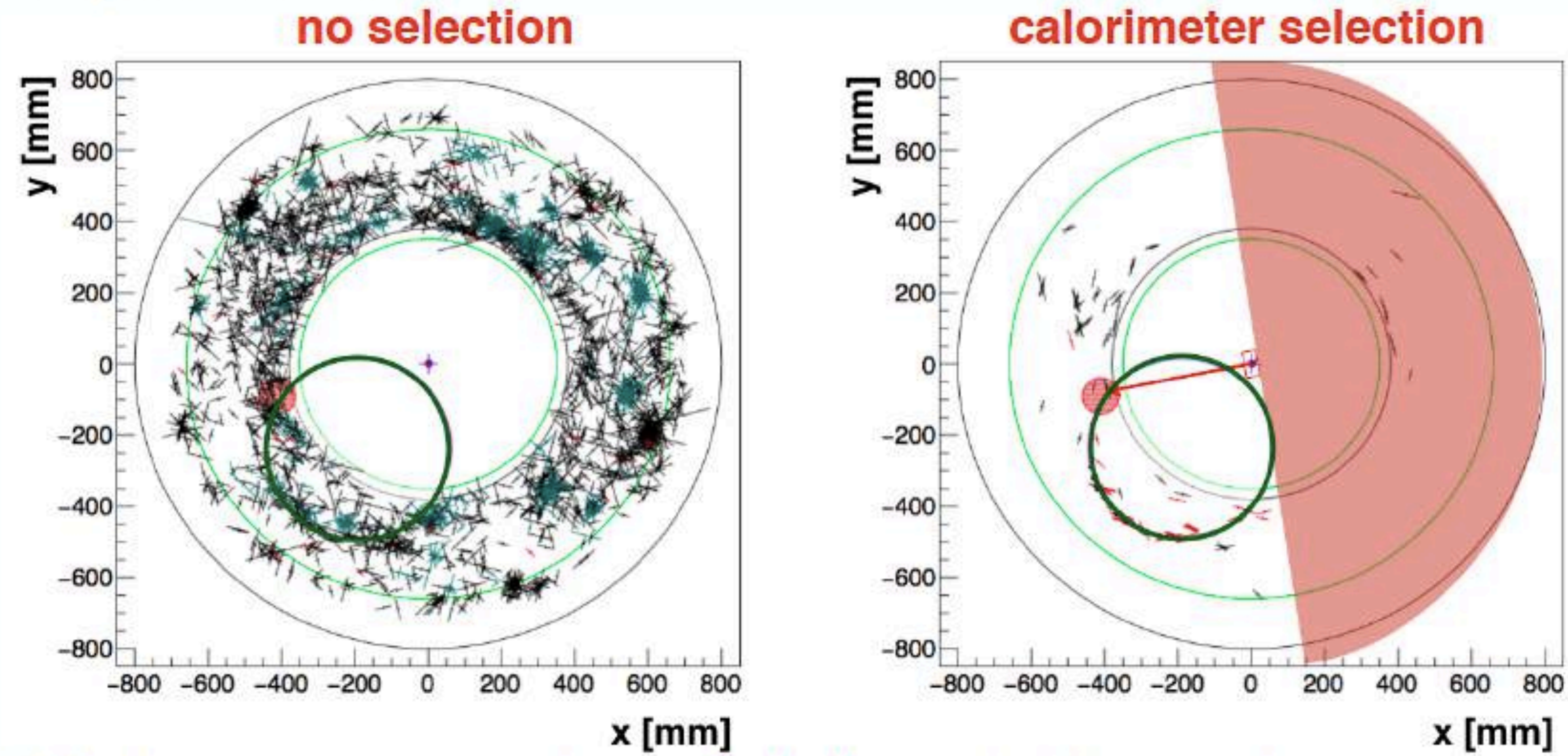
- Calo info can provide additional trigger capabilities in Mu2e:
- Calorimeter seeded track finder
  - Factorized into 3 steps: hit pre-selection, helix serach and track fit
  - ε ~ 95% for background rejection of 200
- Standalone calorimeter trigger that uses only calo info
  - E ~ 65% for background rejection 200





Calorimeter seeded track finder

- Cluster time and position are used for filtering the straw hits:
  - ✓ **time window of ~ 80 ns**
  - ✓ **spatial correlation**



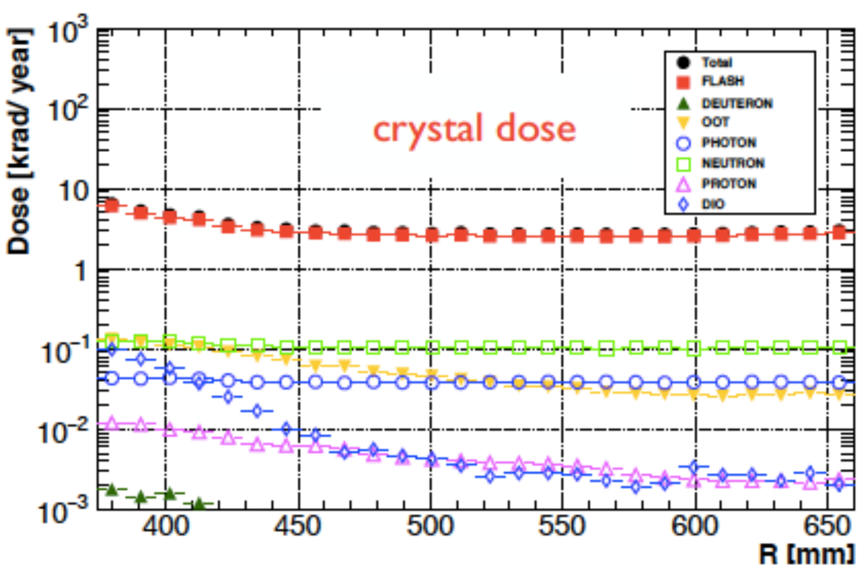
- **black crosses** = straw hits, **red circle** = calorimeter cluster, **green line** = CE track

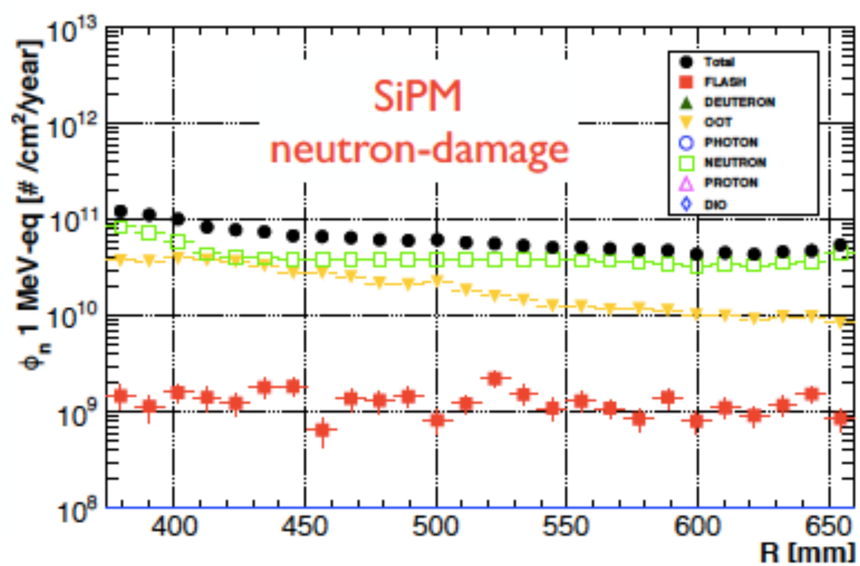
Calorimeter radiation damage

- Calorimeter radiation dose driven by beam flash (interaction of proton beam on target)
- Dose from muon capture is x10 smaller
- Dose is mainly in the inner radius
- Highest dose ~10 krad/year
- Highest n flux on crystals ~ 2×10^{11} n/cm^2/year
- Highest n flux on SiPM ~ 10^{11} n_{1MeVeq}/cm^2/year
-

- **Qualify crystals up to ~ 100 krad, 10^{12} n/cm^2**
- **Qualify SiPM up to ~ 10^{12} n_{1MeVeq}/cm^2**

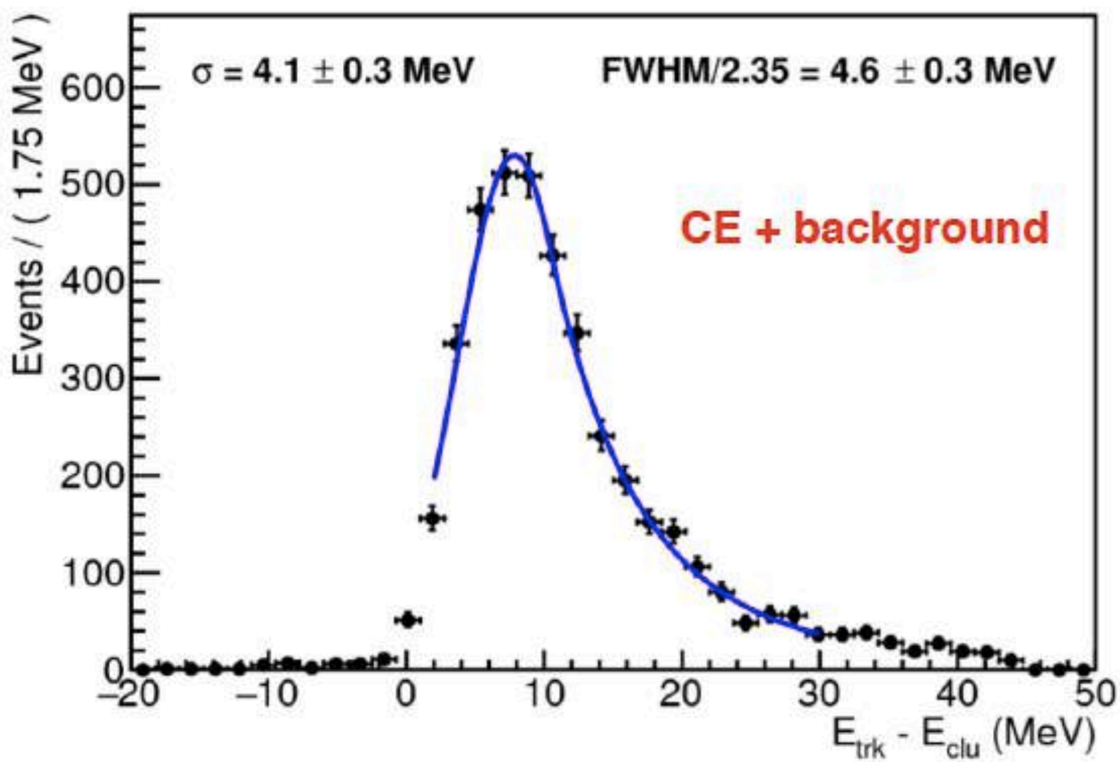
This includes a safety factor of 3 for a 3 year run



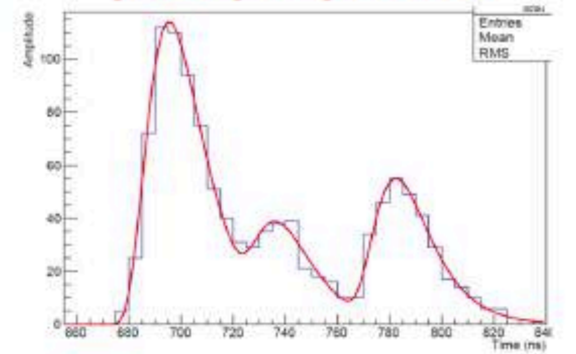


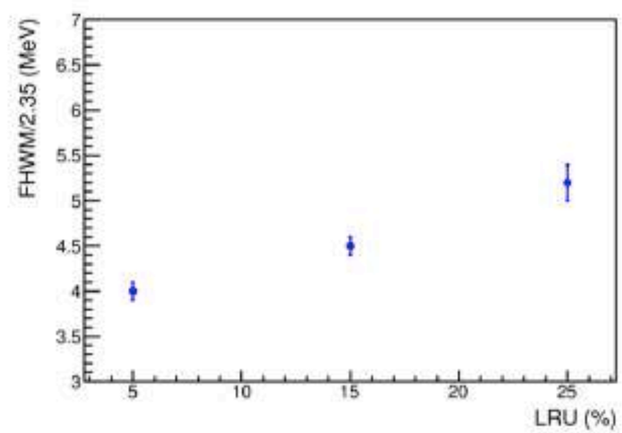
Calorimeter performances

- Offline simulation including background hits
- Experimental effects included: longitudinal response uniformity (LRU), electronic noise, digitization, etc
- Waveform-based analysis to improve pileup separation

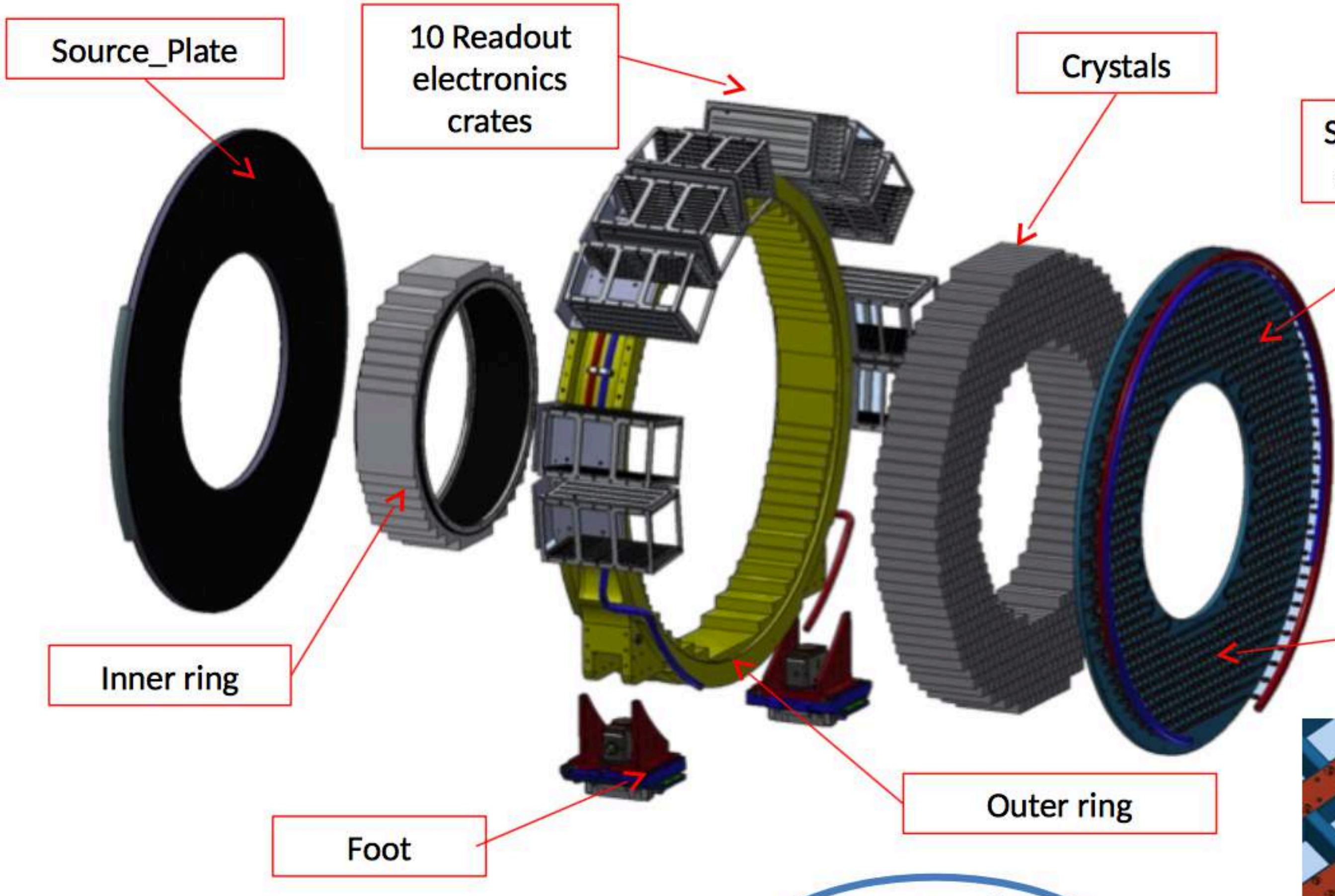


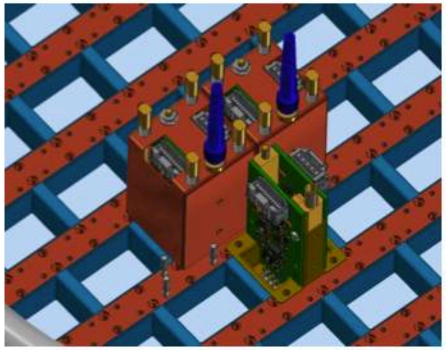
pile-up separation





Calorimeter mechanics

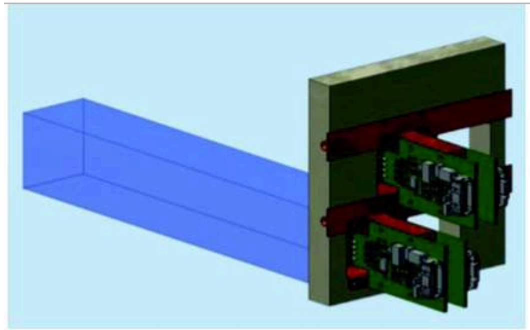




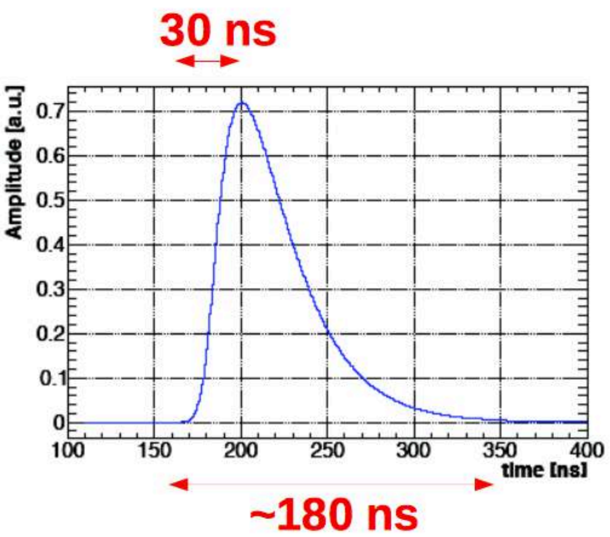
- Manifolds
- Hydraulic connections
- Inner steps
- Outer steps
- Alignment targets
- **SiPM running temperature at 0 °C, Coolant at -10 °C**

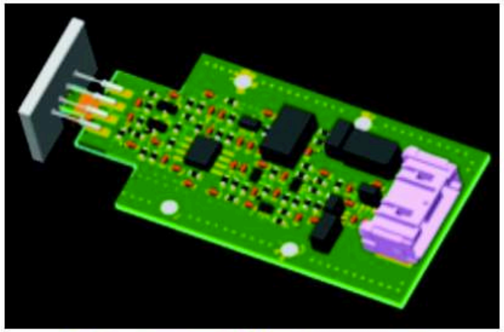
SiPM = Silicon PhotoMultiplier
FEE = Front End Electronics

Calorimeter Readout electronics



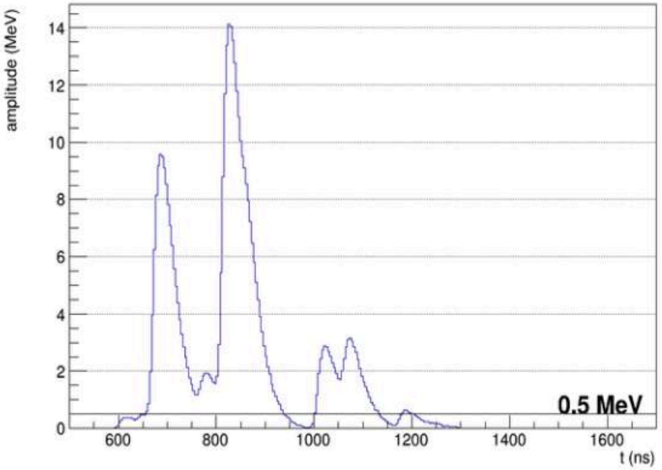
2 SiPM arrays/crystal
1 FEE board/array



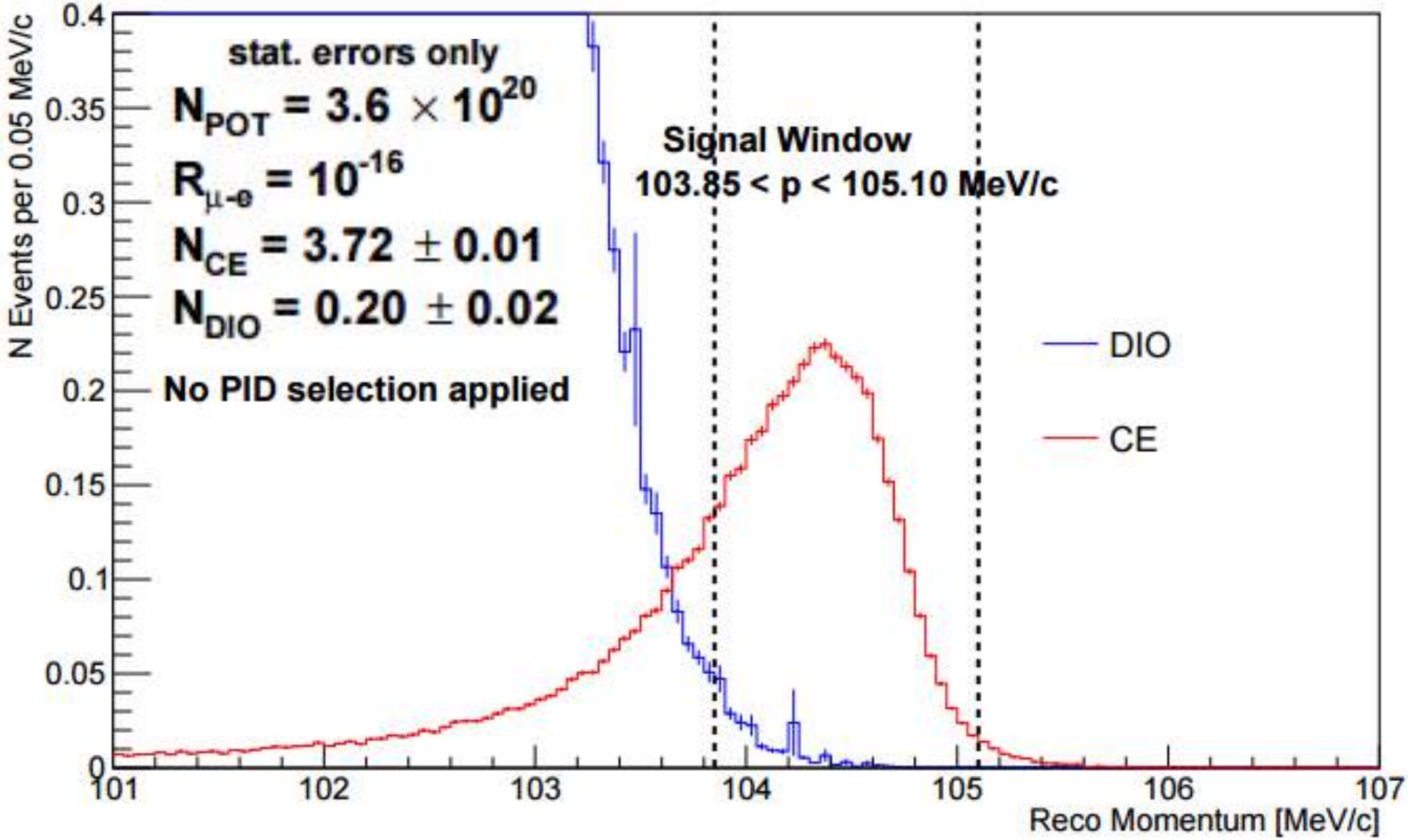


FEE board:
amplification, shaping
and voltage regulation

Waveform Digitizer:
Reads 20 channels
at 200 Mhz
(1 sample each 5 ns)



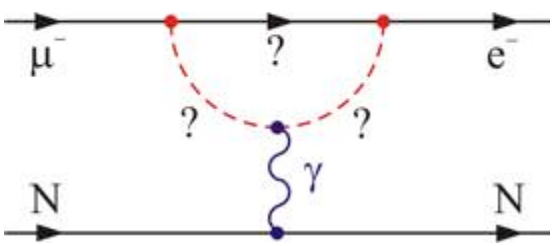
Three years run Expectation by full Simulation



CLFV Lagrangian

$$L_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

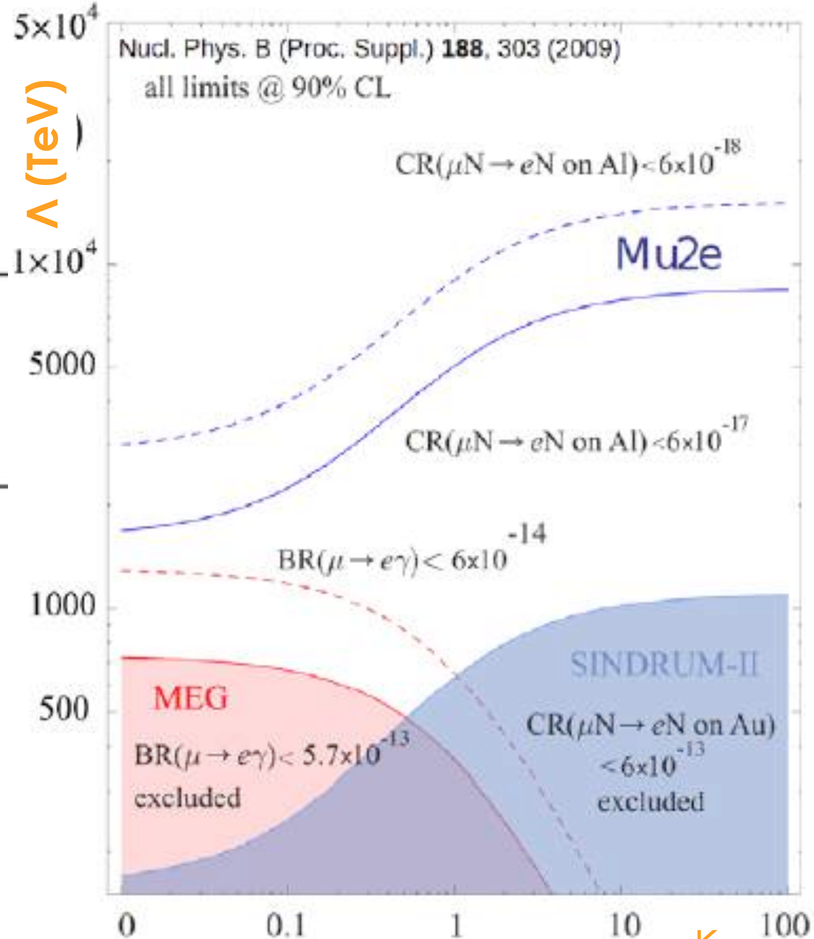
Loops dominate for
κ << 1



μ→eγ

μN→eN

μ→eee



Contact terms dominate for
κ >> 1

~~μ→eγ~~

μN→eN

μ→eee