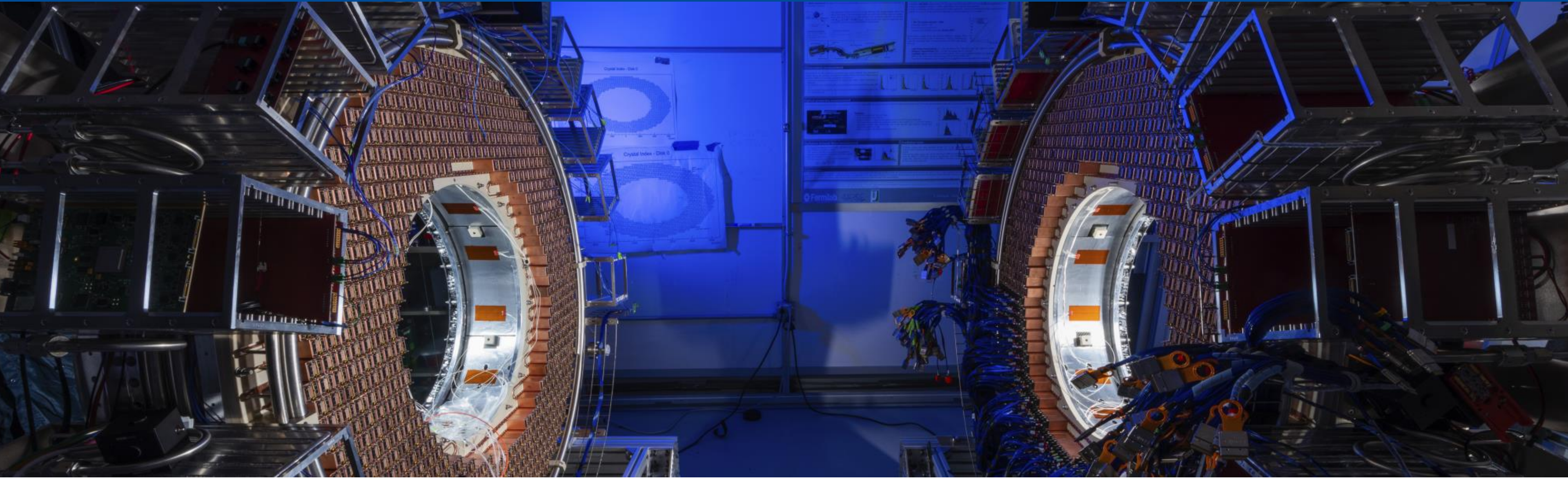


Mu2e calorimeter: in situ calibration of energy and time with selected Cosmic Ray samples

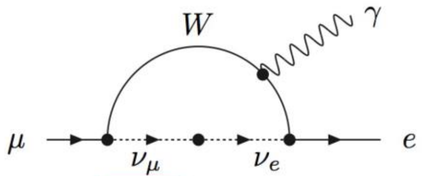
Pierluigi Fedeli – On behalf of the Mu2e calorimeter group

Spring school @ LNF

16-May-2024

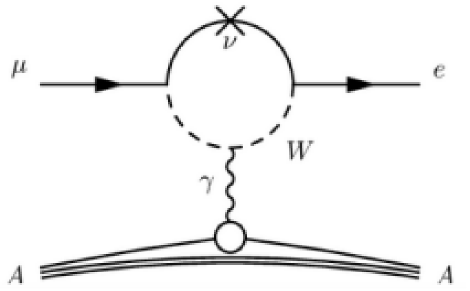
Physics - CLFV

CLFV has never been observed. In the muon sector, the **SM** rate is predicted to be:



$$BR(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i}U_{ei}\frac{m^2_{\nu i} - m^2_{\nu 1}}{M^2_W}\right|^2 < 10^{-54}$$

- A detection of CLFV would be a signature of pysics **BSM**
- CLFV@Mu2e: conversion neutrinoless of a muon to an electron in the field of an Al nucleus: $\mu^- Al \to e^- Al$
- The final state results with a **monoenergetic** electron with energy $E_{\mu e} = \mathrm{m}_\mu - E_b - E_{rec} \sim 104.97$ MeV



The measured quantity is:

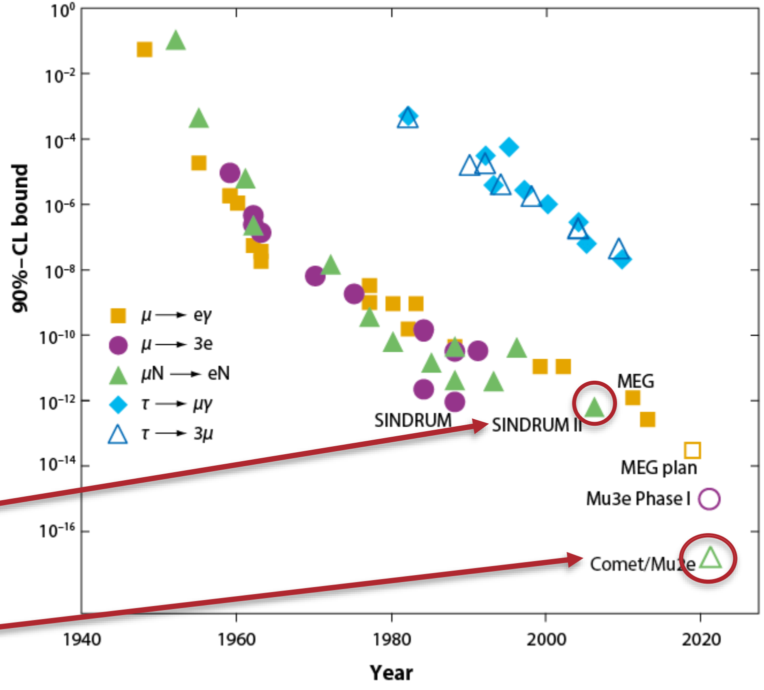
$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \to e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \to All\ captures)}$$

Better upper limit is from Syndrum II @ PSI

$R_{\mu e} \sim 7 \times 10^{-13}$ @ 90% CL

Mu2e aim to improve this upper limit by 10^4

$R_{\mu e} < 8 \times 10^{-17}$ @ 90% CL



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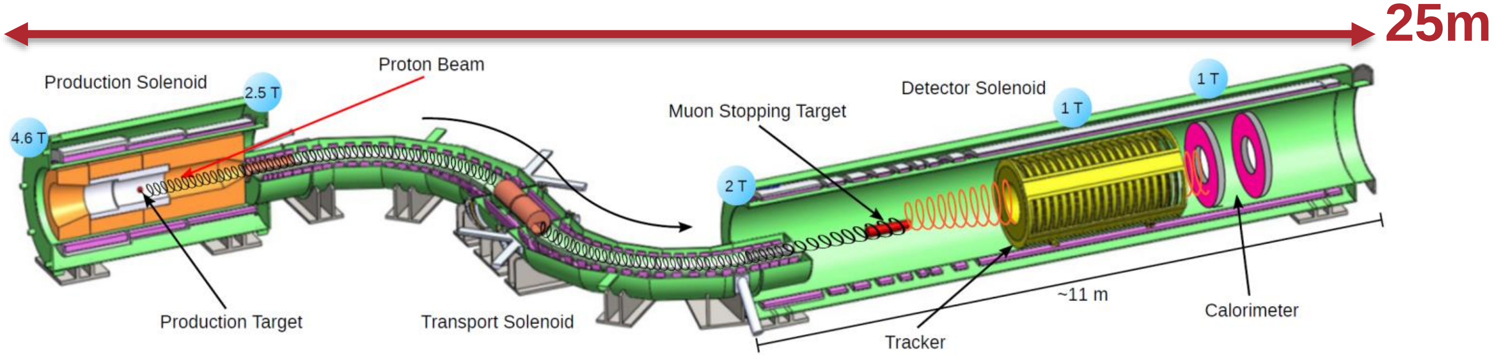
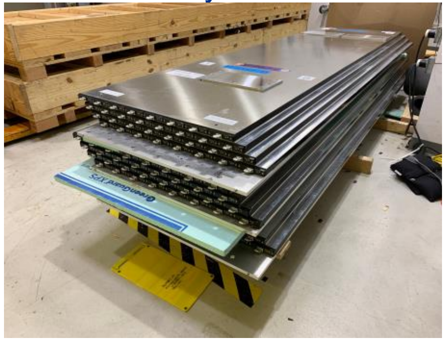
Mu2e experimental setup



Production and transport solenoids
Production, selection and transport of low energy momentum muons

Cosmic ray veto
Covers entire DS and half TS
Efficiency ≥ 99.99%



Tracker
18 stations of ~20,000 low mass straw drift tubes filled with 80:20 Ar-CO_2
Core momentum resolution 159 KeV/c

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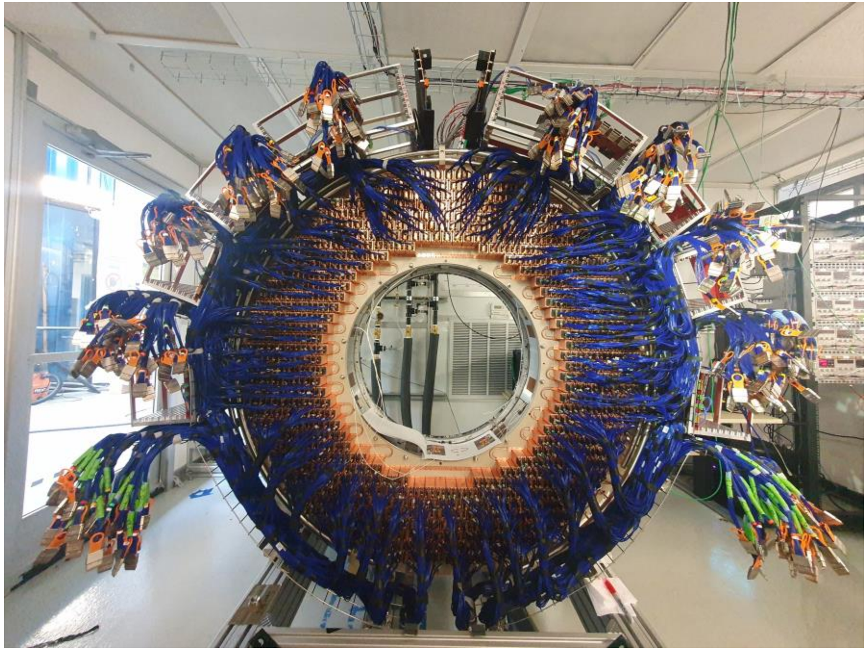
The Mu2e calorimeter



Construction

- The mu2e calorimeter is made by **2 disks**
- Each disk is composed by **674 CsI scintillation crystals**
- Each crystals is readout by **2 custom UV-extended SiPMs**

Physics requirements

- Large acceptance for conversion electrons
- PID capabilities: muon/electron rejection 200
- Seed for tracking
- Tracker independent trigger

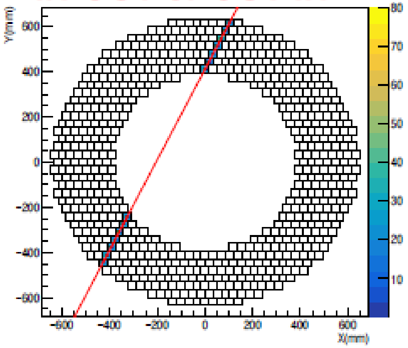
For 105 MeV electrons:

- $\frac{\sigma_E}{E} = \mathcal{O}(10\%)$
- $\sigma_t < 0.5$ ns
- $\sigma_{rz} < 1$ cm
- Hard Radiation resistance

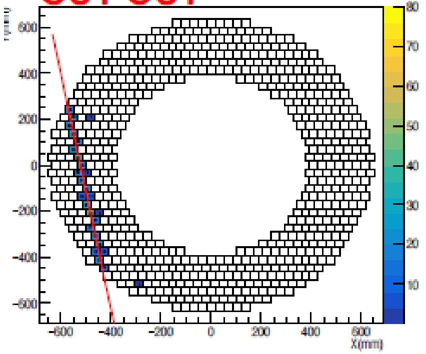
Calibration – Cosmic rays events in MC simulation

We have developed a **fast trigger** which select four kind of minimum ionizing particles (mips) that cross the disks of the calorimeter

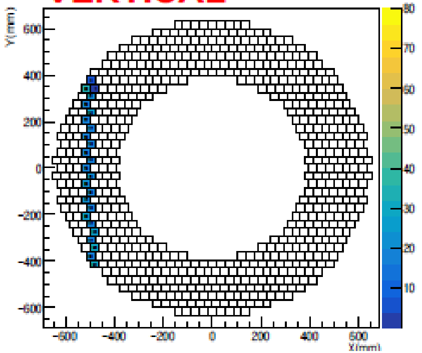
IN-OUT or OUT-IN



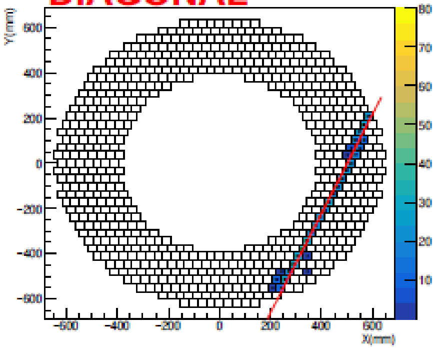
OUT-OUT



VERTICAL



DIAGONAL

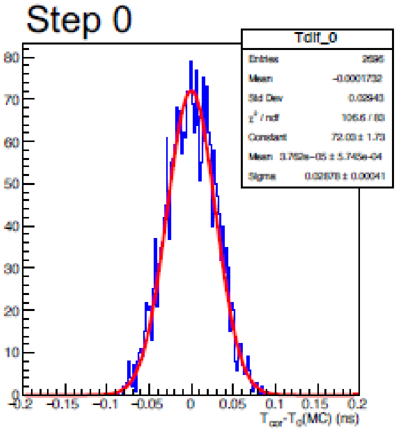


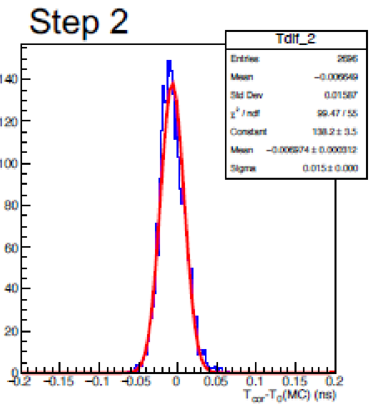
To have an even better selection we also apply **cuts** on:

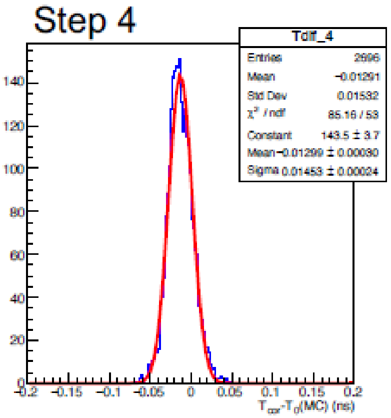
- χ^2/ndf of linear fit to the track
    - For vertical tracks we require a minimum spread in longitudinal direction
- Minum number of cells hit by the mips
- Energy released in the cell by the mips

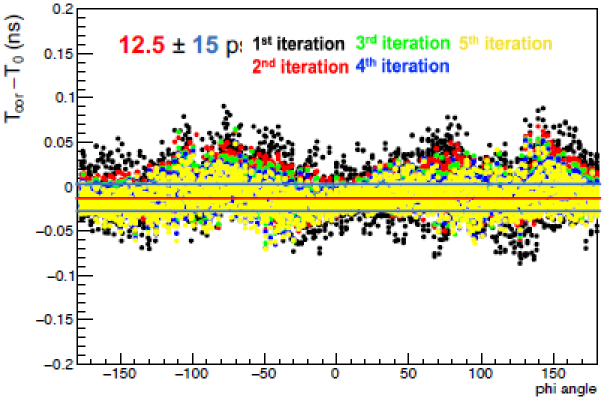
Calibration – Time alignment

Each readout channel has a different proper time, to equalize the response we correct **iteratively** each readout response by the difference between its proper time and the global mean time









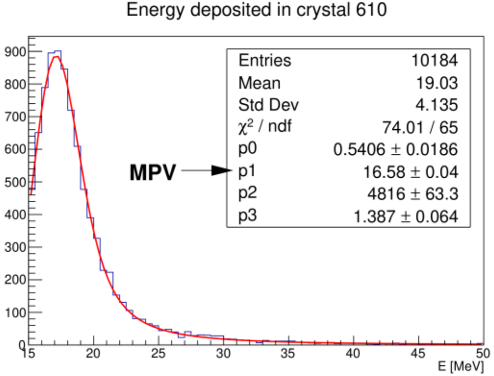
Step	μ (ps)	σ (ps)
0	0.0 ± 0.4	28.8 ± 0.4
1	–0.4 ± 0.4	17.7 ± 0.3
2	–0.7 ± 0.4	15.0 ± 0.2
3	–10.0 ± 0.4	14.4 ± 0.2
4	–13.0 ± 0.4	14.5 ± 0.2

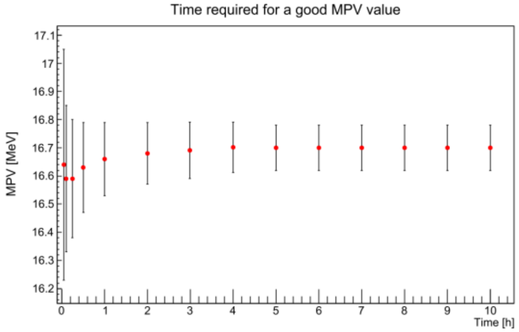
The process is stable after 4 iterations with:

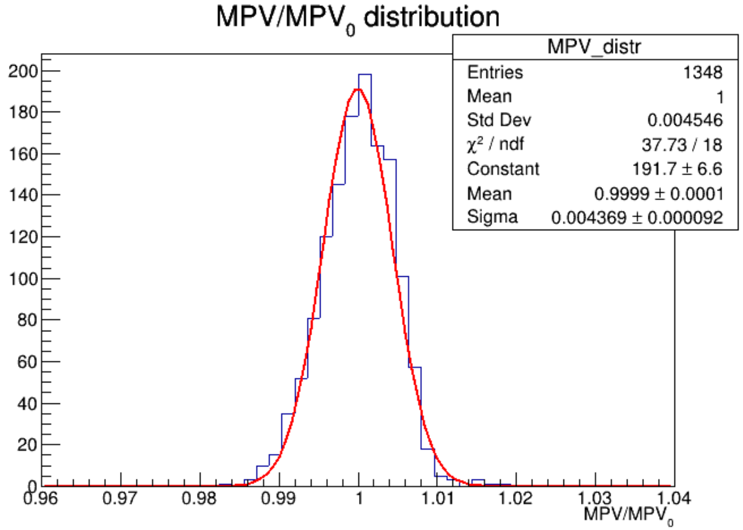
- T0 calibration constant at 15 ps level
- Resolution of ~500 ps/SiPM

Calibration – Energy response

The energy distribution of mips in crystals follow a **langaus distribution**.
We need to equalize the energy response among all the crystals







Energy calibration distribution of MPV has a spread of response of ~4‰

The calibration is performant after 2 hours of data tacking

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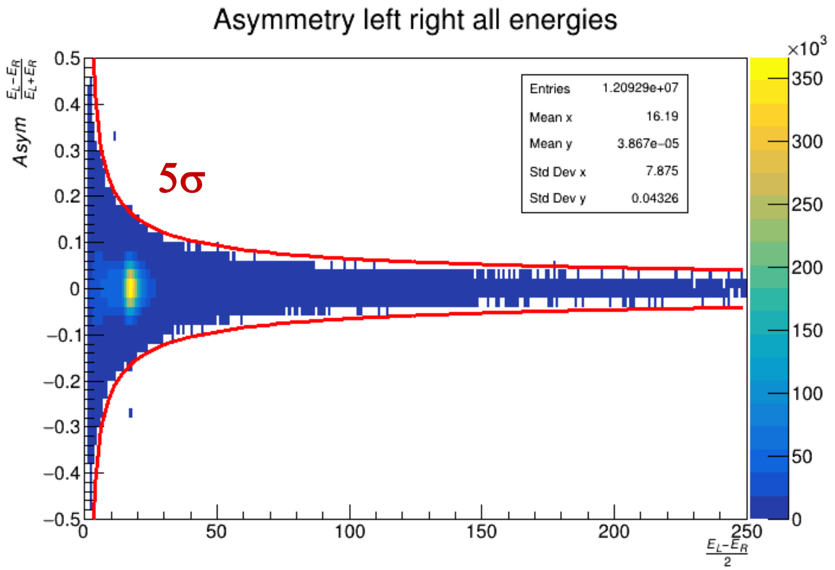
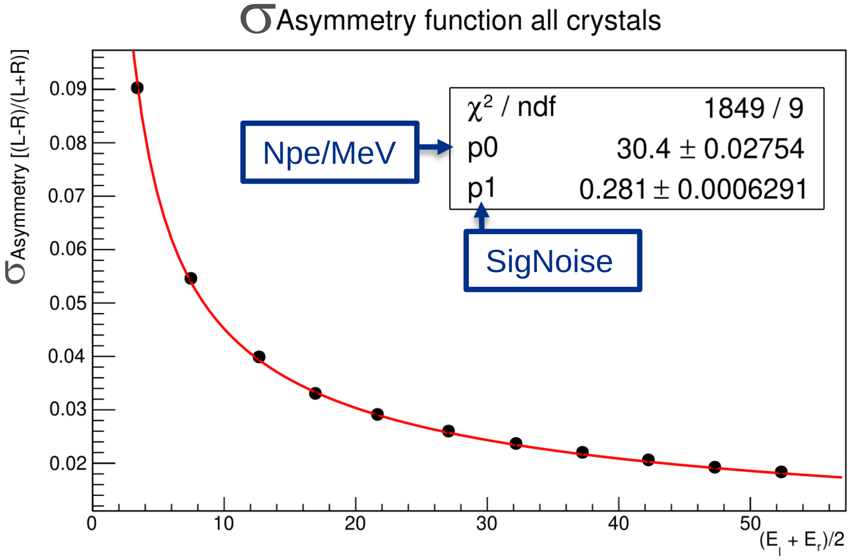
Calibration – SiPM readout consistency

The consistency of the SiPM readout is described by:

- The asymmetry variable Asym := $\frac{E_L - E_R}{E_L + E_R}$ and
- It's Sigma σ(Asym) := $\sqrt{\frac{1}{2}\left(\left(\frac{1}{LY \cdot E}\right) + \left(\frac{SigNoise}{E}\right)^2\right)}$, LY := Npe/MeV





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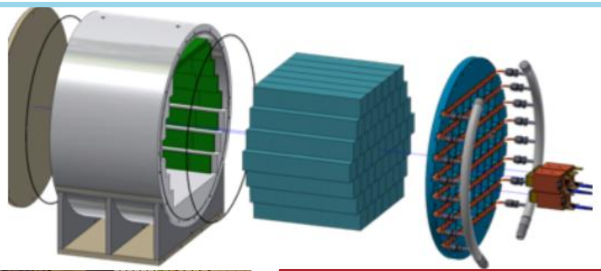
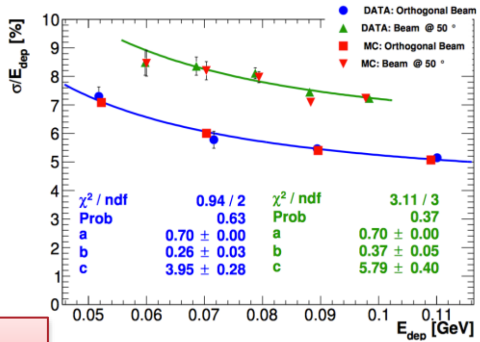
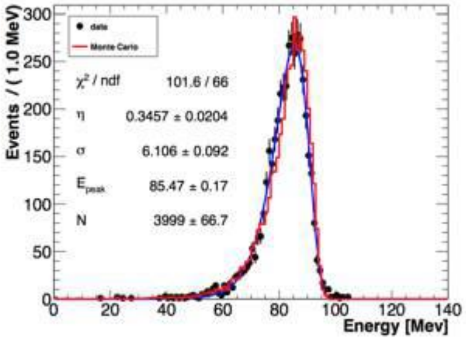
Module 0

Module 0 is a large-scale **calorimeter prototype** of 51 crystals and 102 SiPMs

Energy resolution: 5.4% for 100 MeV at 0°
7.3% for 100 MeV at 50°

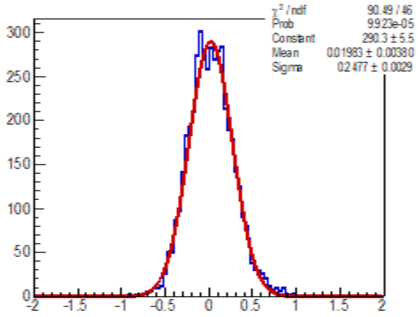


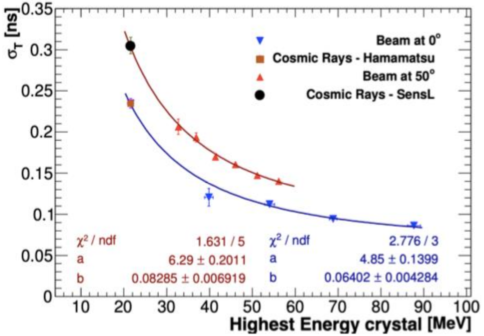


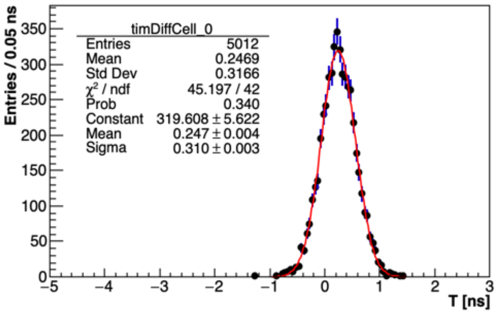


Results satisfy the requirements
→ RB 2017, CR test 2019-2023

Time resolution: $\sigma_t < 0.2$ ns at 100 MeV





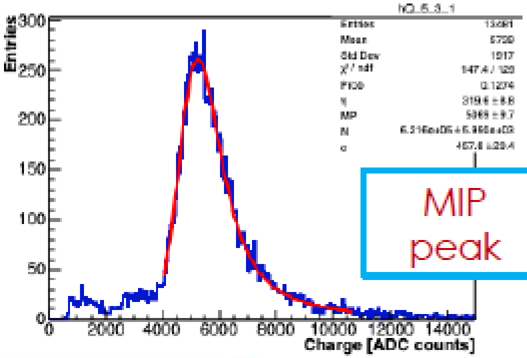


Module 0 – Algorithm validation

CRT

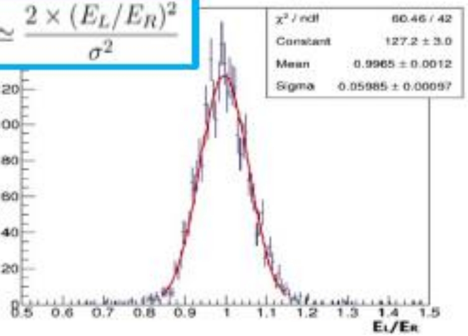
Module0

Calibration algorithms have been tested in a cosmic ray run on Module0 positioned between CRT modules for triggering



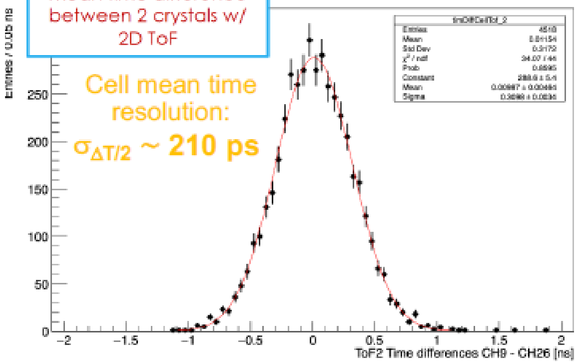
MIP peak

$$\text{Npe} \simeq \frac{2 \times (E_L/E_R)^2}{\sigma^2}$$



mean time difference between 2 crystals w/ 2D ToF

Cell mean time resolution: $\sigma_{\Delta T/2} \sim$ **210 ps**



The results coming from the Module0 data align with the outcomes observed in our simulations

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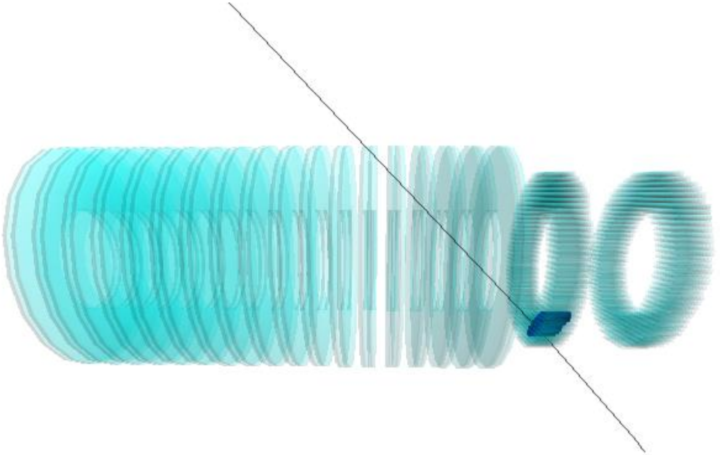
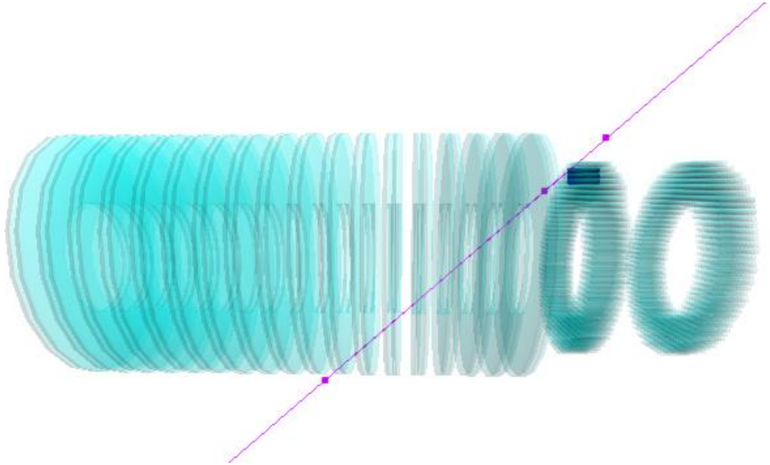
Future Calibration – Inter calibration

The calorimeter is one of the main detector of Mu2e together with the tracker and the cosmic ray veto.
In the experiment every detector needs to be aligned to the experiment global time.

We started to develop an algorithm for the inter-calibration between the tracker and the calorimeter using cosmic ray events

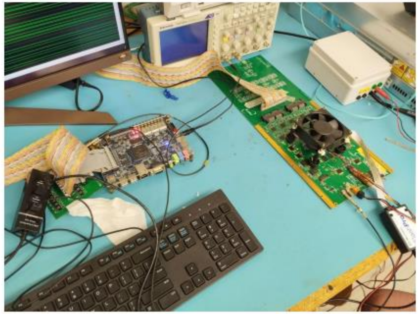


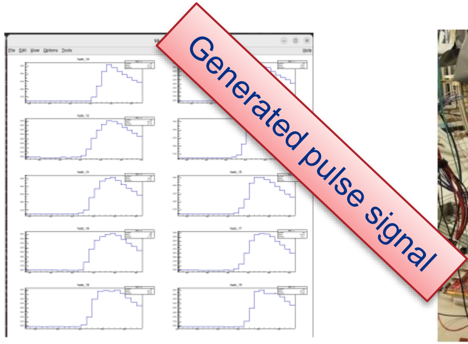


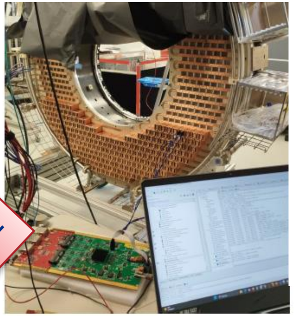
Conclusions

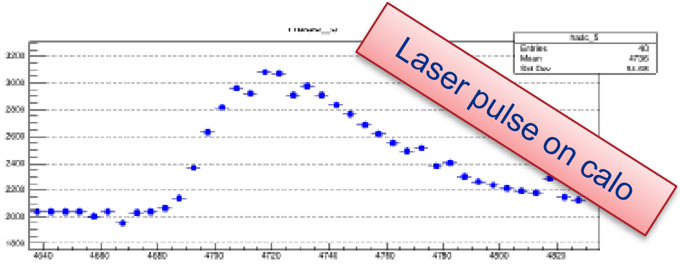
Calibration algorithms for commissioning and operations in situ have been developed for time alignment and energy response; their results are validated with the analysis done on Module 0, a future inter calibration between detectors is under development

A full slice test of ½ calorimeter disk is under preparation in the assembly area so to allow a comparison with simulation before starting the commissioning in the pit
→ Starting July-August 2024









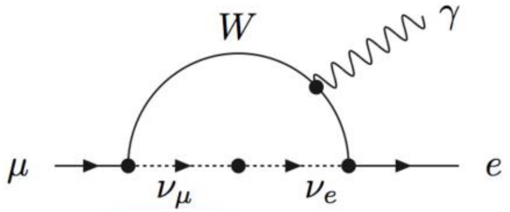
Thanks for the attention!

Backup slides

Physics - CLFV

CLFV has never been observed and in the **SM** is predicted to be:

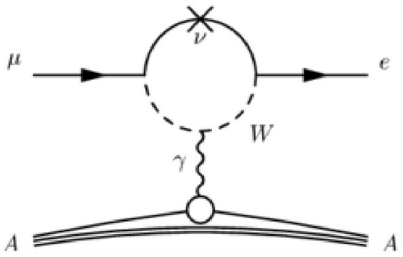
$$BR(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_i U_{\mu i}^* U_{ei} \frac{m_{\nu i}^2 - m_{\nu 1}^2}{M_W^2} \right|^2 < 10^{-54}$$



A detection of CLFV would be a signature of pysics **BSM**

CLVF@Mu2e: conversion neutrinoless of a muon to an electron in the field of an Al nucleus

$$\mu^- N(A,Z) \rightarrow e^- N(A,Z)$$



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Signal and Background

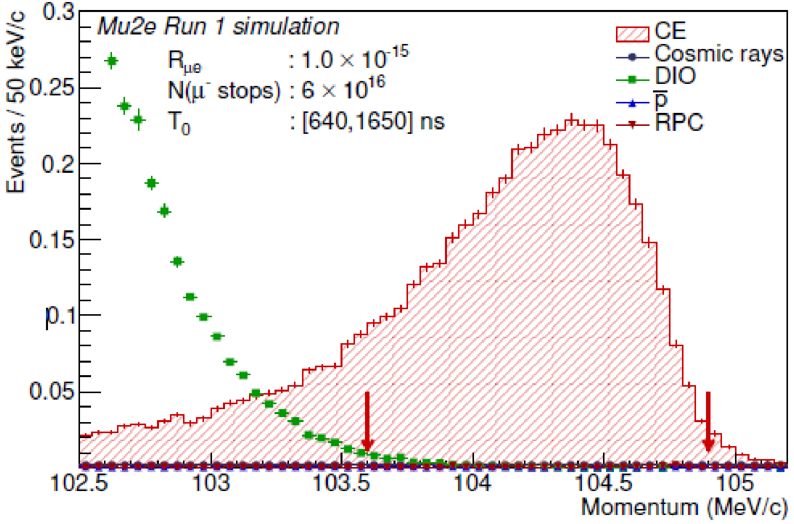
$\mu^- N \rightarrow e^- N$ has the same dynamic of 2-body decay, therefore, the final state results with a **monoenergetic** electron with energy

$$E_{\mu e} = \mathrm{m}_\mu - E_b - E_{rec} \sim 104.97 \text{ MeV}$$

Electrons from high momentum tail of muon decay-in-orbit (DIO) represent the intrinsic background

Other types of background are:

- Cosmic Rays
- Radiative Pion capture
- Electrons in the beam
- Muons decay in flight
- Antiprotons interacting



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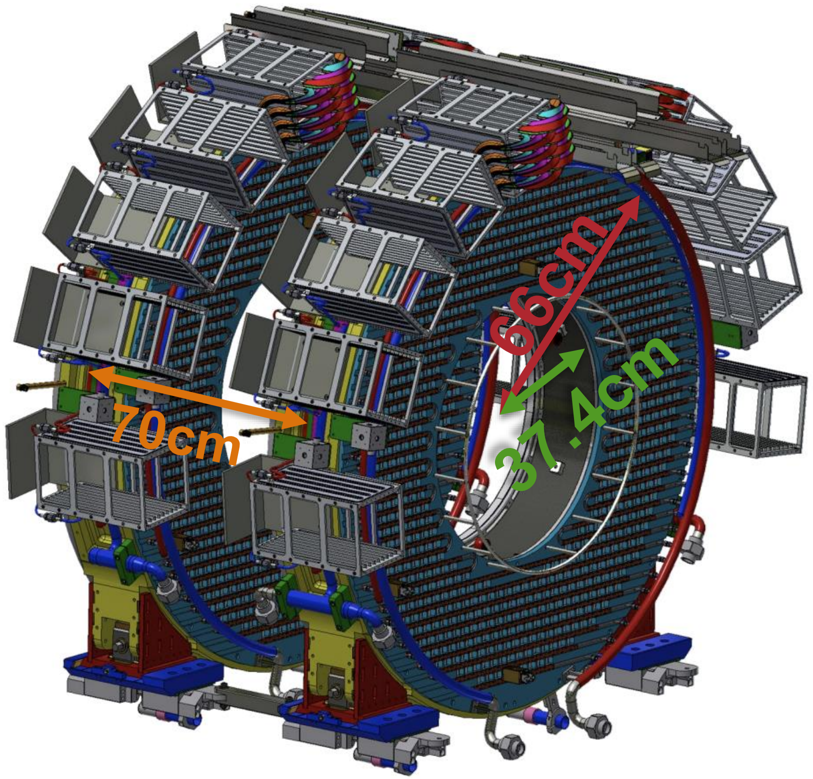
Mu2e Calorimeter - Requirements



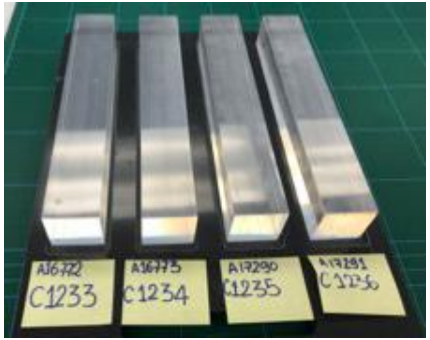
Physics requirements

- Large acceptance for conversion electrons
- PID capabilities: muon/electron rejection 200
- Seed for tracking
- Tracker independent trigger

For 105 MeV electrons:

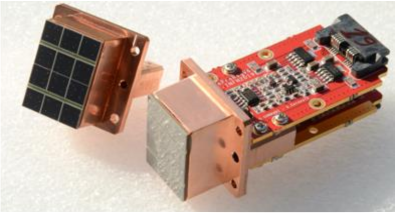
- $\frac{\sigma_E}{E} = \mathcal{O}(10\%)$
- $\sigma_t < 0.5$ ns
- $\sigma_{rz} < 1$ cm
- Radiation resistance
  - TID up to ~90 $\frac{\text{krad}}{\text{year}}$
  - neutron fluence up to $10^{12}\ \frac{\text{n}_1\text{MeV}}{\text{cm}^2\ \text{year}}$
- It reside in the DS at 1T and 10^{-4} Torr
- Fast response ($\tau < 40$ ns)
- Temperature ±1C
- Gain stability within ±0.5%
- Sensors at -10 C for mitigating leakage current due to neutrons

Mu2e Calorimeter - Design



•Each disk is composed by 674 undoped CsI scintillation crystals 3.4x3.4x20 cm³
•CsI crystals are the best compromize for reliability, radiation hardness and response (τ=30 ns) with light yield above 100 (p.e.)/MeV

- Each crystal is readout by two custom UV-extended SiPMs
- Each one is a 2x3 monolithic sensor of 6x6 mm²
- This array configuration has an active area of 1.2x1.8 cm² keeping a small total capacitance
- Each SiPM is read by one FEE



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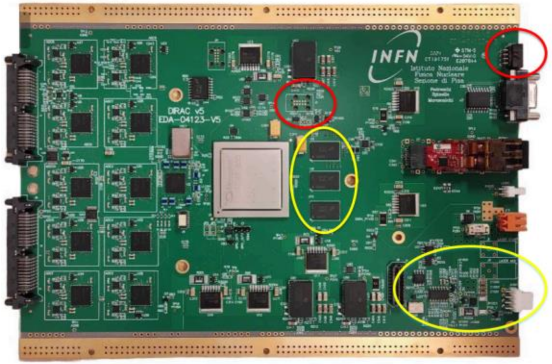
Mu2e Calorimeter - Design

- Mezzanine board (MZB) interfaces between DiRAC, HV supplies and SiPMs FEE
- One MZB can read 20 FEE channels
- Production of 85 MZB completed (1/2 production)
- Ready for burnin and QC tests

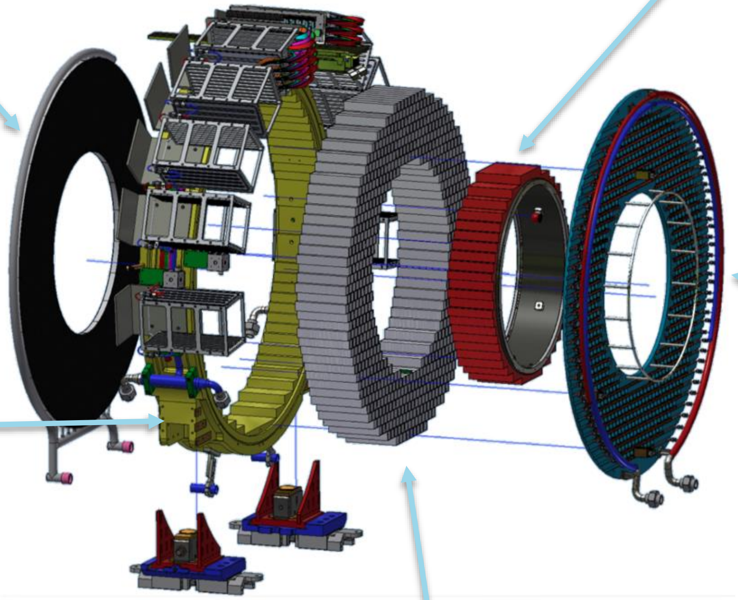


- DiRAC board is the digitizer board
- Digitizes 20 channels with ADC sampling at 200 MHz
- 10 DiRAC prototypes qualified
- Readout with fibers proven. Interface with DTC under development

Mu2e Calorimeter - Design

Front plate with liquid source tubing system

Outer ring structure



Inner ring

Back plate and cooling system

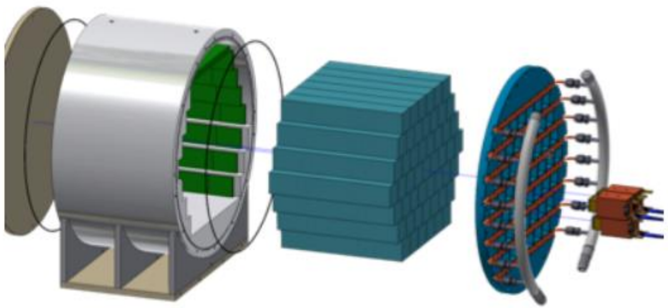
Crystal stack

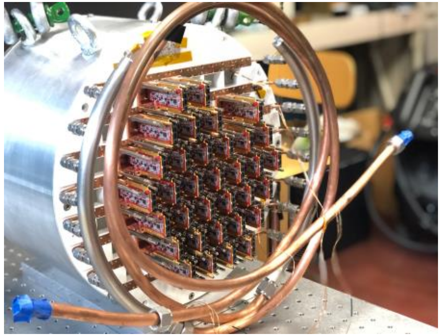
Module 0

Module 0 is a large-scale calorimeter prototype of 51 crystals and102 SiPMs + FEE board.

Goals:

- Test the integration and assembly procedure
- Measure calorimeter performance @ test beam
- Work under vacuum, low temperature, irradiation test
- Validate the electronic readout chain
- Vertical slice test with cosmic ray events

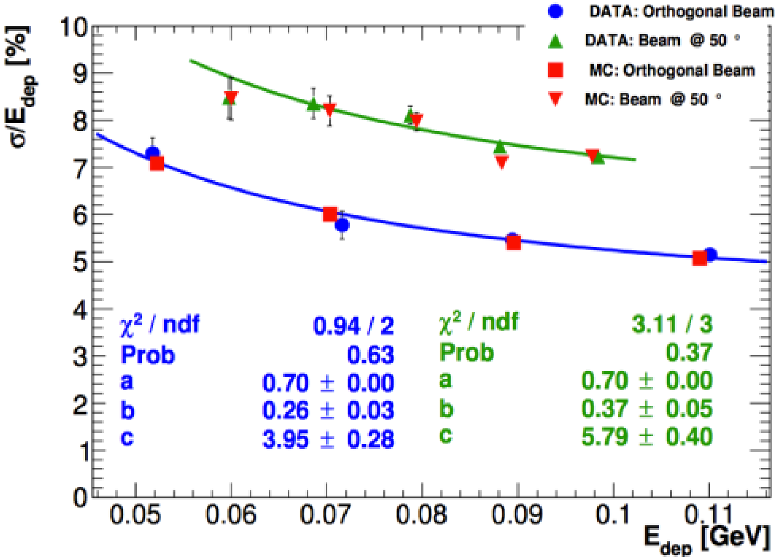


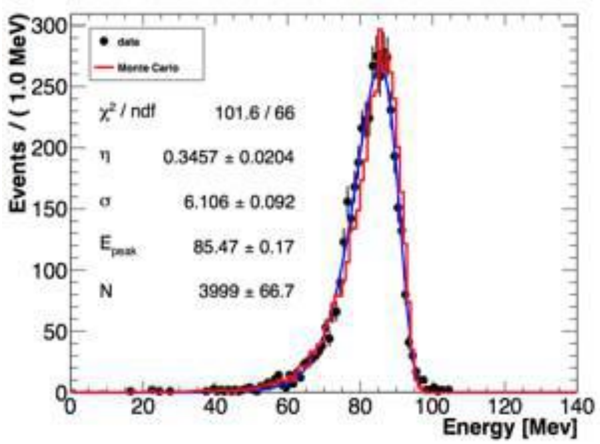


Module0 – Performance

Module 0 tested @ BTF (Frascati) with 60-120 MeV e− beam @ 0° and 50°

Energy resolution:





Fit function:

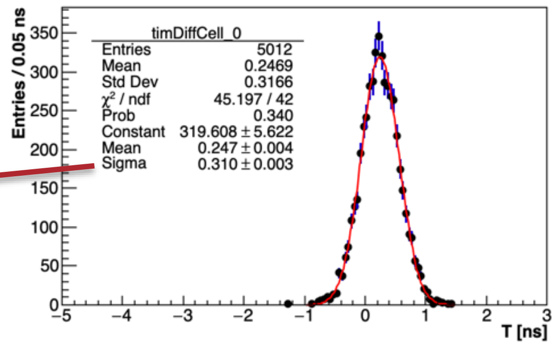
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E[\mathrm{GeV}]}} \oplus \frac{b}{E[\mathrm{Gev}]} \oplus c \;:$$

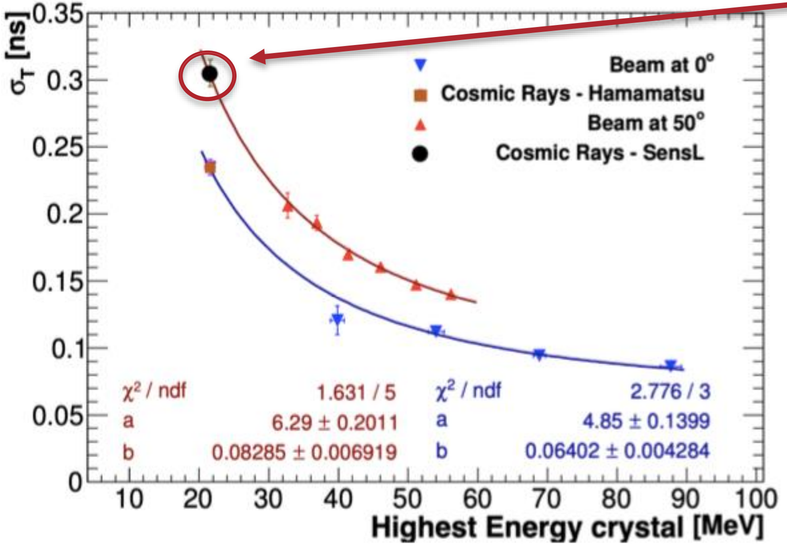
- a := Stochastic term
- b := Noise term
- c := Costant term, dominant due to leakage

Found an energy resolution of
5.4% for 100 MeV at 0°
7.3% for 100 MeV at 50°

Module0 – Performance

Time resolution is evaluated as the difference between the time of the two SiPMs coupled to the same crystal





Fit function:

$$\frac{\sigma_E}{E} = \frac{a}{E[\mathrm{Gev}]} \oplus b$$

- a := proportional to the emission time constant of the undoped CsI
- b := additional contribution due to the readout electronics

Found a time resolution $\sigma_t < 0.2$ ns at 100 MeV

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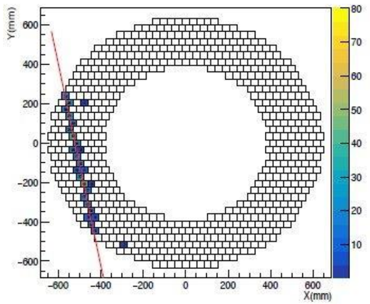
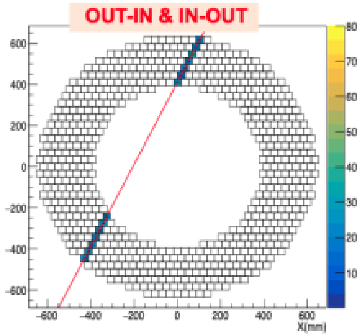
Monte Carlo studies for development of in-situ calibration

Calibration algorithms are being developed for carrying out time alignment and energy response calibration with cosmic rays in-situ via MC simulations

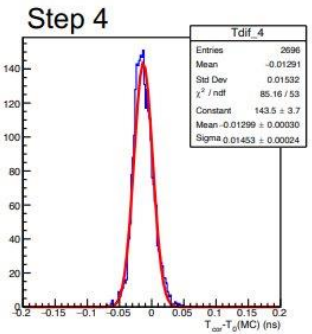




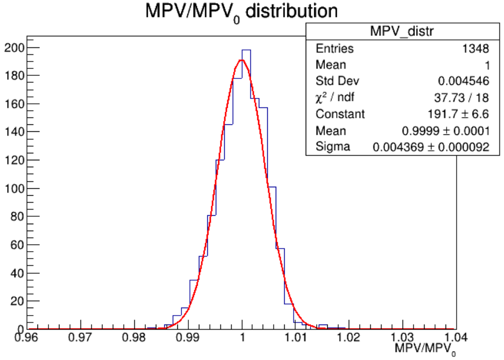
Time calibration is an iterative process, stable after 4 iterations with a T0 calibration at 15ps level and a resolution of ~500 ps/SiPM

Energy calibration distribution of MPV has a spread of response of ~4‰

Results consistent with Module0 experimental data –
10 hours data taking simulated



Step	μ (ps)	σ (ps)
0	0.0 ± 0.4	28.8 ± 0.4
1	–0.4 ± 0.4	17.7 ± 0.3
2	–0.7 ± 0.4	15.0 ± 0.2
3	–10.0 ± 0.4	14.4 ± 0.2
4	–13.0 ± 0.4	14.5 ± 0.2



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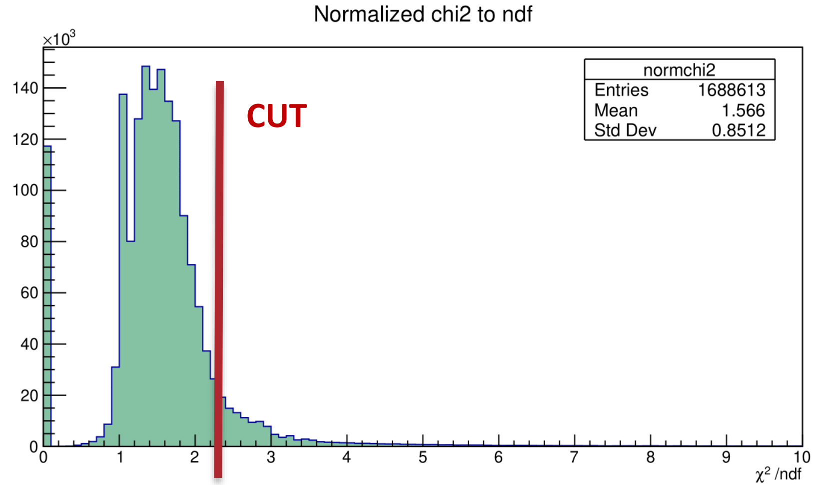
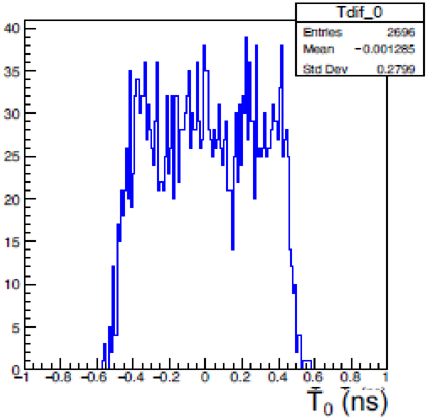
Event selection

- At least 3 crystals with E_{cry} > 15 MeV connected to a calorimeter cluster
- Selection of three types of straight tracks:
  - Vertical tracks, requiring ΔX < 35 mm
  - Diagonal tracks i.e. CRs hitting 1 crystal per layer
  - General tracks χ^2/Ndf < 2.5 from the linear fit applied to cell center positions

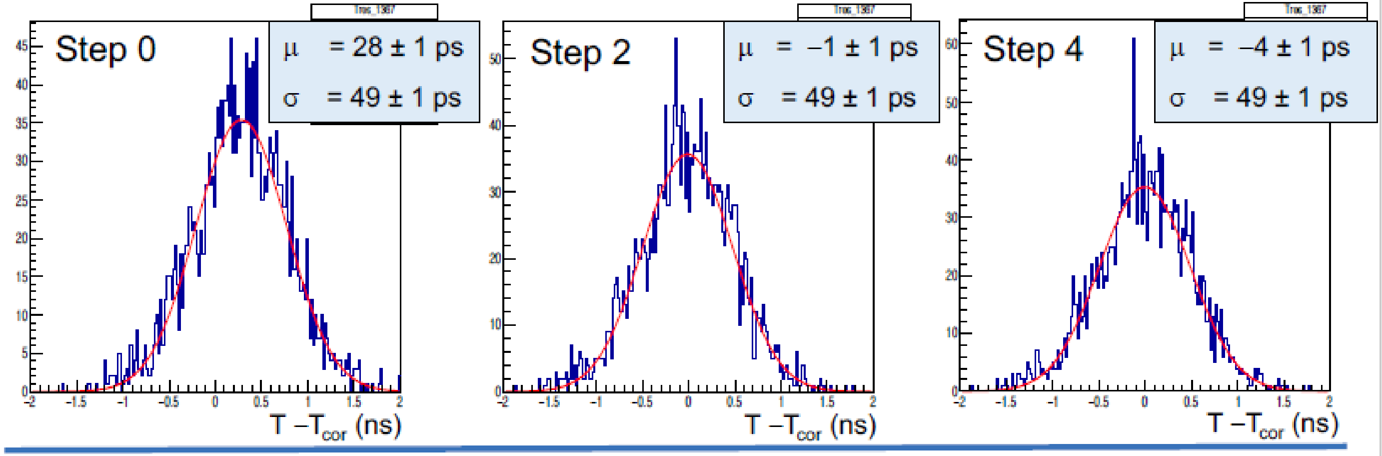


In-situ calibration – Time alignment t0 offset



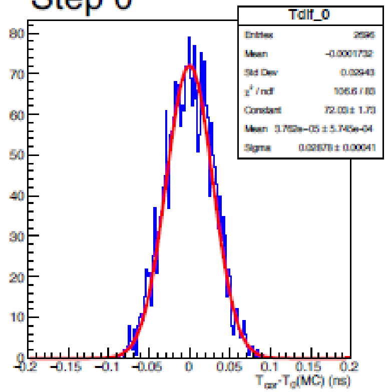
T_0 offset for each readout channel applied:
± 0.5 ns uniform distribution

Time distribution for a specific channel (ROid =1367)
at different steps of the procedure

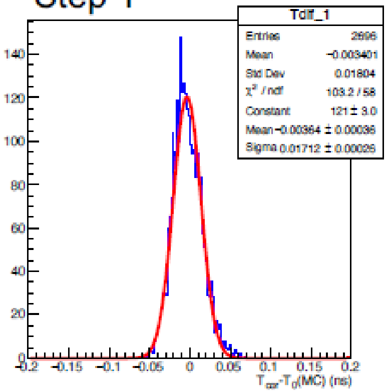


In-situ calibration – Time alignment steps

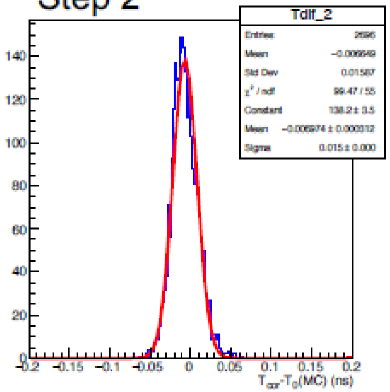
Step 0



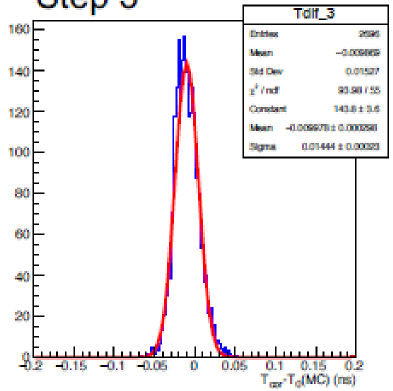
Step 1



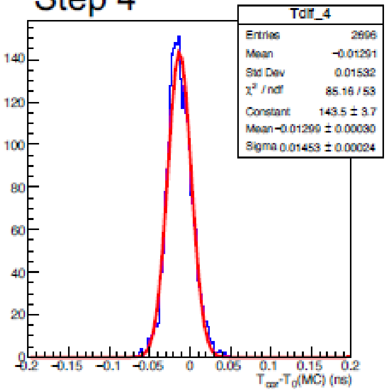
Step 2



Step 3



Step 4



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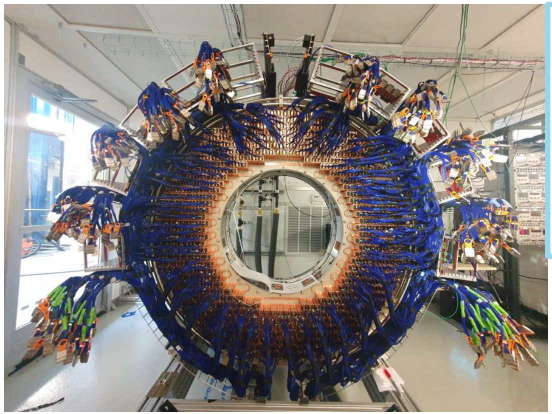
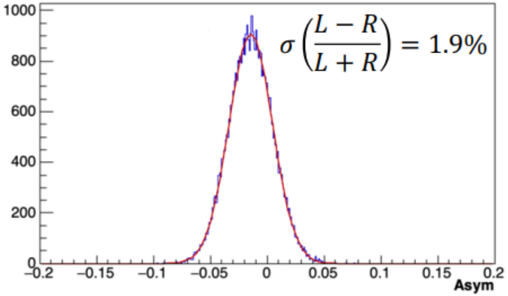
Calorimeter status as today

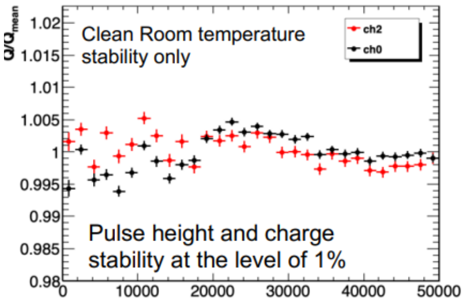


- Both calorimeter disks have been assembled
- Disk-1 is fully cabled
- Disk-0 cabling ongoing

DAQ calorimeter cables and optical fiber cables are being installed in the Mu2e experiment hall



24h



First VST test with:
- Laser pulses on calorimeter disk
- Full electronic chain

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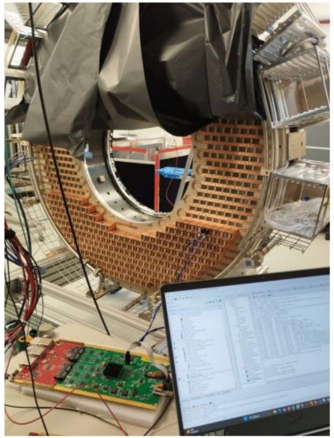
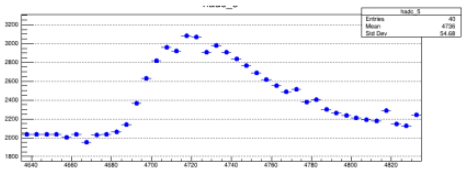
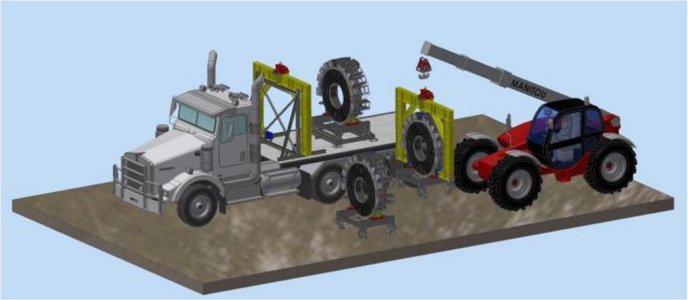
Conclusions & Next steps

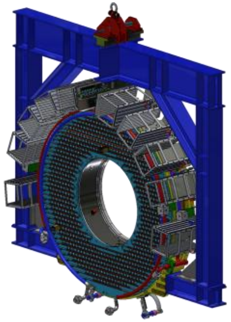
We are preparing to read half calorimeter:

- 4 PC server installed can read more than ½ Disk-1
- We are ultimating the firmware for the DAQ to read the first events









The GOAL is to have the first test of Disk-1 with cosmic rays in summer 2024

We plan the calorimeter transport from the cleanroom to the Mu2e Hall this fall