INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

International MUON Collider Collaboration

Crilin: a semi-homogeneous calorimeter solution for the future Muon Collider

Elisa Di Meco on behalf of the Crilin Calorimeter group

aMUSE General Meeting Workshop YSF – Padova, Italy, Sept 18, 2024

Road to 2025

Master thesis (2022):

Thesis project fully dedicated to the first protoype of Crilin

→ **FEE testing**
→ **SiPM radiation hardness**
→ **Proto-0 H2 Test beam**

1st PhD year (2023)

Half on PADME Run3 analysis, half on Crilin Proto-1 testing

→ **Proto-1 BTF Test beam**
→ **Proto-1 H2 Test beam**

2nd PhD year (2024)

Half on PADME Run3 analysis, half on Crilin Proto-1 irr studies

→ **TB for LY evaluation before and after γ-irradiation**

3rd PhD year (2025)

Half on PADME Run3 analysis, half on Crilin final matrix studies

→ **Test beams and lots of funny stuff :)**

Crilin and the Muon Collider

Crilin (crystal calorimeter with longitudinal information): ECAL R&D for the future Muon Collider, which is being considered as an option for a next generation facility; studies for 3 and 10 TeV designs are being carried out.

Muon Collider pros:

- **m_{μ}>>m_{e}** (negligible synchrotron radiation)
- **point-like particle:** all energy is available in collisions
- perfect for **direct search of heavy states**

Muon Collider cons:

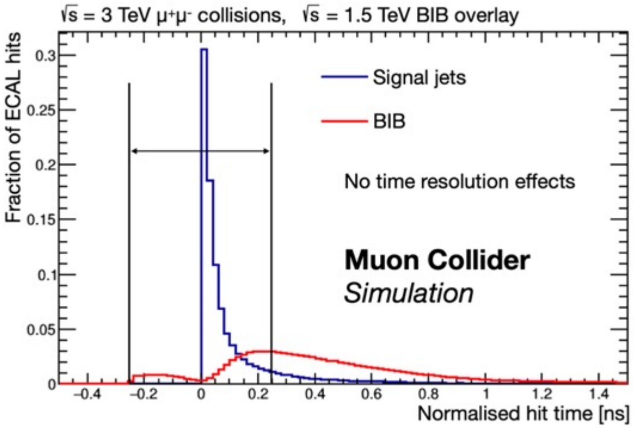
- **τ_0= 2.2μs :** very fast cooling and fast-ramping magnet system needed
- **μ** decay + interaction with machine: **beam-induced background (BIB)**, partially shielded by nozzles

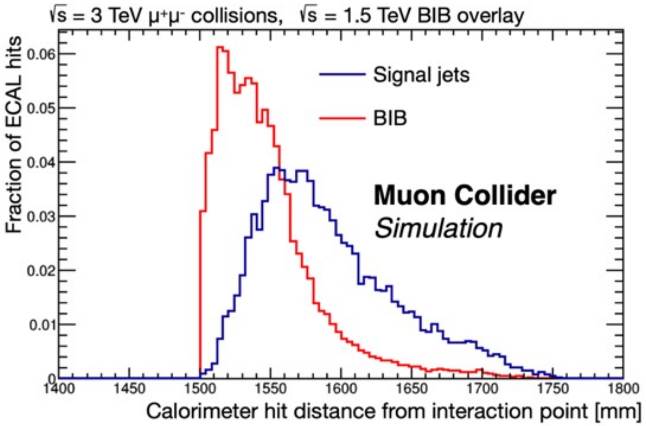
→ detectors must be able to cope with the BIB and to have good physics performances

Muon Collider requirements

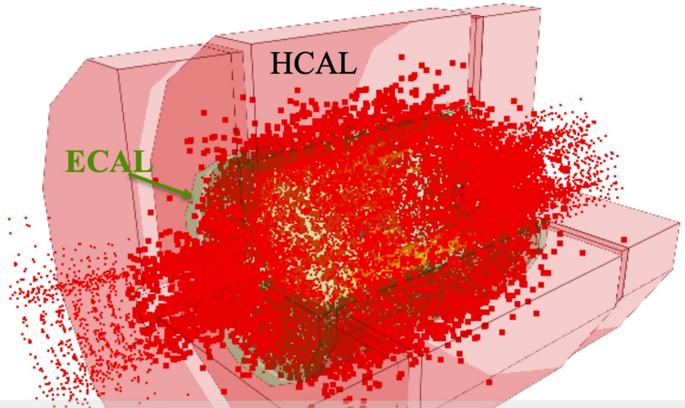
BIB in the ECAL region (after nozzles and tracking system):

- Flux of 300 particles per cm^2 through the ECAL surface mainly γ (96%) and n (4%), average photon energy 1.7 MeV
- **Time of arrival flatter** throughout the bunch crossing → can exclude most of BIB with an acquisition window of ~240 ps
- Different **hit longitudinal profile** wrt signal
- **Total Ionising Dose**: ~1 kGy/year
- **Neutron fluence**: 10^{14} $n_{1MeVneq}/cm^2$ / year





BIB hits in the calorimeters



a MC ECAL should have:

- σ_t ~ 80 ps
- longitudinal segmentation
- fine granularity to distinguish BIB and signal
- radiation resistance
- σ_E/E ~ $10\%/\sqrt{E}$

→ The W-Si sampling calorimeter (CALICE-like) stands out as a strong contender: initially considered as the primary candidate.

The Crilin calorimeter

Crilin is a **semi-homogeneous** electromagnetic calorimeter made of **crystal matrices** interspaced and readout by **SiPMs.** Each crystal is independently read by 2 channels, each consisting of 2 SiPMs in series.

Key Features:

Excellent timing: (<100 ps) to reject the BIB out- of-time hits and for good pileup capability.

Longitudinal segmentation: allows to recognize fake showers from the BIB.

Fine granularity: reduced hit density in a single cell and distinguish the BIB hits from the signal.

Good resistance to radiation: good reliability during the experiment

Crystal choice:

High-density crystal: selected to balance the need for increased layer numbers with space constraints

Speed response: Cherenkov/fast crystals, ensuring accurate and timely particle detection

→ **PbF2, $PbWO_4$-UF, LYSO…**

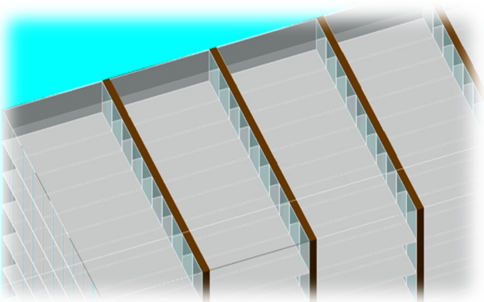
*S. Ceravolo et al 2022 JINST **17** P09033*

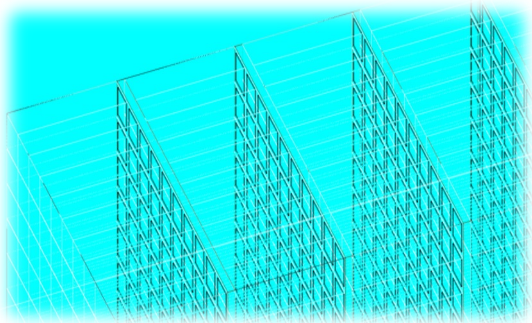
Differentiation:

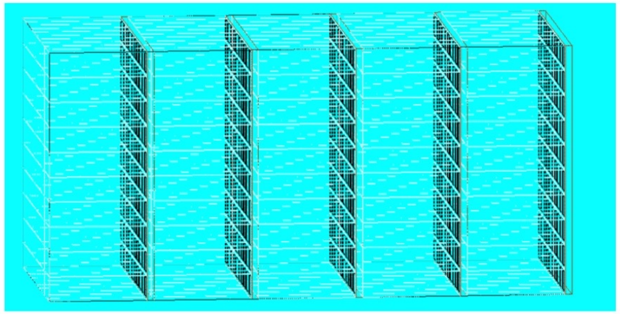
Semi-homogeneous : strategically between homogeneous and sampling calorimeters → able to exploit the strengths of both kinds

Flexibility: able to modulate energy deposition for each cell and adjust crystal size for tailored solutions

Compactness: Unlike segmented or high granularity calorimeters CRILIN can optimize energy detection while staying compact





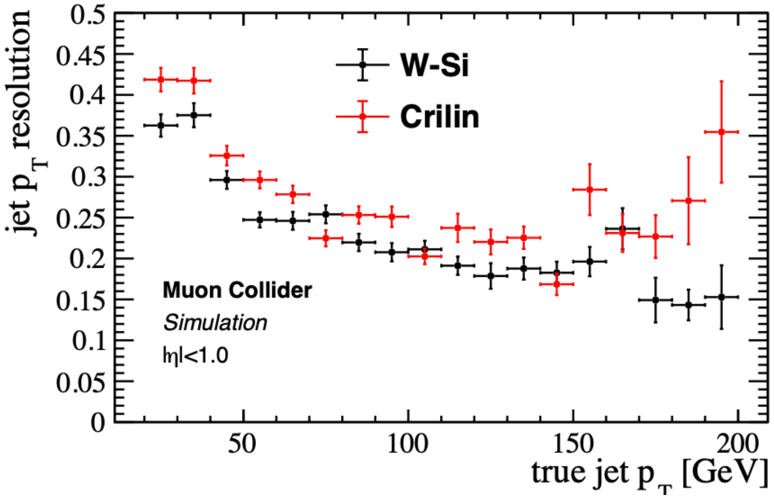


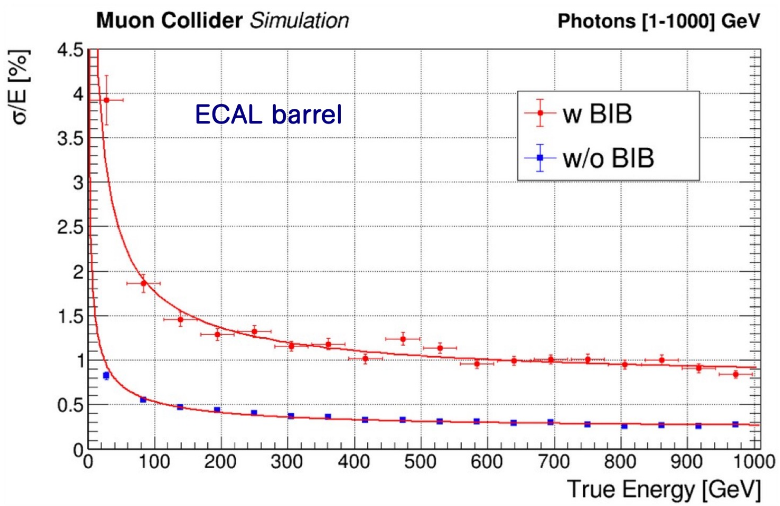
Simulated performances

- The ECAL barrel with Crilin technology has been implemented in the Muon Collider simulation framework
  - ➢ 5 layers of 45 mm length, 10 X 10 mm^2 cell area → **21.5 X_0**
  - ➢ **In each cell:** 40 mm PbF_2 + 3 mm SiPM + 1 mm electronics + 1 mm air

See C. Giraldin's talk

- Design optimized for BIB mitigation: having thicker layers, the BIB energy is integrated in large volumes → reduced statistical fluctuations of the average energy
- 5 layers wrt to 40 layers of the W-Si calorimeter → **factor 10 less in cost (6 vs 64 Mchannels)**





w/out BIB

$$\frac{\sigma_E}{E} \sim \frac{4\%}{\sqrt{E[GeV]}} \oplus 0.2\,\%$$

w/ BIB

$$\frac{\sigma_E}{E} \sim \frac{15\%}{\sqrt{E[GeV]}} \oplus 0.8\,\%$$

R&D status

Prototype versions

- Proto-0 (2 crystals → 4 channels)
- Proto-1 (3x3 crystals x 2 layers → 36 channels)

Front-end electronics

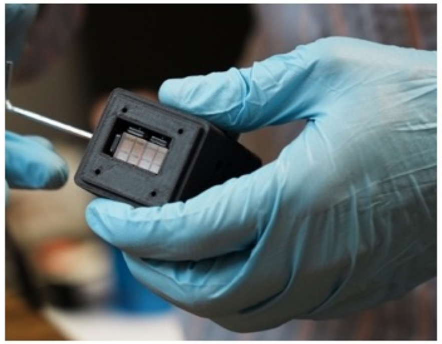
- Design completed
- Production and QC completed

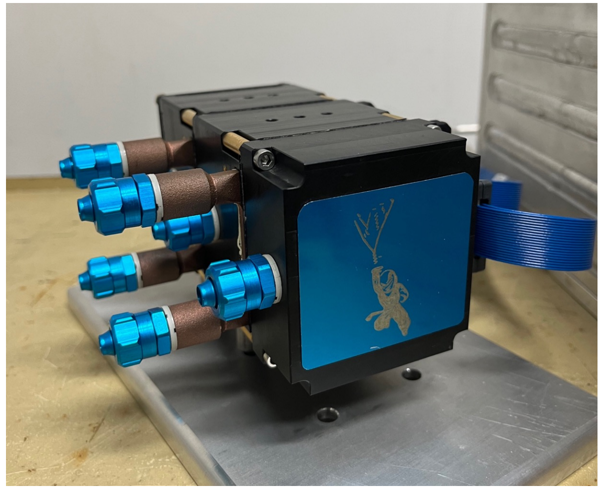
Radiation hardness campaigns

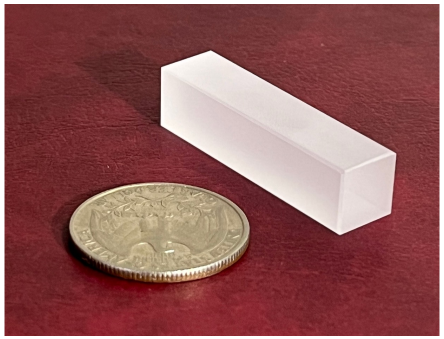
See E. Diociaiuti's talk

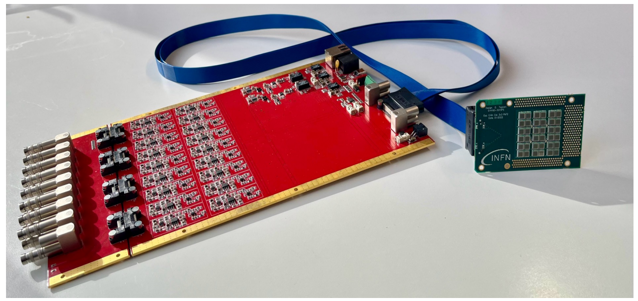
Beam test campaigns

- Proto-0 at CERN H2 (August 2022)
- Proto-1 at LNF-BTF (July 2023-April 2024)
- Proto-1 at and CERN (August 2023)





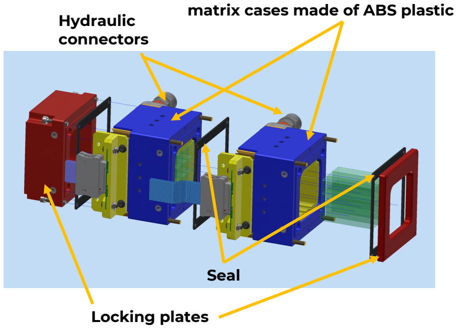


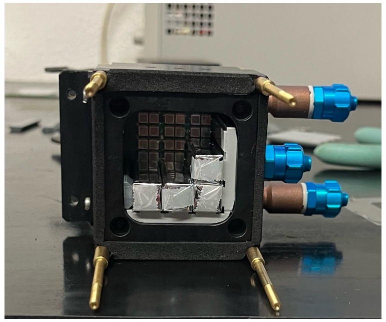


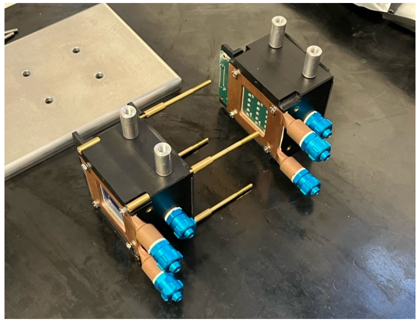
Proto-1: Mechanics and Electronics

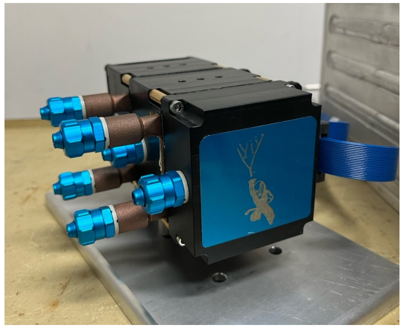
Mechanics:

- Two stackable and interchangeable submodules assembled by bolting, each composed of 3x3 crystals+36 SiPMs (2 channel per crystal)
- light-tight case which also embeds the front-end electronic boards, and the heat exchanger needed to cool down the SiPMs.



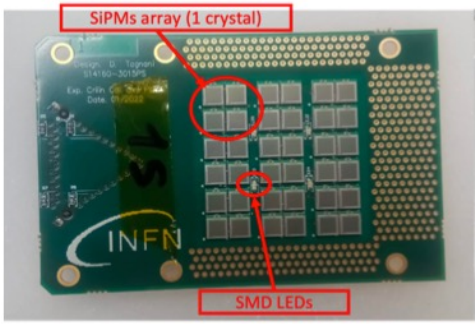


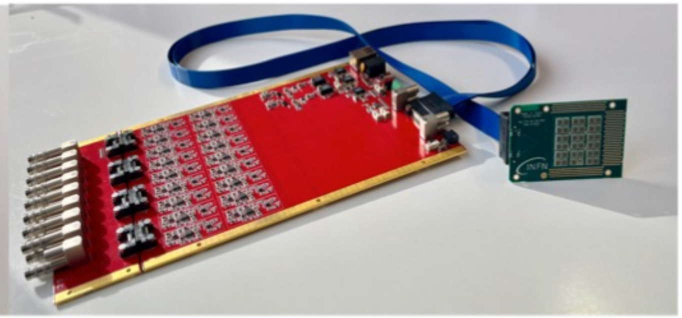




Electronics:

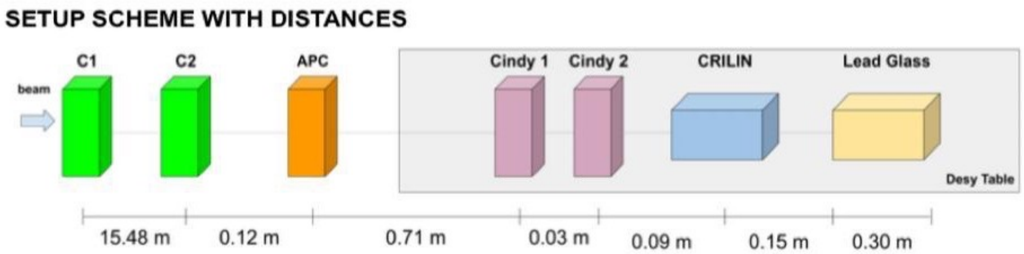
- **SiPMs board:** custom SiPM array board 36x10 µm Hamamatsu SMD SiPMs
- **Mezzanine board:** 18x readout channels → amplification, shaping and individual bias regulation, slow control routines

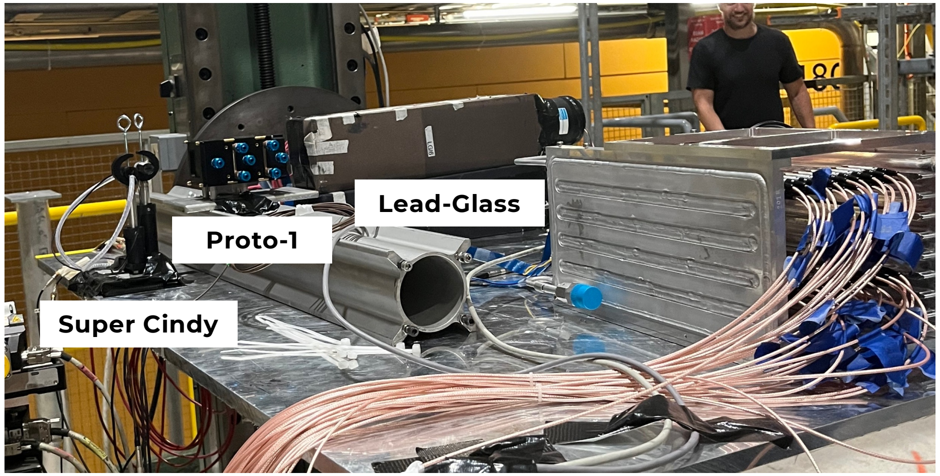


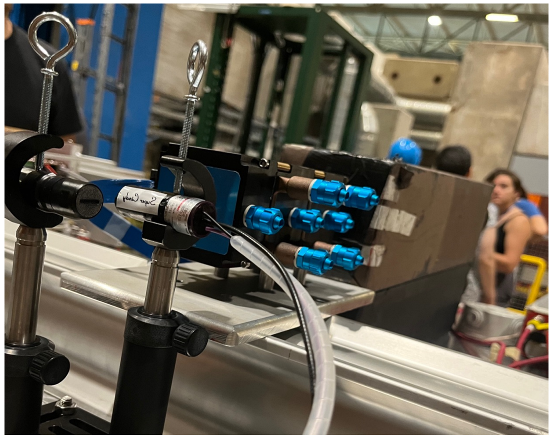


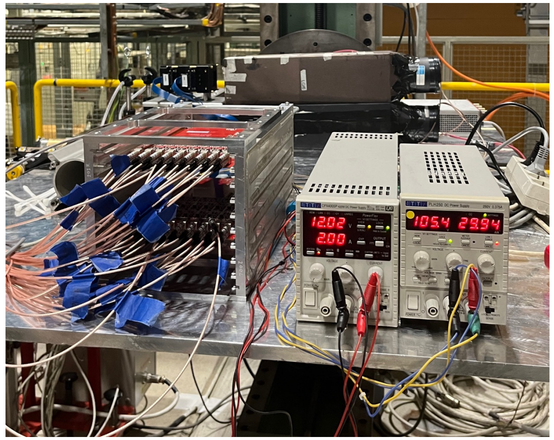
Beam test @ CERN

H2-SPS-CERN, August 2023







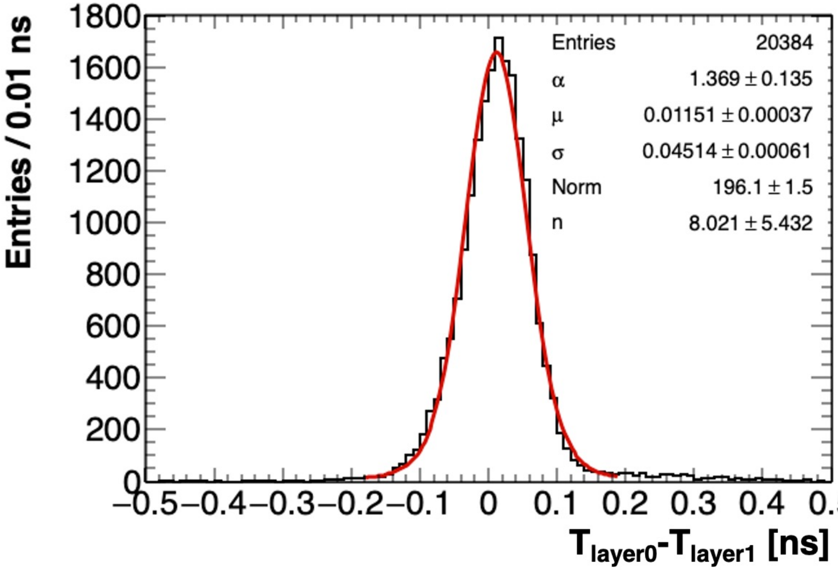


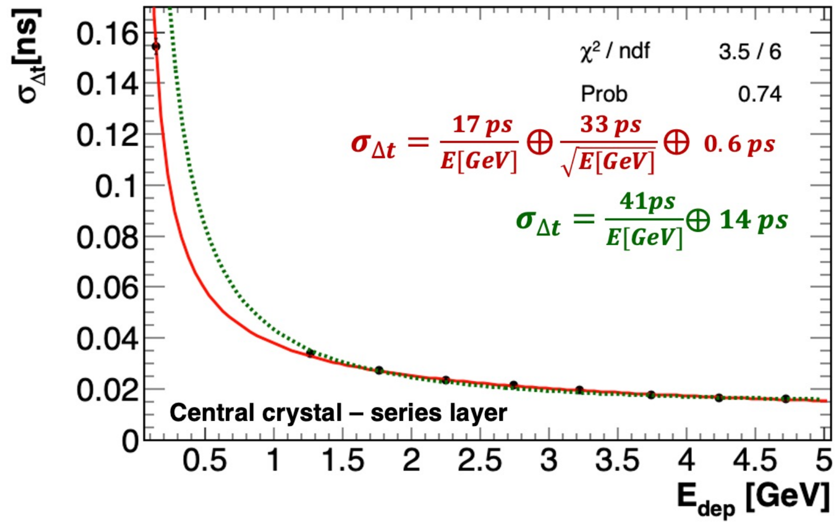
- Electron beam from 40 GeV up to 150 GeV
- Beam reconstructed with 2 silicon strip telescopes
- Data acquisition with 2 CAEN V1742 (32 ch each) modified @ 2 Vpp
- 5 Gs/s sampling rate

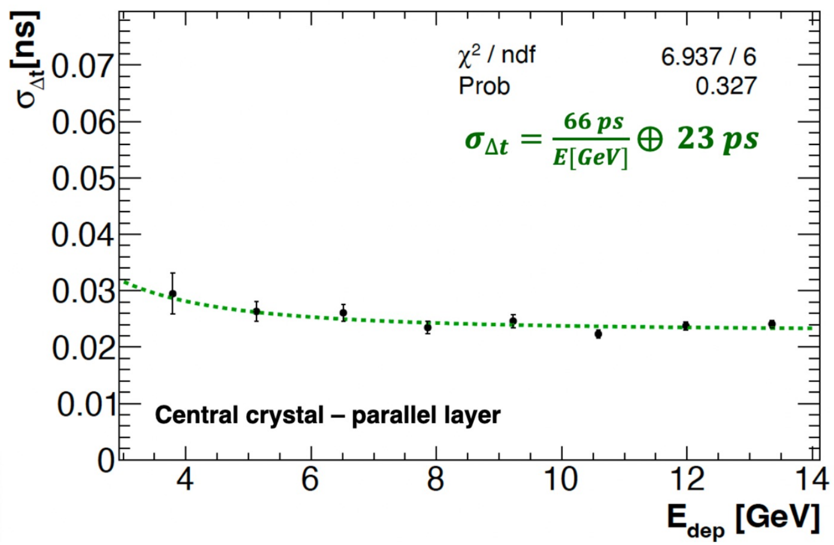
Beam test @ CERN: Timing

- Time Resolution of **O(20 ps)** both in the series and in the parallel layers using the SiPMs time difference of the central crystals

- Excellent results using most energetic crystal of different layers. **Time resolution dominated by the 2 boards synchronisation jitter** O(32ps)



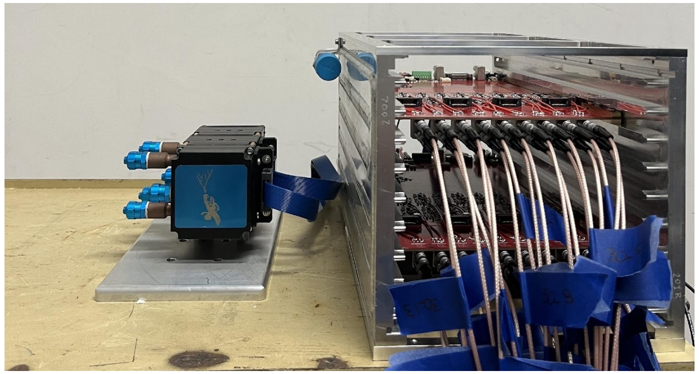


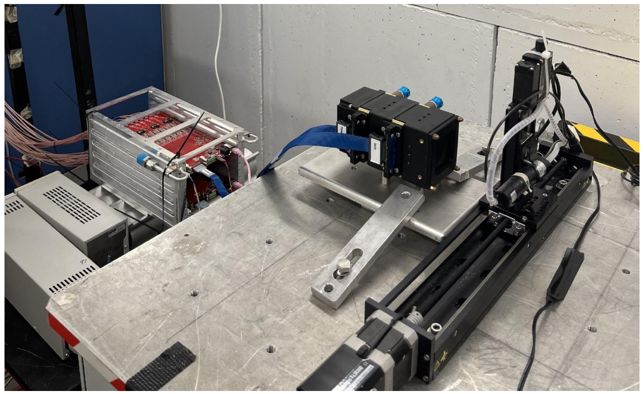


Beam test @ BTF

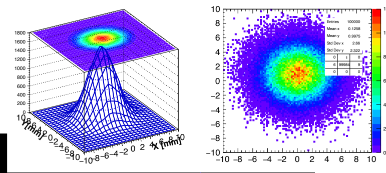
BTF, April 2024

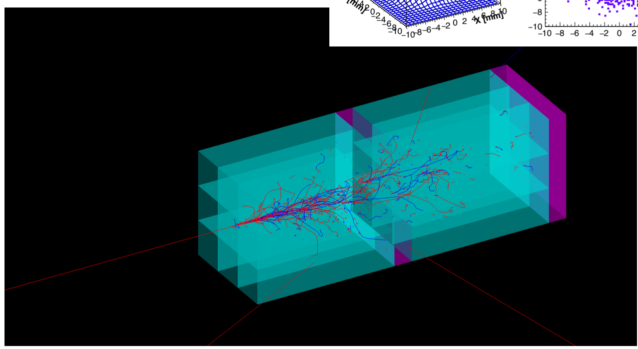
- Study of the LY loss of one layer of Proto-1 after Gamma ray irradiation
- Beam: 450 MeV electrons with multiplicity 1
- Beam centered on a different crystal at each run

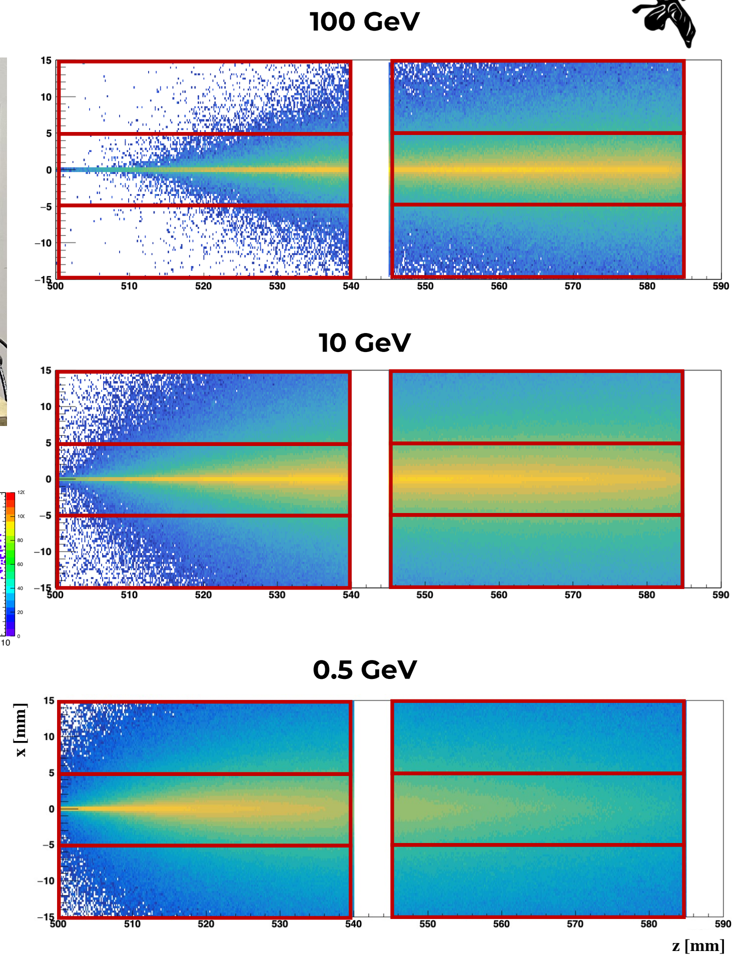




Monte Carlo





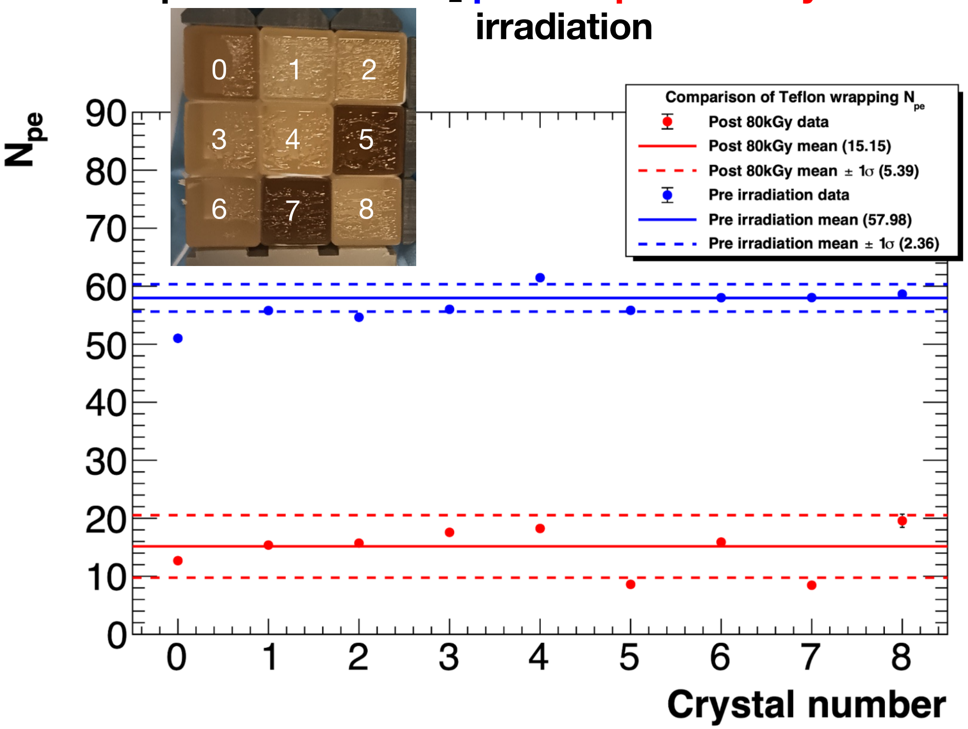


Beam test @ BTF: crystals

- Crystals tested with two different wrapping, Teflon and Mylar, up to 80 kGy
- LY loss evaluated through variation in charge and number of photo-electrons

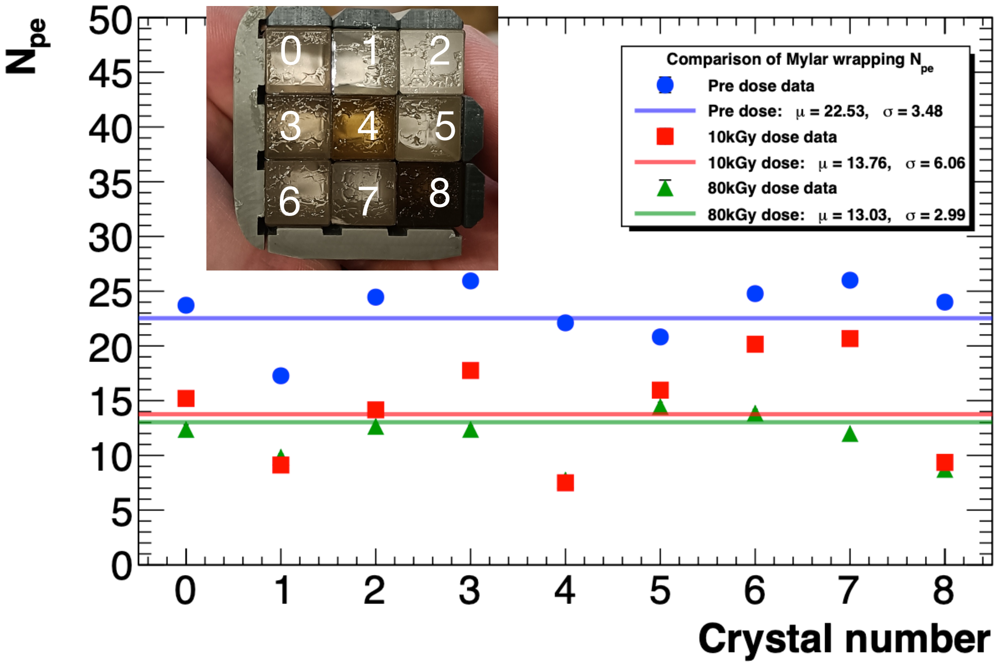
Telfon wrapping

Npe values of PbF_2 pre and post 80 kGy irradiation



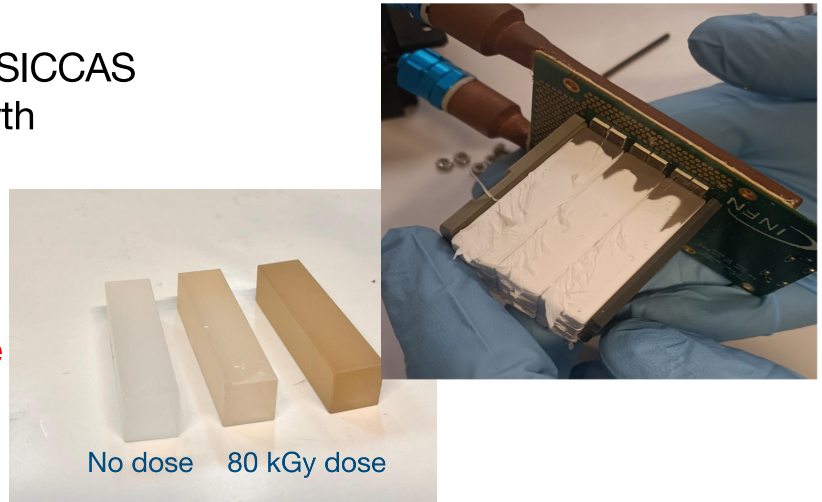
Mylar wrapping

Npe values of PbF_2 pre, after 10 kGy and after 80 kGy irradiation

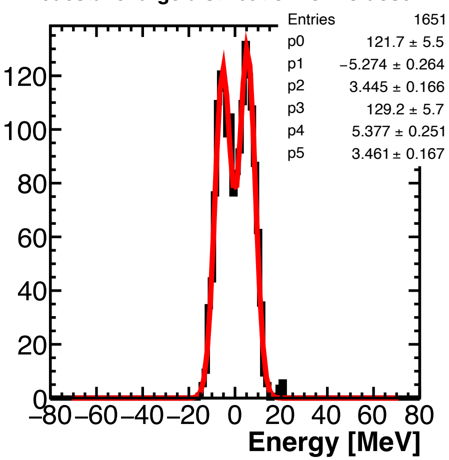


Beam test @ BTF: considerations

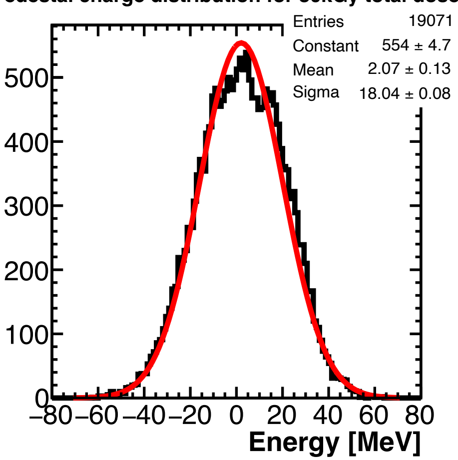
- Considerable variability in crystals' response to radiation, despite SICCAS claiming use of high-purity (>99.9%) PbF_2 powder for crystal growth
- Crystals evident loss of transparency
- Transparency loss was uniform length-wise in the crystals
- Teflon was damaged and brittle
- SiPM dark counts increases significantly with the absorbed dose
- New tests planned to evaluate SiPMs PDE loss and optical grease degradation



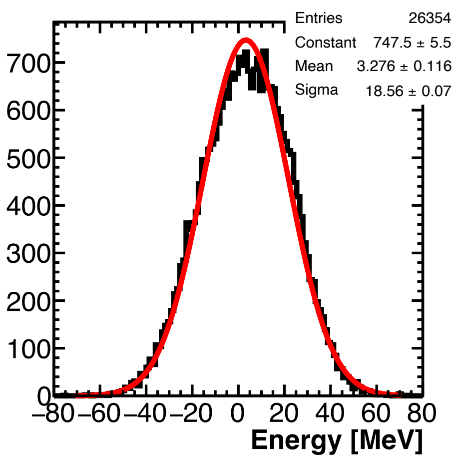
Pedestal charge distribution for no dose



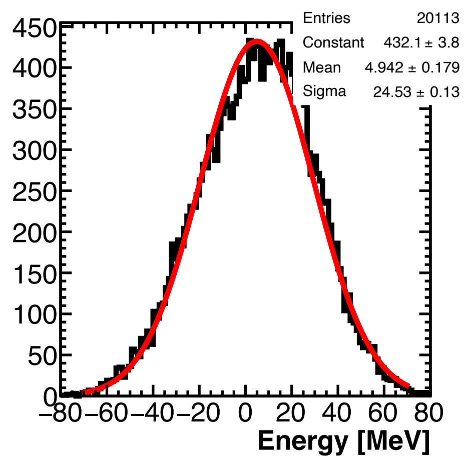
Pedestal charge distribution for 80kGy total dose



Pedestal charge distribution for 90kGy total dose



Pedestal energy distribution for 160kGy total dose



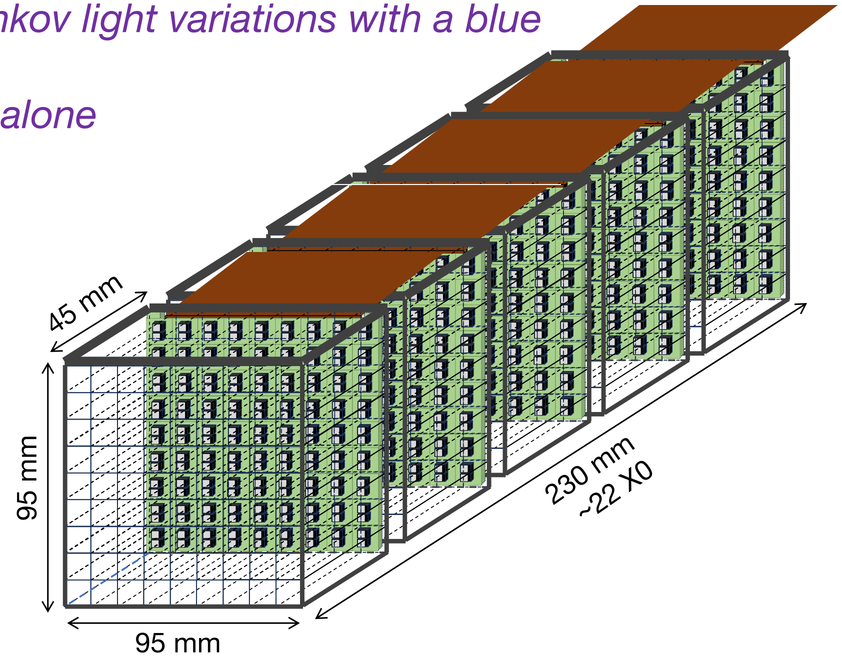
Summary

- **Time resolution**: < 40 ps for single crystals, for E_{dep} > 1 GeV
- **Radiation resistance:** PbF_2($PbWO_4$-UF) robust to > 35(200) Mrad and SiPMs validated up to 10^{14} n_{1MeV}/cm^2 displacement-damage eq. fluence

- *Use PbWO-UF or LYSO in the first calorimeter layer.*
- *Conduct new irradiation tests and monitor Cherenkov light variations with a blue laser.*
- *Simultaneously test crystals with SiPM and SiPM alone*

Next steps (2024 - 2025)

➢ We submitted and won a PRIN grant for the project CALORHINO: *an innovative radiation-hard calorimeter proposal for a future Muon Collider Experiment*.
→ founds assigned to develop a 5x5x4 (layers) Crilin prototype: 1 M_R – 16.8 X_0

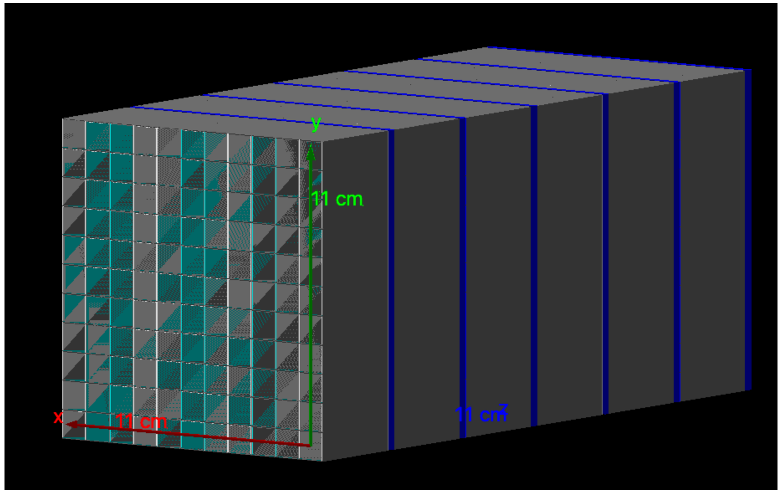


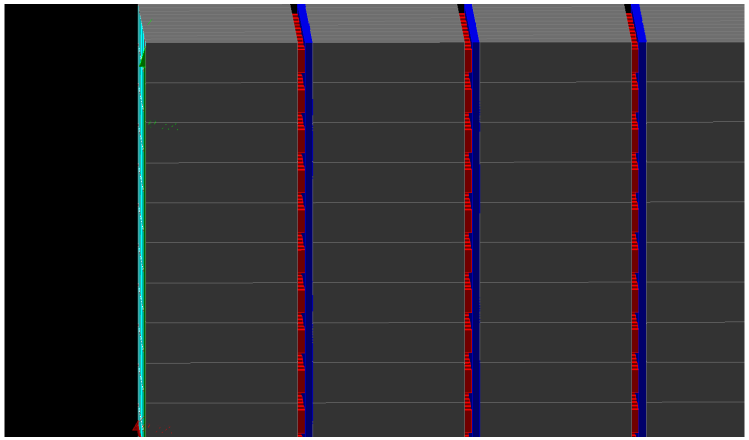
DRD6-WP3 from 2025

➢ Expanding upon the PRIN prototype to a 9x9x5(layers) configuration, with a target of 2 M_R – 22 X_0.

Geant4 simulation of the new prototype

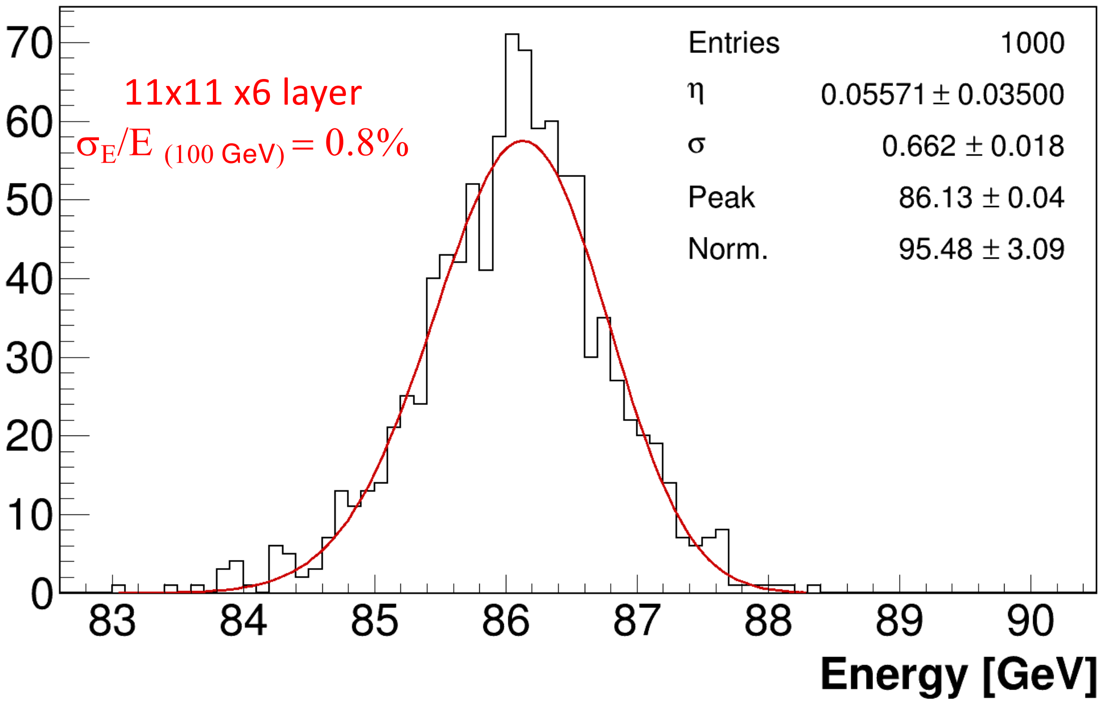
- Initial proposal **11x11 x6 layer** (crystals 10x10x40 mm^2 each) → **2.5 R_M – 26 X_0**
- Crystals wrapped in 150 um Mylar foils and placed a 150 um aluminum honeycomb
- 2 SiPMs 3x3 mm^2 per cystal, 2 mm thick, per layer
- 2 mm thck PcB, per layer
- Photostatistics and noise measured during beam tests : Poisson 0.3 p.e./MeV, Gauss 5 MeV

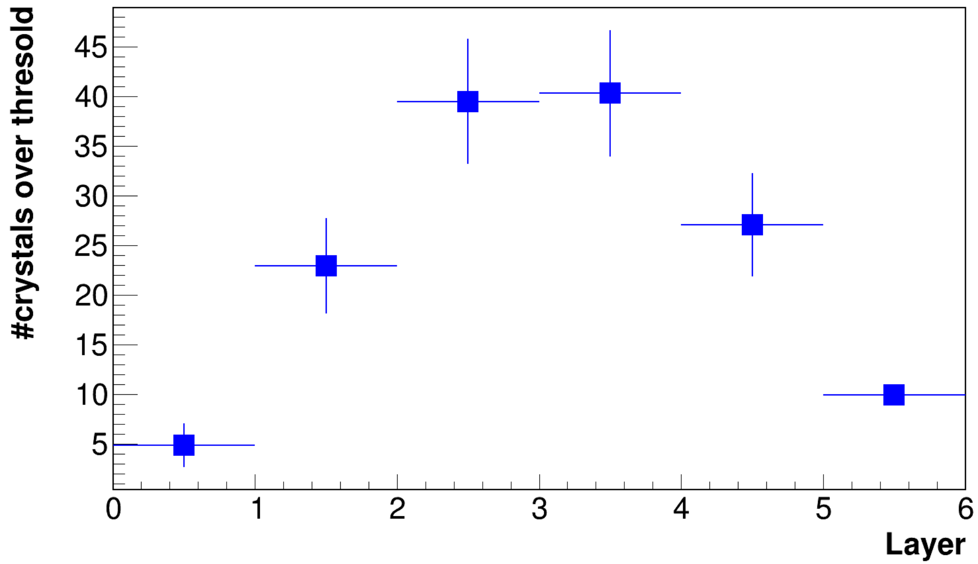




Number of crystals optimization

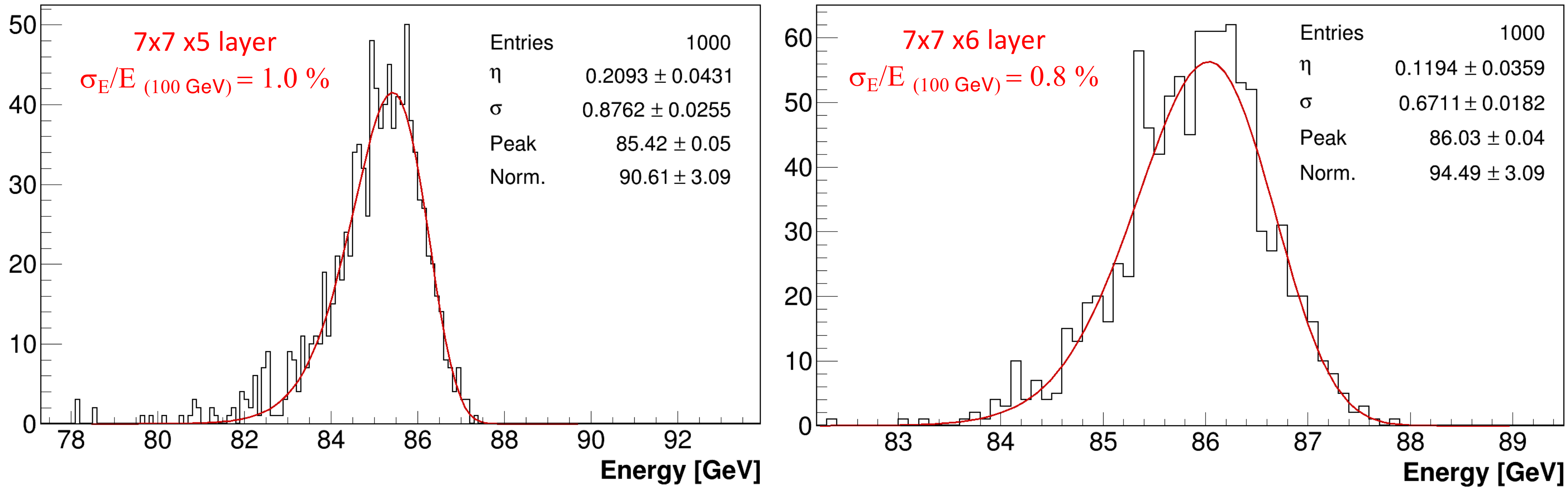
- By setting a threshold similar to that expected for the Muon Collider (i.e. 40 MeV) per crystal, we optimized the number of crystals, with the goal of minimizing the energy resolution loss → optimization performed for an electron beam with 100 GeV of energy.





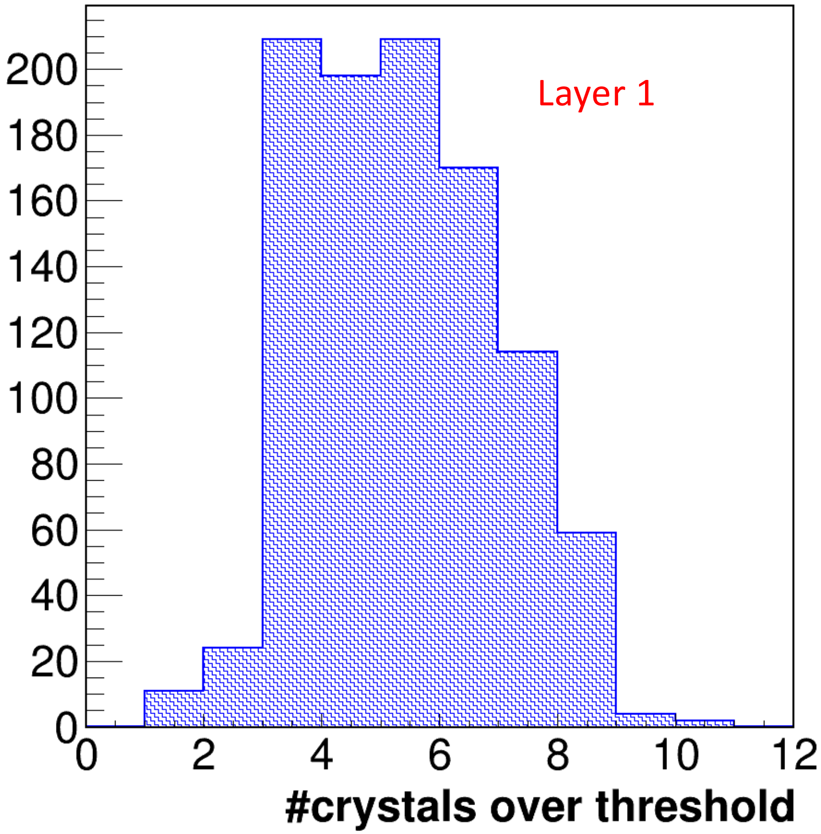
Number of layers optimization

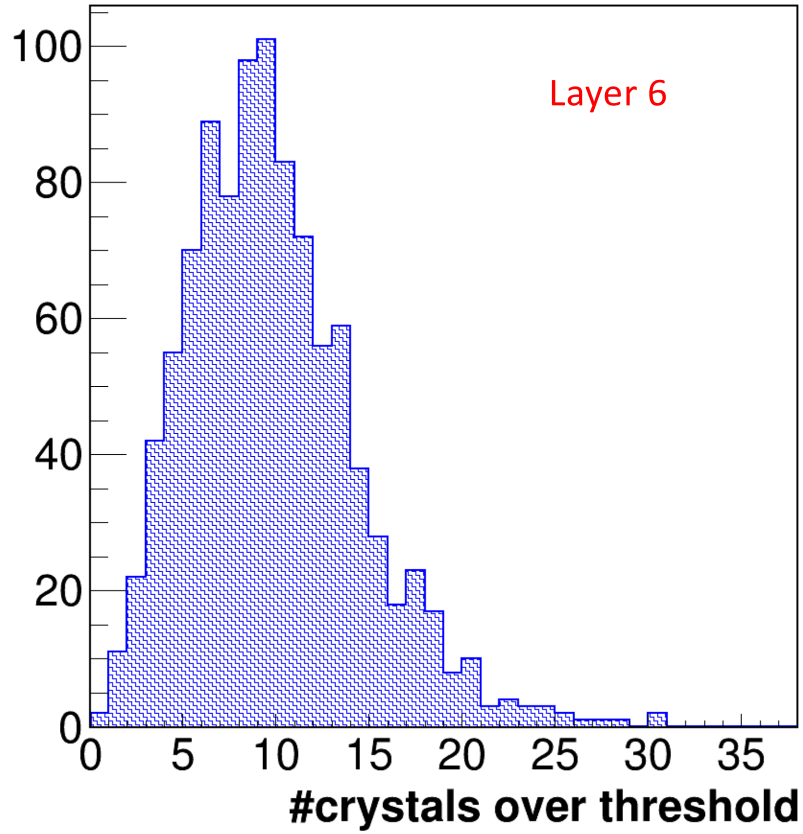
- The average number of crystals triggered above the threshold leads to a 7x7 configuration for layers 2, 3, 4, and 5.
- **The sixth layer is crucial for maximizing energy resolution**→ longitudinal leakage creates a much larger energy fluctuation compared to lateral leakage (for the same amount of leakage).



Number of layers optimization-2

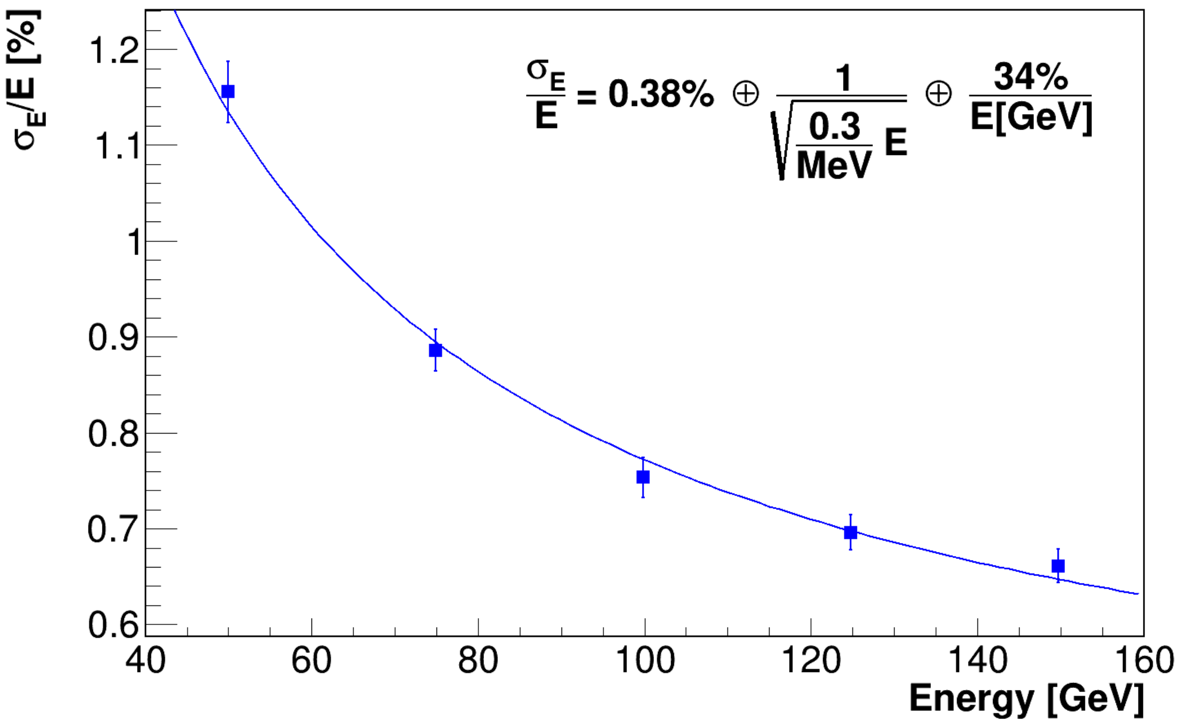
- The average number of crystals triggered above the threshold leads us to a 5x5 configuration for layers 1 and 6.

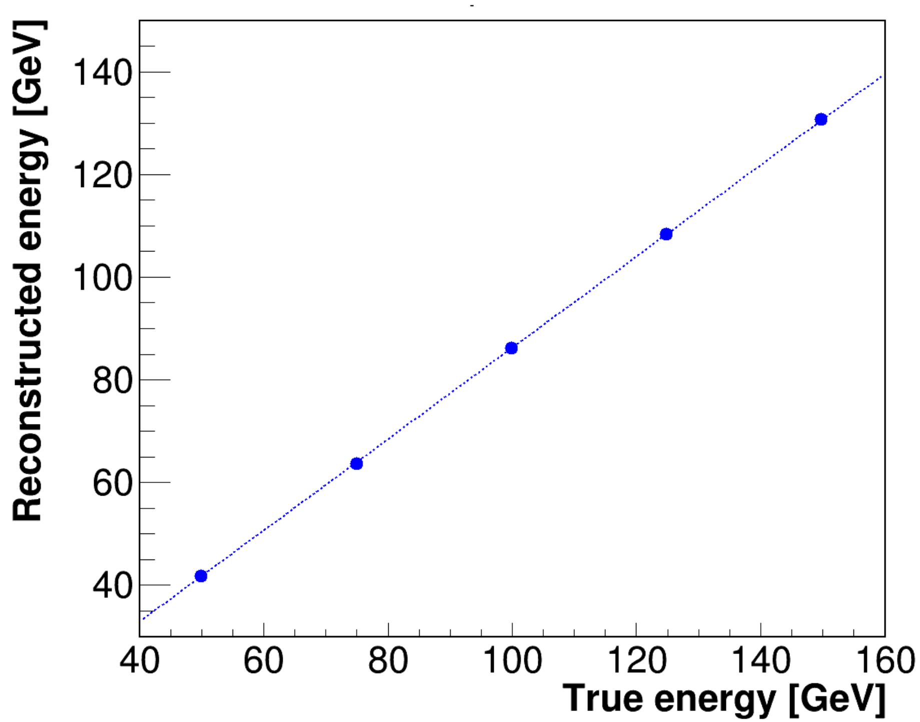




Energy resolution

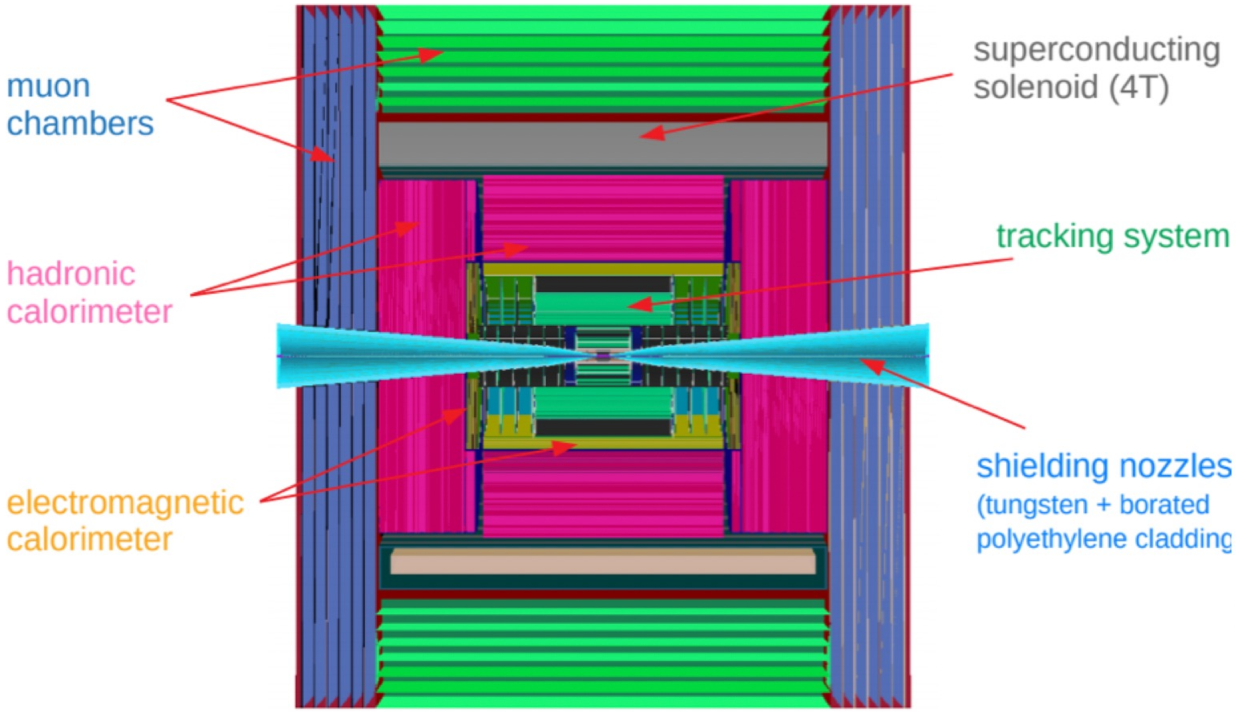
- Energy Resolution and Linearity as a function of E for the reduced matrix:
- 7x7 in layers 2, 3, 4, and 5, and 5x5 in layers 1 and 6 → ~250 crystals in total.





Backup slides

Muon Collider



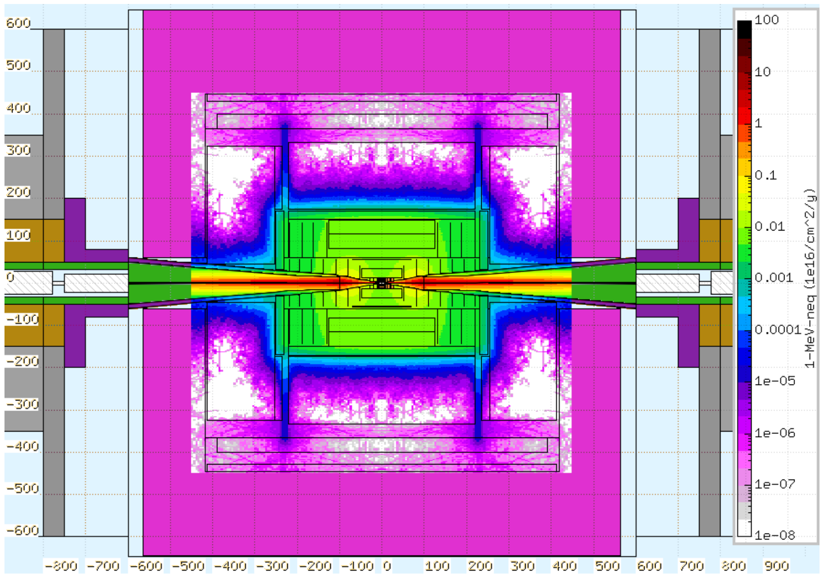
Main issues: BIB and radiation damage

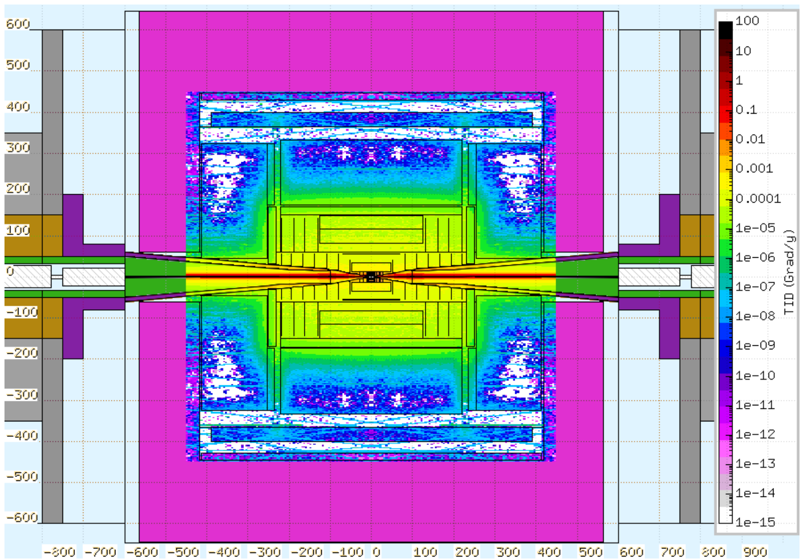
Optimized detector interface:

- Based on CLIC detector, with modification for BIB suppression.
- Dedicated shielding (nozzle) to protect magnets/detector near interaction region.

Radiation enviroment

FLUKA simulation for the BIB at $\sqrt{s}$=1.5 TeV



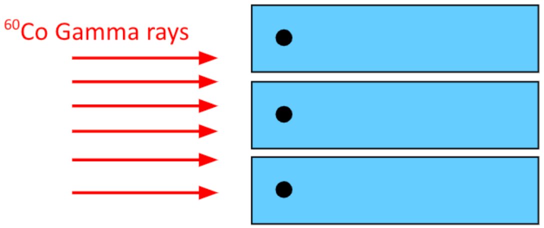


- **Neutron fluence** $\sim \mathbf{10^{14}}$ $n_{1MeVeq}/\boldsymbol{cm^2}$**year** on ECAL.
- **TID** ~ **1 kGy/year** on ECAL.

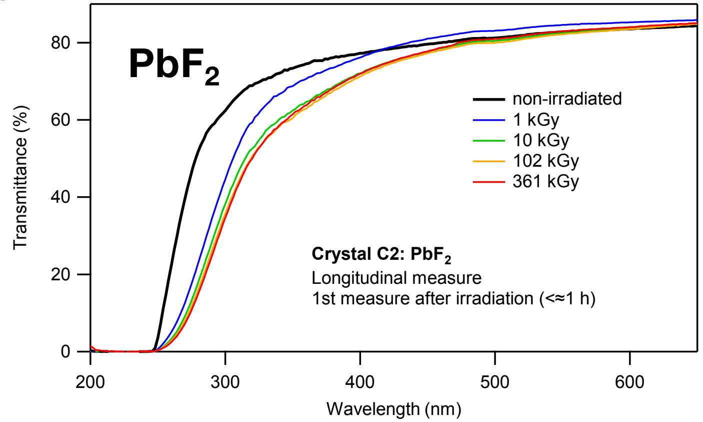
Crystal radiation hardness

Neutron fluence: $\sim 10^{14} n_{1MeVeq}/cm^2$ **year** on ECAL **TID:** $\sim$ **1 kGy/ year** on ECAL.

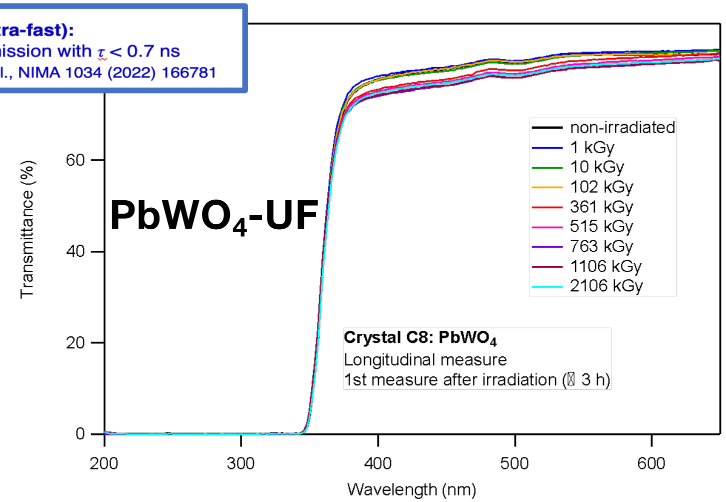
Radiation hardness of two PbF_2 and $PbWO_4$-UF crystals (10x10x40 mm^3) checked for TID and neutrons



Source is 20 cm apart



PWO-UF (ultra-fast):
Dominant emission with τ < 0.7 ns
M. Korzhik et al., NIMA 1034 (2022) 166781



Crystal	PbF_2	PWO-UF
Density [g/cm^3]	7.77	8.27
Radiation length [cm]	0.93	0.89
Molière radius [cm]	2.2	2.0
Decay constant [ns]	-	0.64
Refractive index at 450 nm	1.8	2.2
Manufacturer	SICCAS	Crytur

- **For PbF_2:**
  - **after a TID > 350 kGy no significant decrease** in transmittance observed.
  - Transmittance after up to 10^{13} n/cm^2 irradiation showed no deterioration
- **For $PbWO_4$-UF:**
  - **after a TID > 2 MGy no significant decrease** in transmittance observed.

SiPMs radiation hardness

Neutron fluence: $\sim 10^{14} n_{1MeVeq}/cm^2$ **year** on ECAL **TID:** ~ **1 kGy/ year** on ECAL.

Neutrons irradiation: 14 MeV neutrons with a total fluence of 10^{14} n/cm^2 for 80 hours on a series of two SiPMs (10 and 15 μm pixel-size).

Extrapolated from I-V curves at 3 different temperatures:

- Currents at different operational voltages.
- Breakdown voltages;

15 μm pixel-size

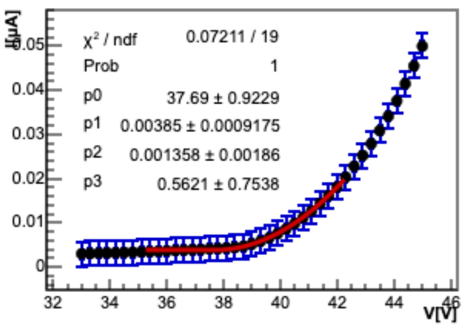
T [°C]	V_{br} [V]	I(V_{br}+4V) [mA]	I(V_{br}+6V) [mA]	I(V_{br}+8V) [mA]
-10 ± 1	75.29 ± 0.01	12.56 ± 0.01	30.45 ± 0.01	46.76 ± 0.01
-5 ± 1	75.81 ± 0.01	14.89 ± 0.01	32.12 ± 0.01	46.77 ± 0.01
0 ± 1	76.27 ± 0.01	17.38 ± 0.01	33.93 ± 0.01	47.47 ± 0.01

10 μm pixel-size

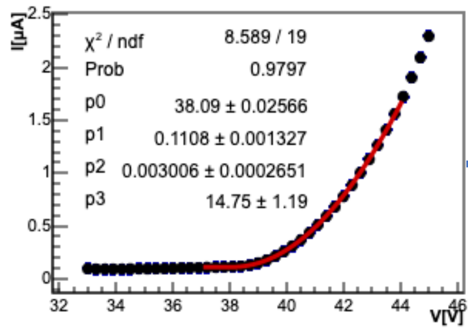
T [°C]	V_{br} [V]	I(V_{br}+4V) [mA]	I(V_{br}+6V) [mA]	I(V_{br}+8V) [mA]
-10 ± 1	76.76 ± 0.01	1.84 ± 0.01	6.82 ± 0.01	29.91 ± 0.01
-5 ± 1	77.23 ± 0.01	2.53 ± 0.01	9.66 ± 0.01	37.51 ± 0.01
0 ± 1	77.49 ± 0.01	2.99 ± 0.01	11.59 ± 0.01	38.48 ± 0.01

For the expected radiation level, **the best SiPMs choice are the 10 μm ones** for their minor dark current contribution.

Pre 10kGy



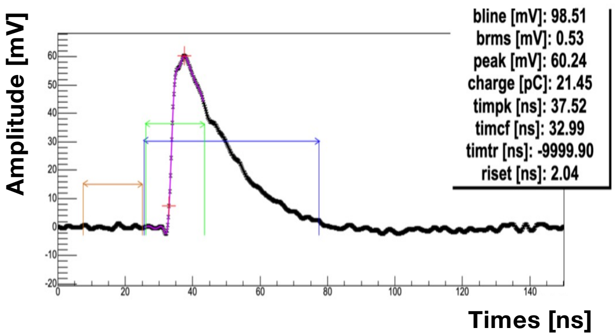
Post 10kGy



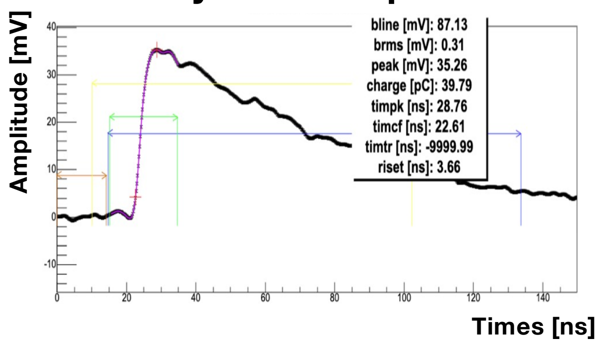
Dark current @ Vop goes from 12 nA to 600 nA

Beam test @ CERN: Configuration

1st layer: SiPMs series



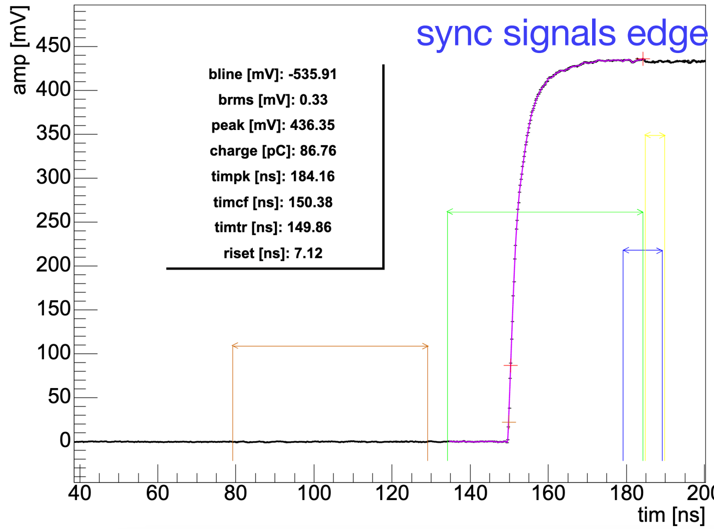
2nd layer: SiPMs parallel



- **Two different connection in the two layers:** series and parallel
- **Low pass filtering** (Bessel 2nd order) cutoff_parallel ~ 2* cutoff_series.
- Cut-off frequency based on two parameters: baseline RMS and risetime (10-90%)
- Wave quality flag based on baseline RMS, peak, and risetime to discard bad waves
- **Processing cuts:** peak > 2 mV

Syncronisation pulses reconstruction:

- **O(10 ps) ch-to-ch in the same chip**
- **O(30 ps) board-to-board jitter**

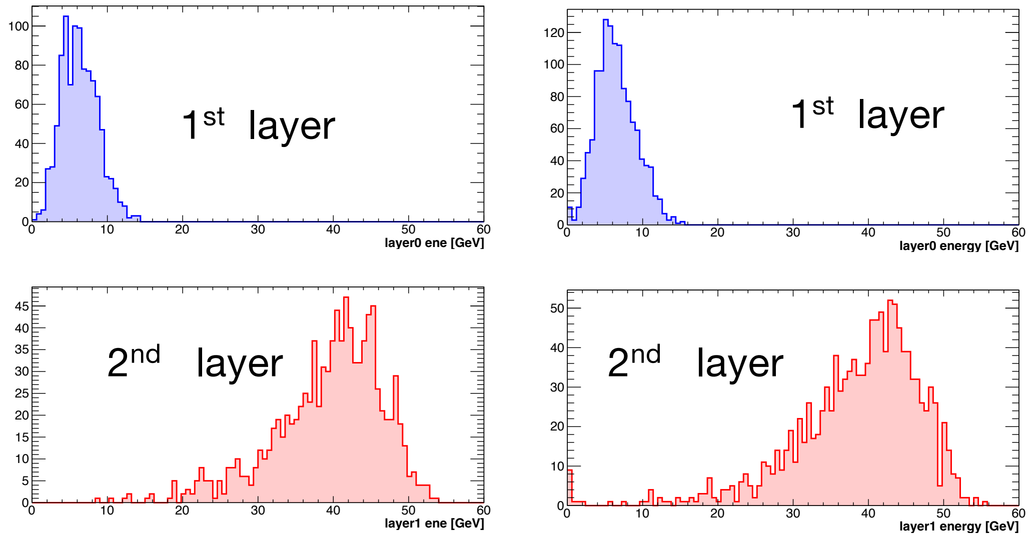


Beam test @ CERN: Energy

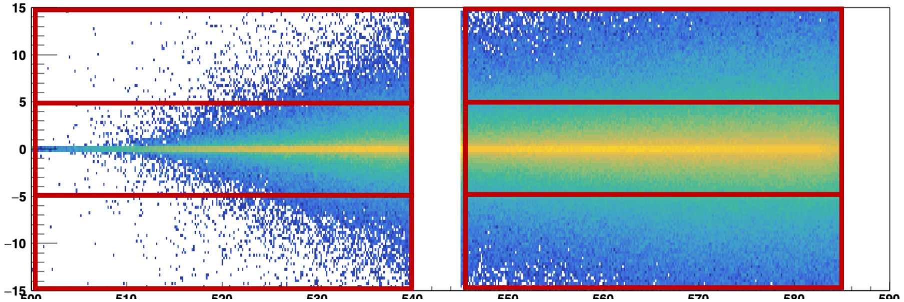
Good agreement between data e MC

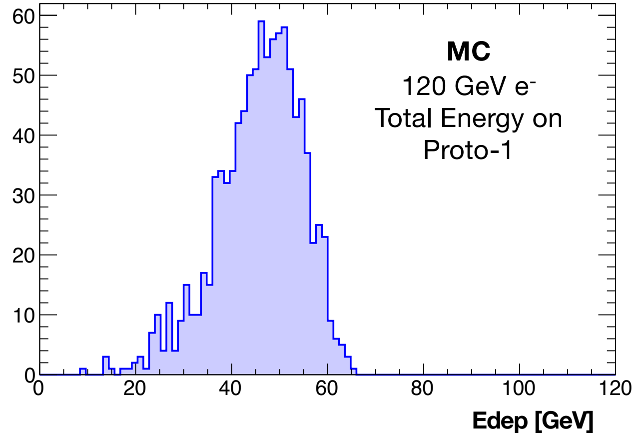
MC
120 GeV e-

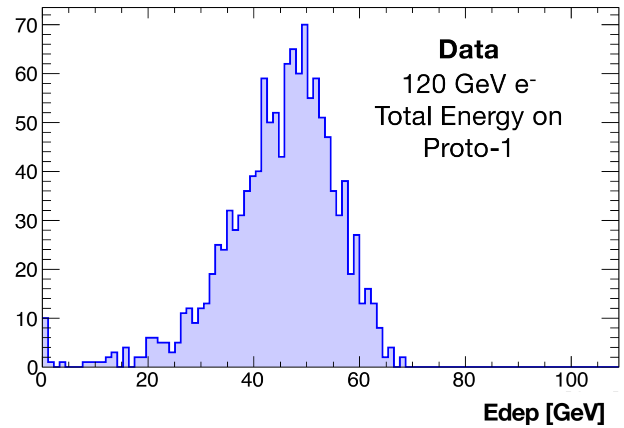
DATA
120 GeV e-



MC
120 GeV e-



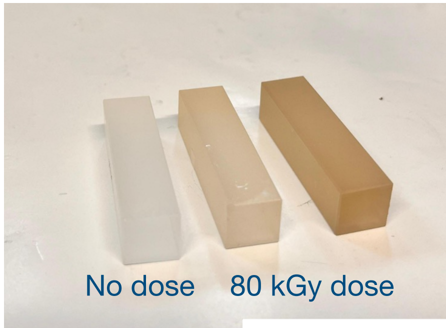


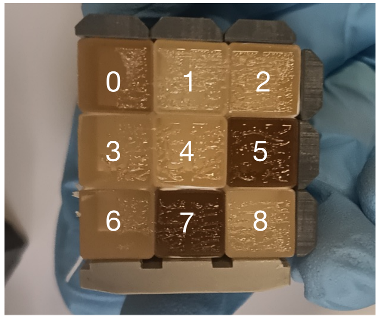


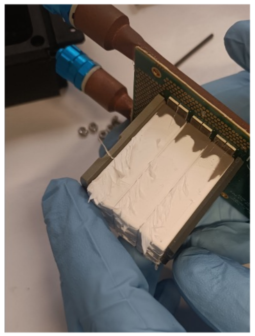
Beam test @ BTF: Teflon wrapping

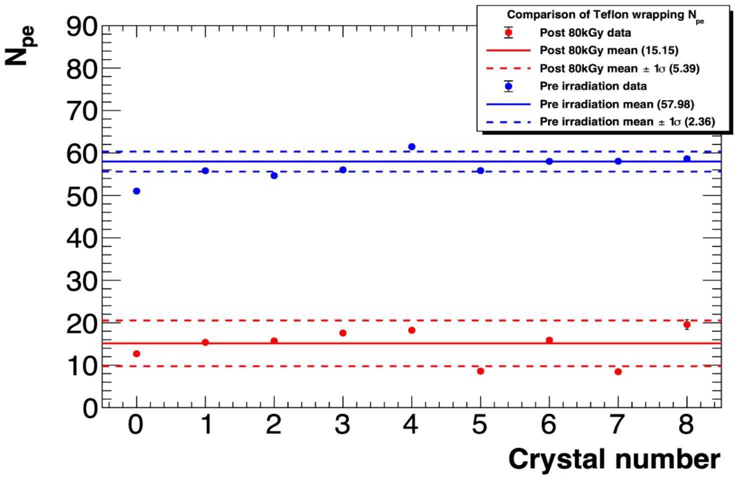
After 80 kGy (8 Mrad) irradiation

- Teflon was damaged and brittle
- Crystals evident loss of transparency

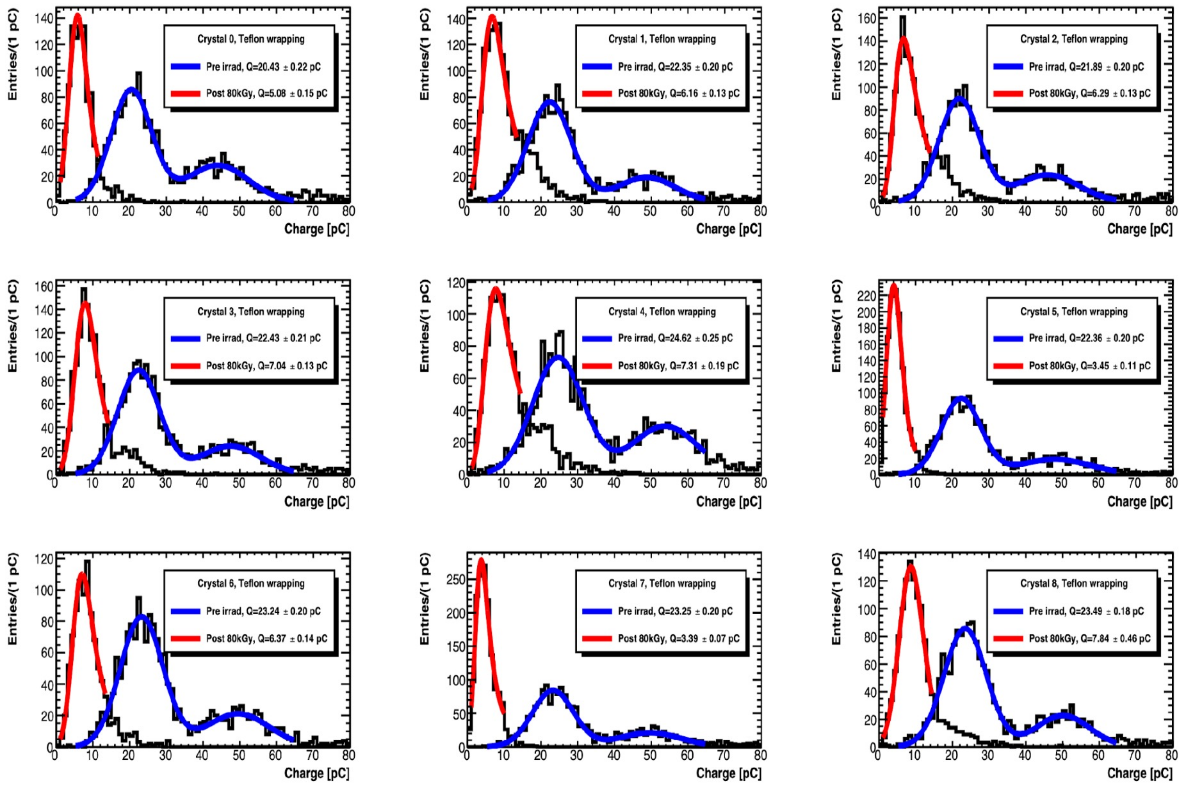






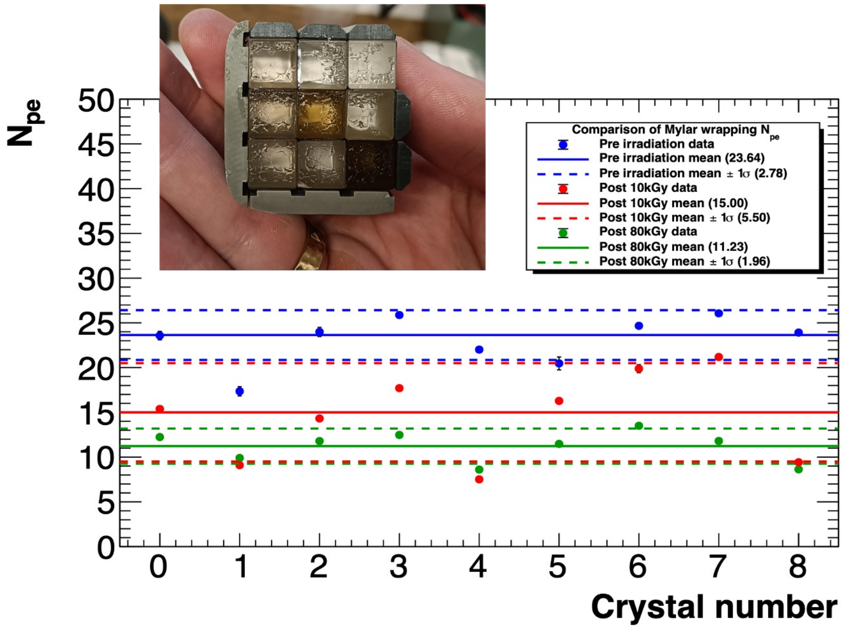


Charge distribution of PbF_2 pre and post irradiation

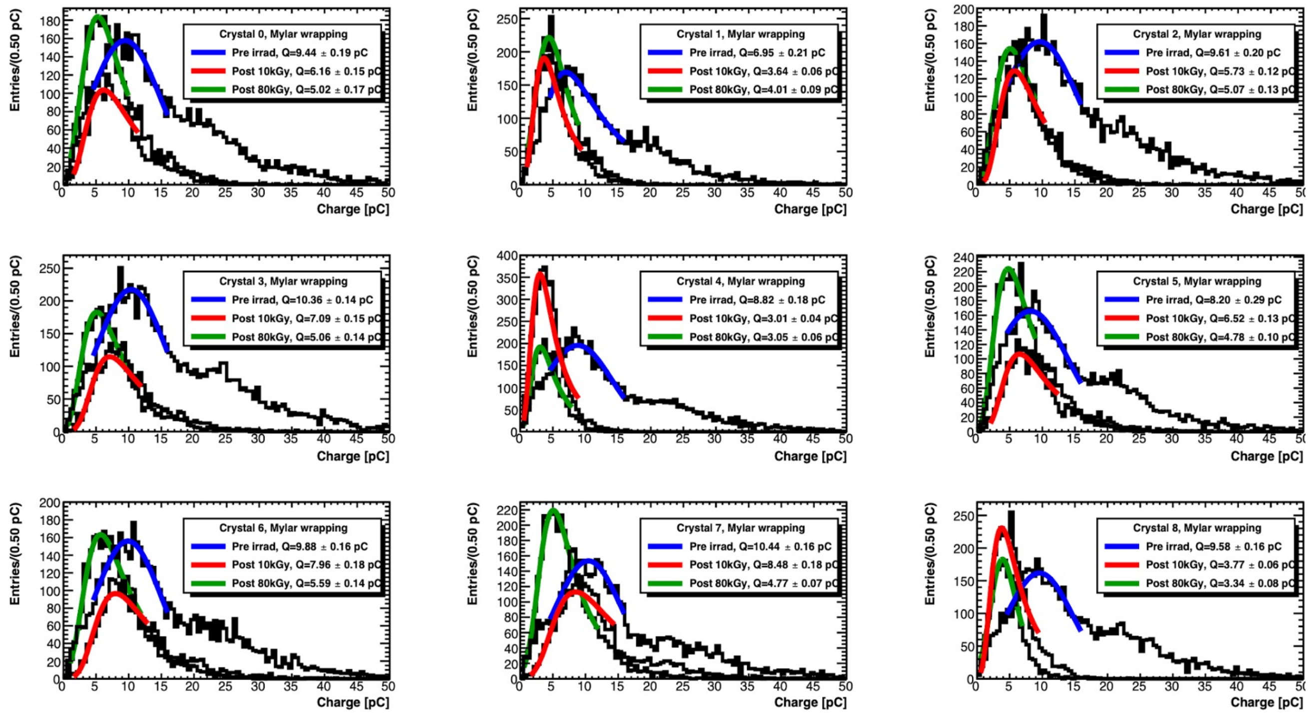


Beam test @ BTF: Mylar wrapping

- Test repeated with a Mylar wrapping
- **No annealing after 48h and 60h observed**
- New test planned to evaluate SiPMs PDE loss and optical grease degradation

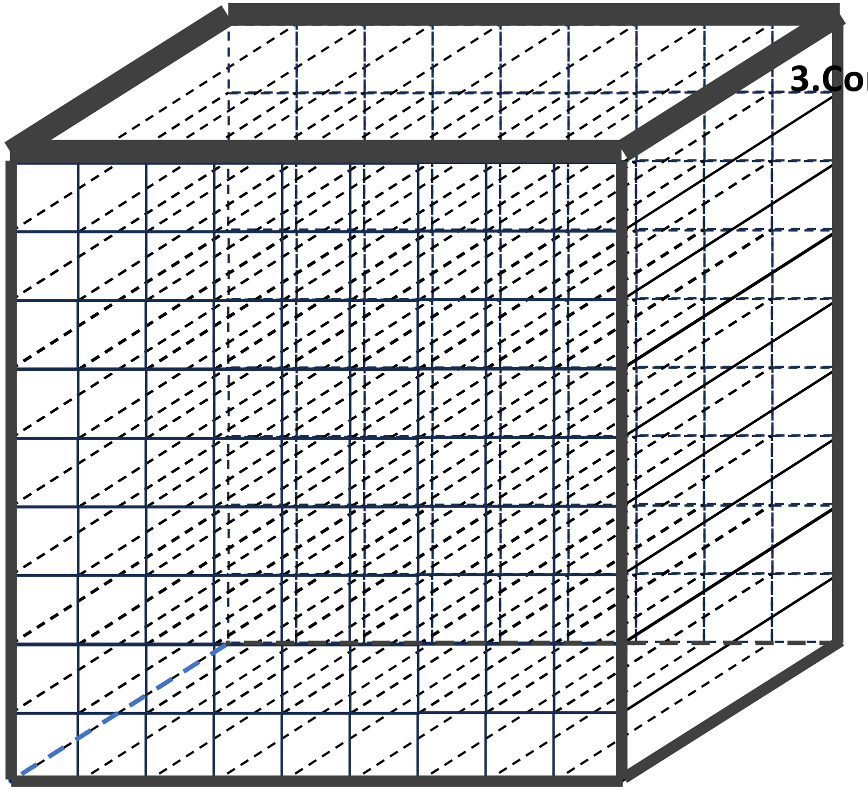


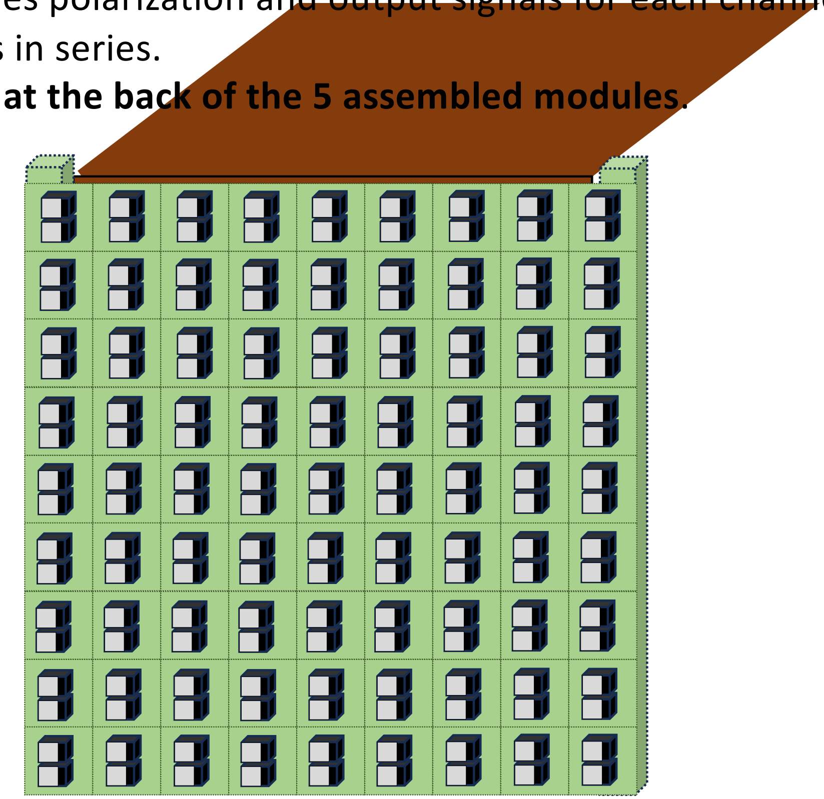
Charge distribution of PbF_2 pre, after 10 kGy and after 80 kGy irradiation



Crilin Module Prototype

1. **Aluminum matrix to hold the crystals**:
    1. 50 µm thickness between crystals
    2. Thicker (~ 2mm) in the external envelope with channels for cooling
2. **Kapton strip for polarization and output signal**:
    1. Handles polarization and output signals for each channel of two SiPMs in series.
3. **Connectors at the back of the 5 assembled modules.**





Crilin Module Prototype

1. **Aluminum matrix to hold the crystals**:
   1. 50-100 μm thickness between crystals
   2. Thicker (~ 2mm) in the external envelope with micro channels for cooling
2. **Kapton strip for polarization and output signal**:
   1. Handles polarization and output signals for each channel of two SiPMs in series.
3. **Connectors at the back of the 5 assembled modules.**