Istituto Nazionale di Fisica Nucleare
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International MUON Collider Collaboration

Advancements in Muon Collider Calorimetry: Design, Testing, and Radiation Resistance of the Crilin Calorimeter Prototype

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Calor 2024 – Tsukuba City, Japan, May 22 2024

CALOR 2024
第２０回 素粒子・原子核物理学
カロリメータ検出器国際会議
（つくば国際会議場, 2024年5月20日～２４日）

Introduction

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:

- **mμ>>me** (negligible synchrotron radiation)
- **point-like particle:** all √s 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 ECAL requirements

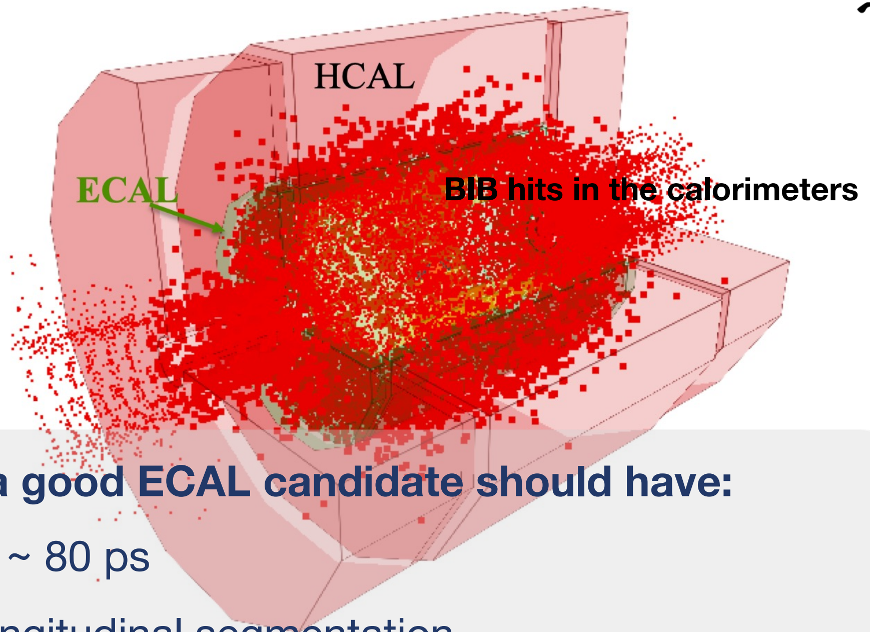
BIB in the ECAL region (after nozzles and tracking system):

- The BIB produces a flux of 300 particles per cm^2 through the ECAL surface
- 96% photons and 4% neutrons, average photon energy 1.7 MeV

→ different **hit longitudinal profile** wrt signal

→ **arrival time flatter** wrt bunch crossing → can exclude most of BIB with an acquisition window of ~240 ps

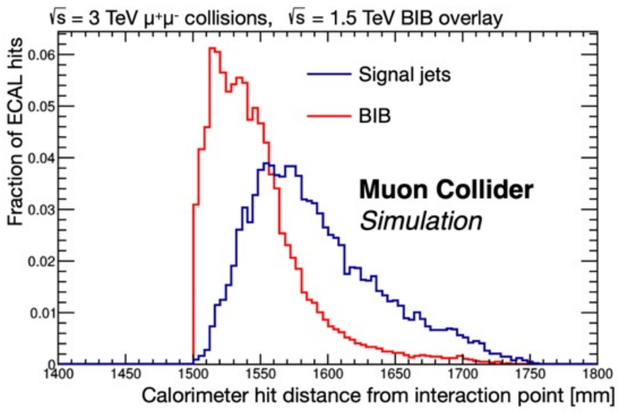
- total ionising dose: ~1 kGy/year (100 krad/year)
- total neutron fluence: 10^{14} $n_{1MeVneq}/cm^2$ / year

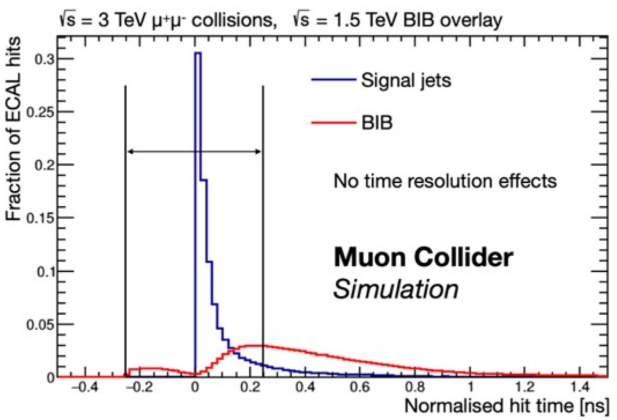


→ a good ECAL candidate should have:

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

→ The W-Si sampling calorimeter (Calice-like) stands out as a strong contender and was 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 consisted 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: Fast crystals, ensuring accurate and timely particle detection

→ **PbF2, PbWO-UF, LYSO…**

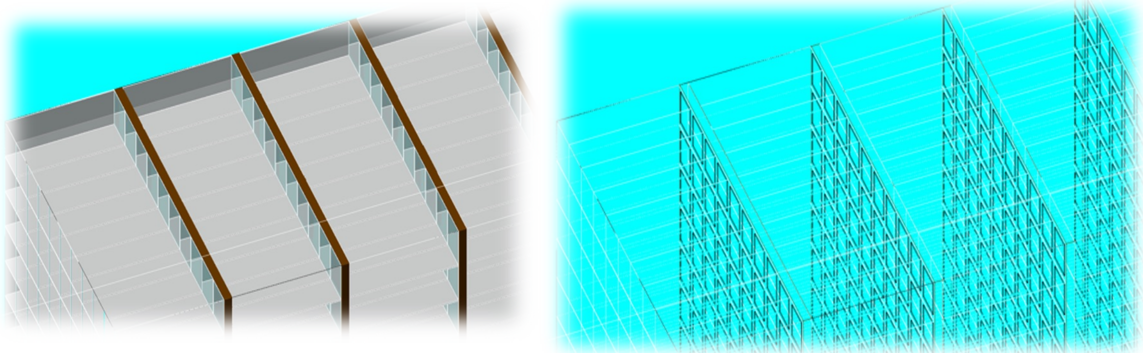
*S. Ceravolo et al 2022 JINST **17** P09033*

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

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

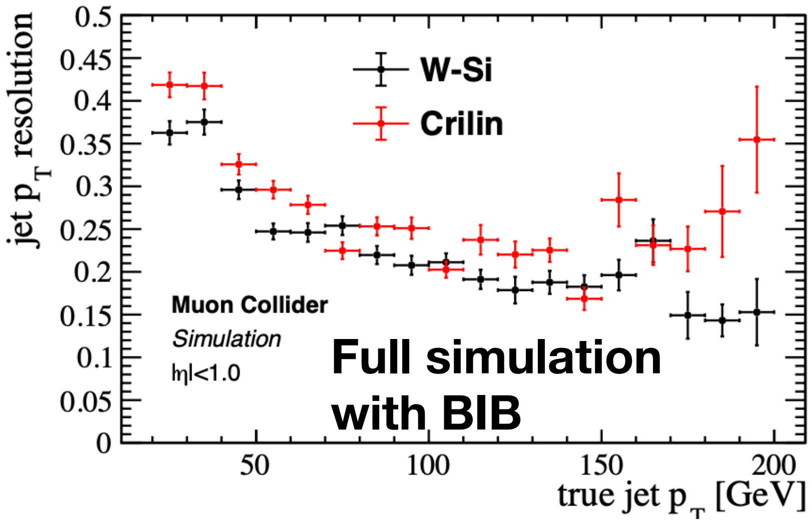


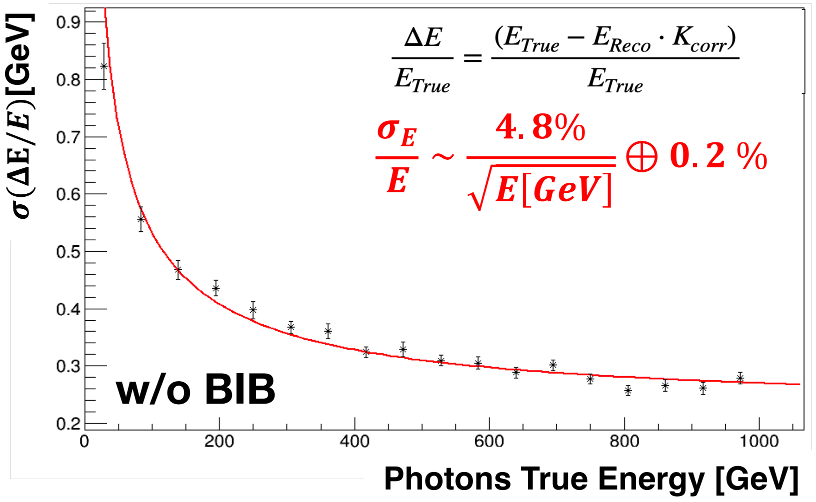
Simulated performances

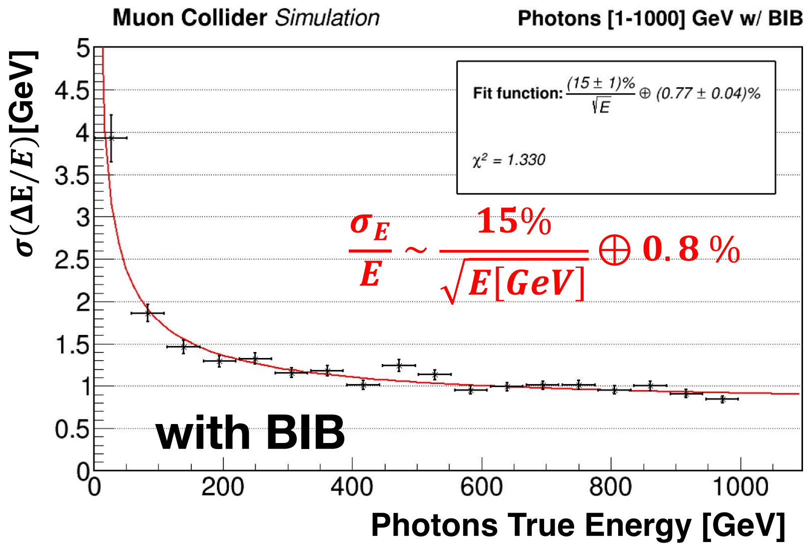
- The ECAL barrel with Crilin technology has been implemented in the Muon Collider simulation framework
  - ➢ 5 layers of 45 mm length, 10 X 10 mm^2 cell area → **21.5 X_0**
  - ➢ **In each cell:** 40 mm PbF_2 + 3 mm SiPM + 1 mm electronics + 1 mm air

- 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 Mchs)**







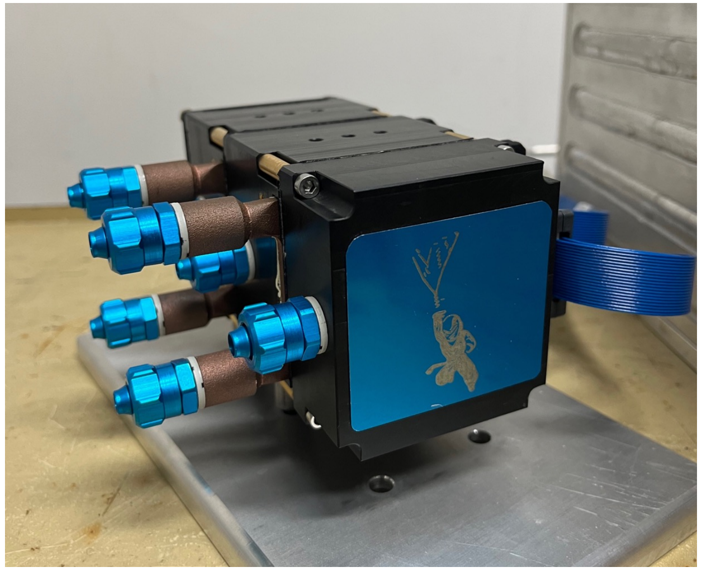
R&D status

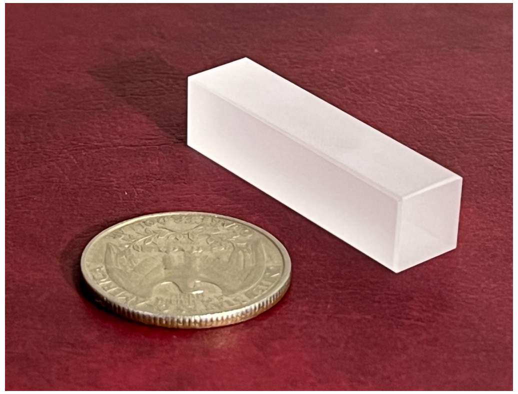
Prototype versions
- Proto-0 (2 crystals → 4 channels)
- Proto-1 (3x3 crystals x 2 layers → 36 channels)

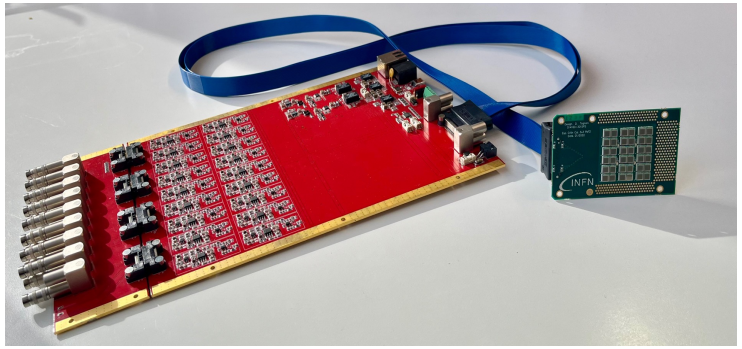
Front-end electronics
- Design completed
- Production and QC completed

Radiation hardness campaigns

Beam test campaigns
- Proto-0 at CERN H2 (August 2022)
  C. Cantone et al. 2023 Front. Phys. 11:1223183
- Proto-1 at LNF-BTF (July 2023-April 2024)
  C. Cantone et al. 2024: doi:10.1109/TNS.2024.3364771
- Proto-1 at CERN (August 2023)

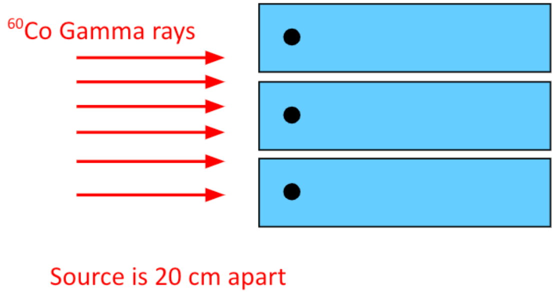


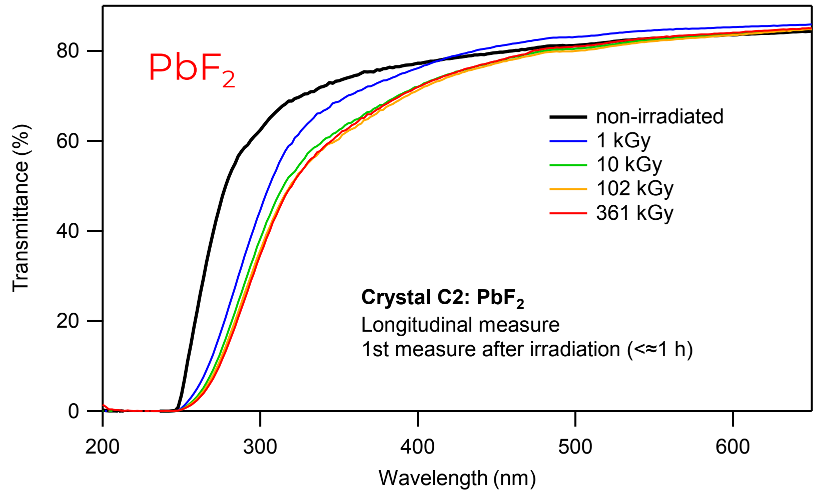




Crystal radiation hardness

Radiation hardness of two PbF_2 and $PbWO_4$-UF crystals (10x10x40 mm^3) checked for TID (up to 100 Mrad @ Calliope, Enea Casaccia) and neutrons (14 MeV neutrons from Frascati Neutron Generator, Enea Frascati, up to 10^{13} n/cm^2)

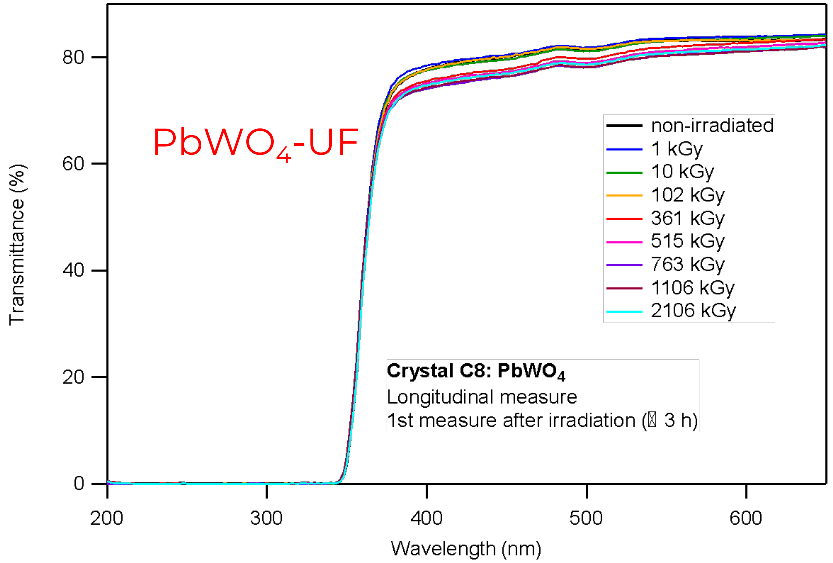




- For PbF_2:
  - **after a TID > 350 kGy no significant decrease** in transmittance observed.
  - Transmittance after neutron irradiation showed no deterioration
- For $PbWO_4$-UF:
  - **after a TID > 2 MGy no significant decrease** in transmittance observed.

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

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



SiPMs radiation hardness

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

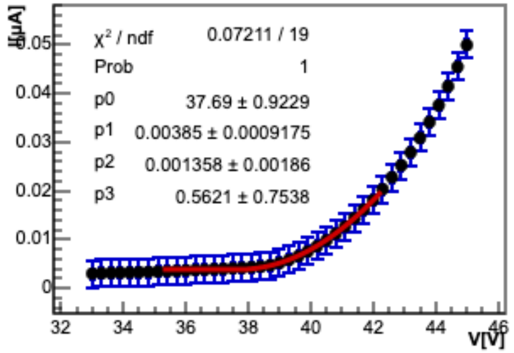
10 μm pixel-size

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

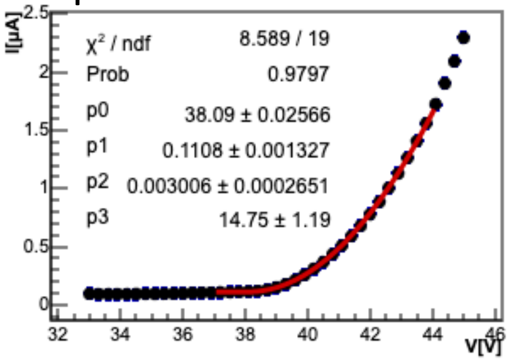
For the expected radiation level **the best SiPMs choice are the 10 μm one** for its minor dark current contribution.

pre

SiPM with bias



post

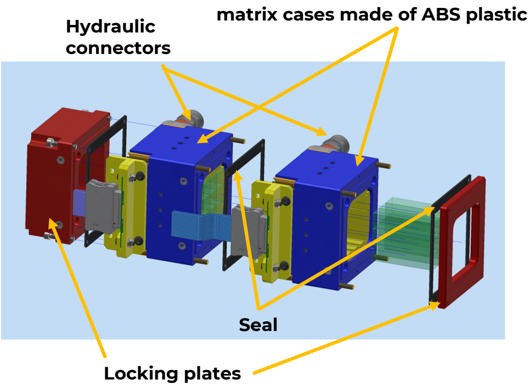


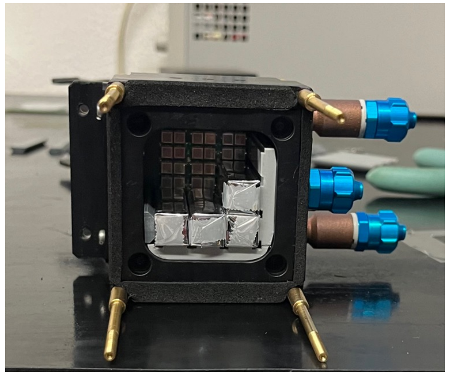
Dark current from 12 nA → 600 nA after 10 kGy (1 Mrad)

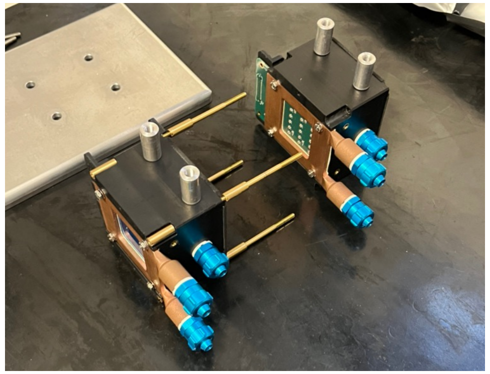
Proto-1: Mechanics and Electronics

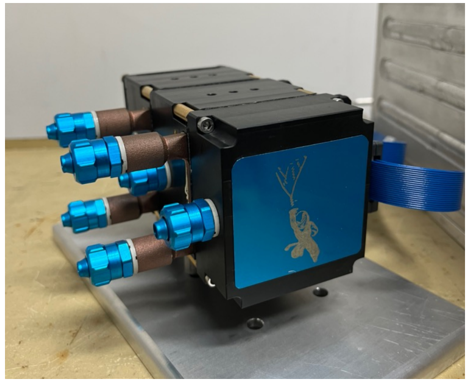
Mechanics:

- 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.



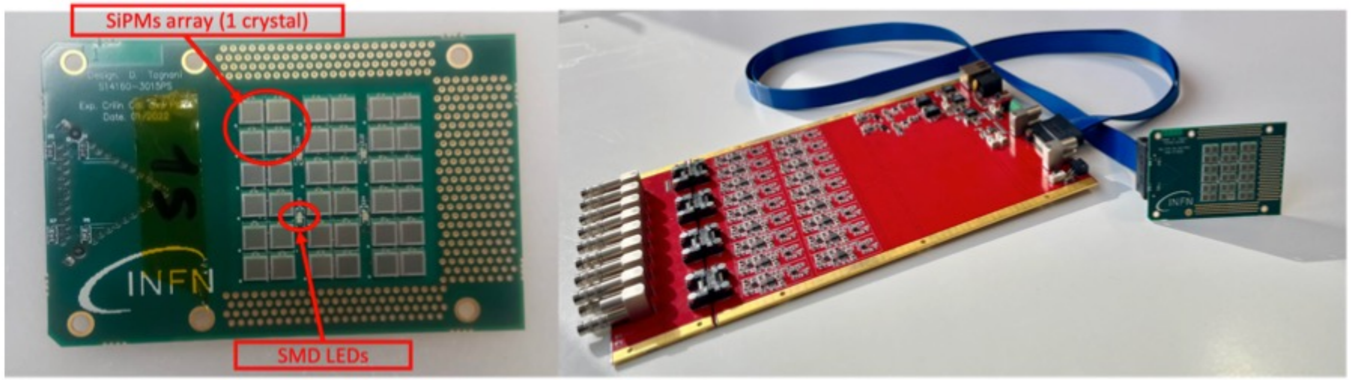






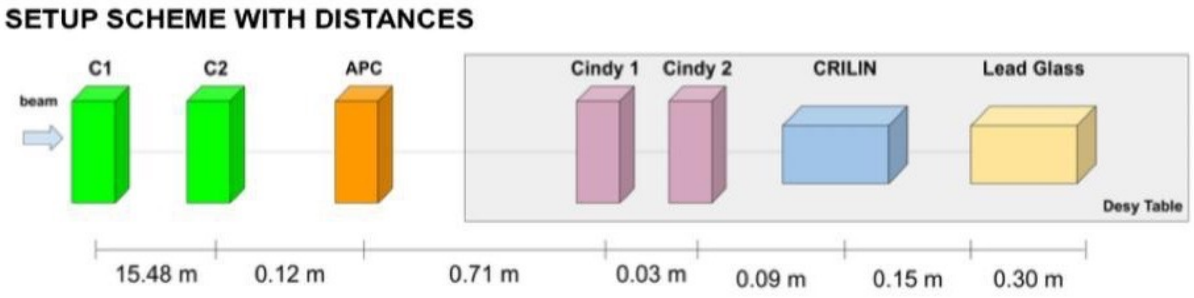
Electronics:

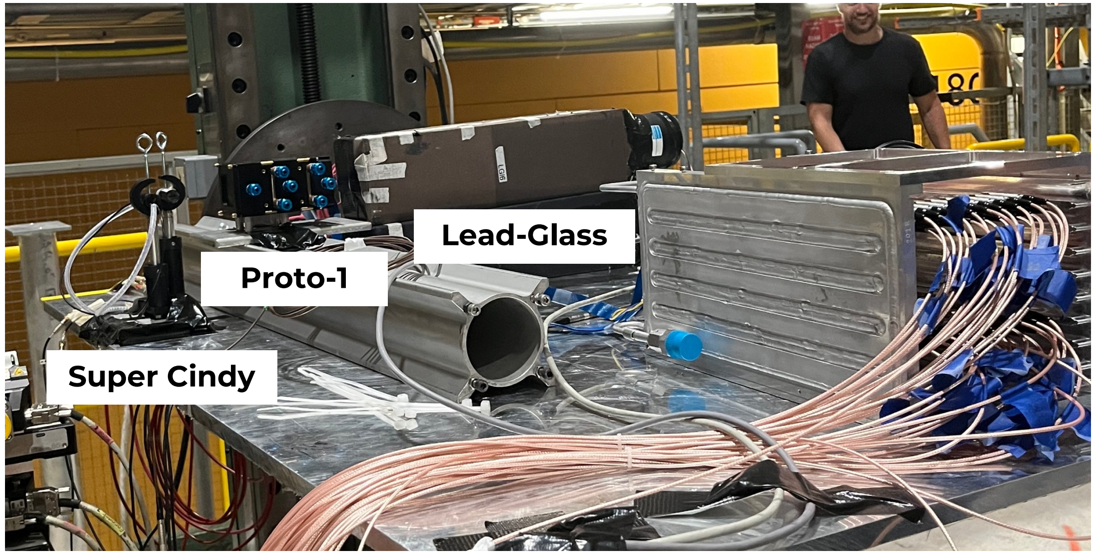
- **SiPMs board:** custom SiPM array board 36x10 µm Hamamatsu SMD SiPMs
- **Mezzanine board:** 18x readout channels → amplification, shaping and individual bias regulation, slow control routines



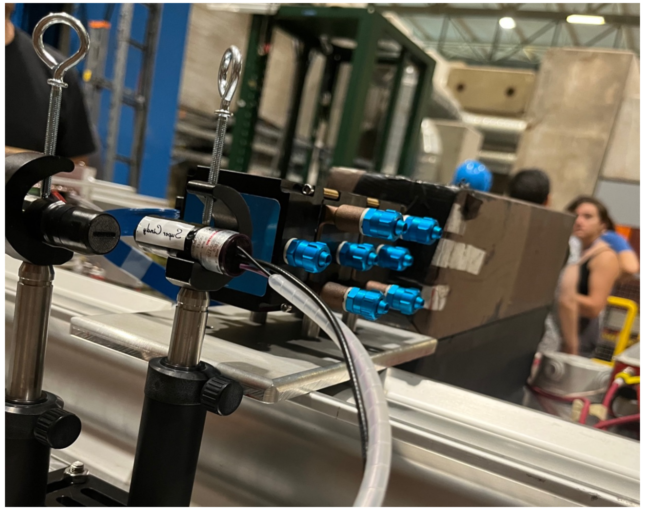
Beam test @ CERN

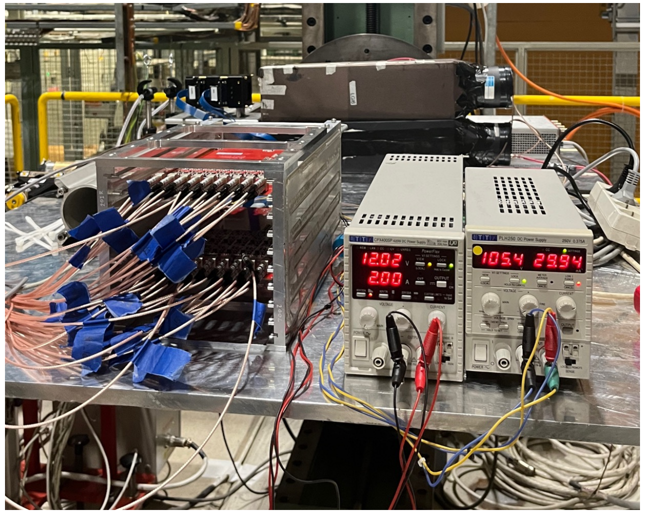
H2-SPS-CERN, August 2023





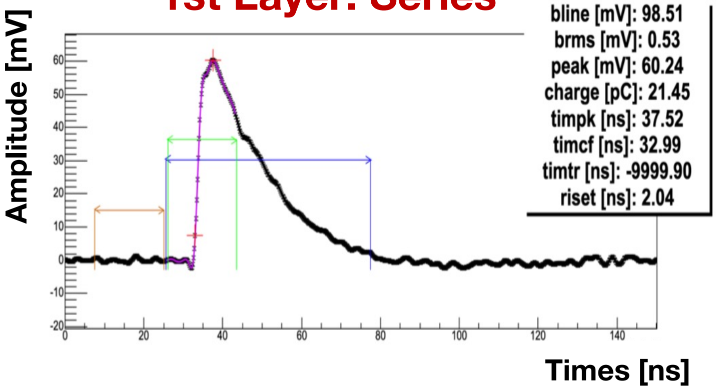
- Electron beam from 40 GeV up to 150 GeV
- Beam reconstructed with 2 silicon strip telescopes
- Data acquisition with 2 CAEN V1742 (32 ch each) modified @ 2 Vpp
- 5 Gs/s sampling rate



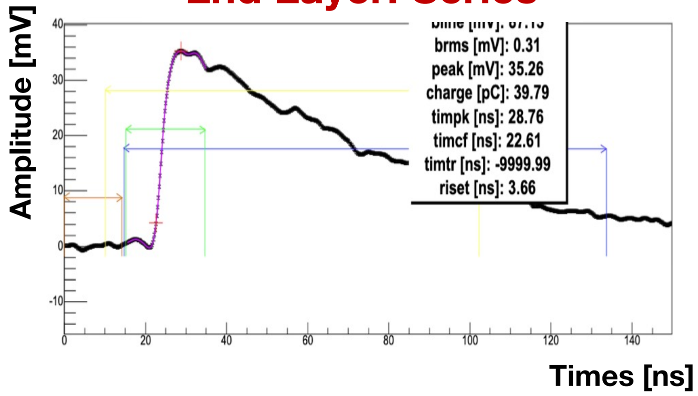


Beam test @ CERN: Configuration

1st Layer: Series



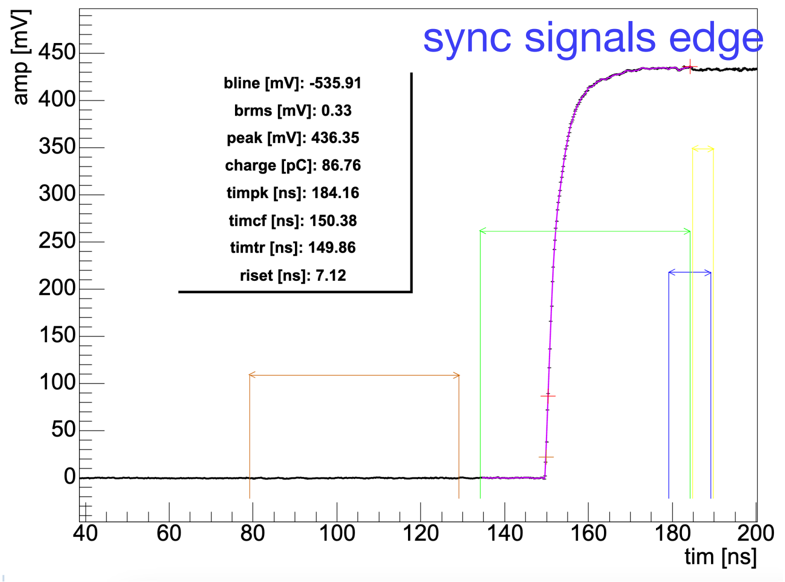
2nd Layer: Series



Sync pulses reconstruction:

- O(10 ps) ch-to-ch in the same chip

- O(30 ps) board-to-board jitter



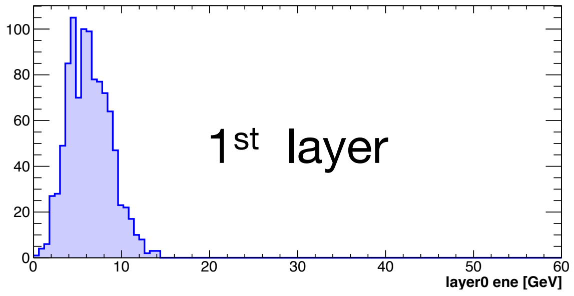
- **Two different connection in the two layers:** series and parallel
- **Low pass filtering** (Bessel 2nd order) cutoff_parallel ~ 2 * cutoff_series.
- Cut-off frequency based on two parameters: baseline RMS and risetime (10-90%)
- Wave quality flag based on baseline RMS, peak, and risetime to discard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

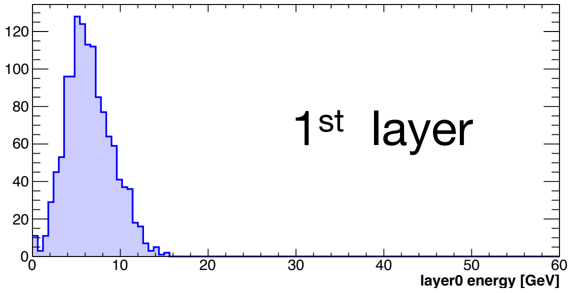
Beam test @ CERN: Result

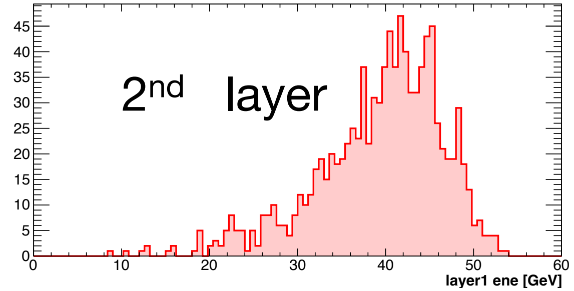
Excellent agreement between data e MC

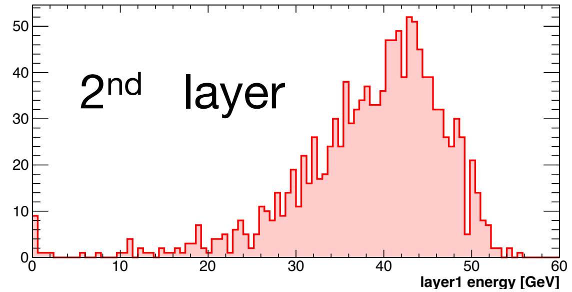
MC
120 GeV e$^-$

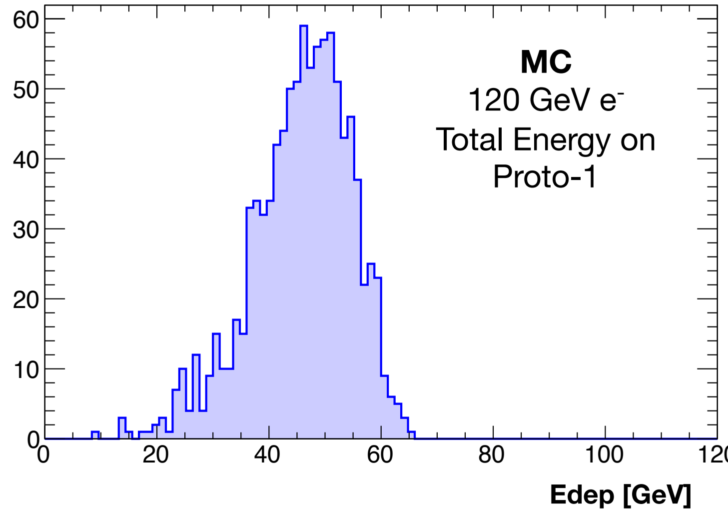
DATA
120 GeV e$^-$



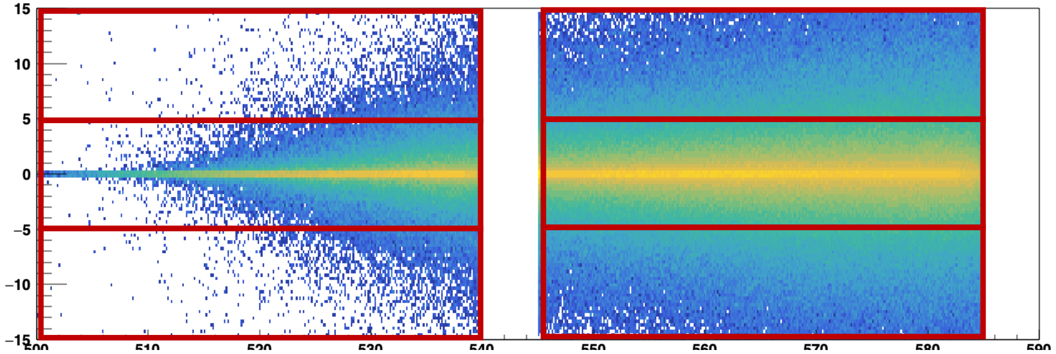


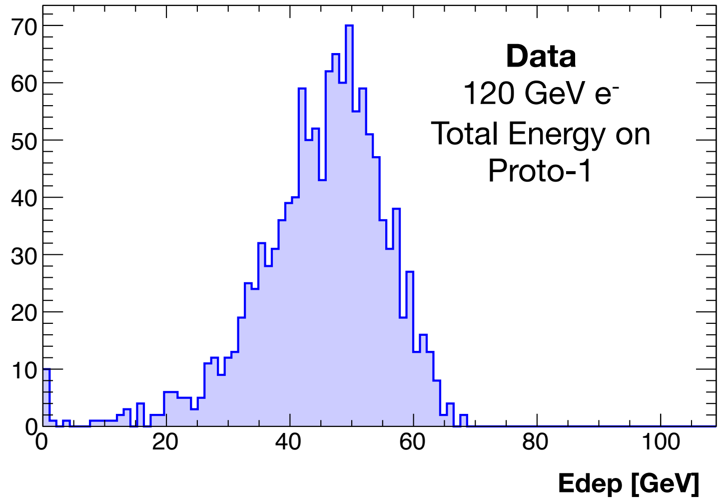






MC
120 GeV e$^-$

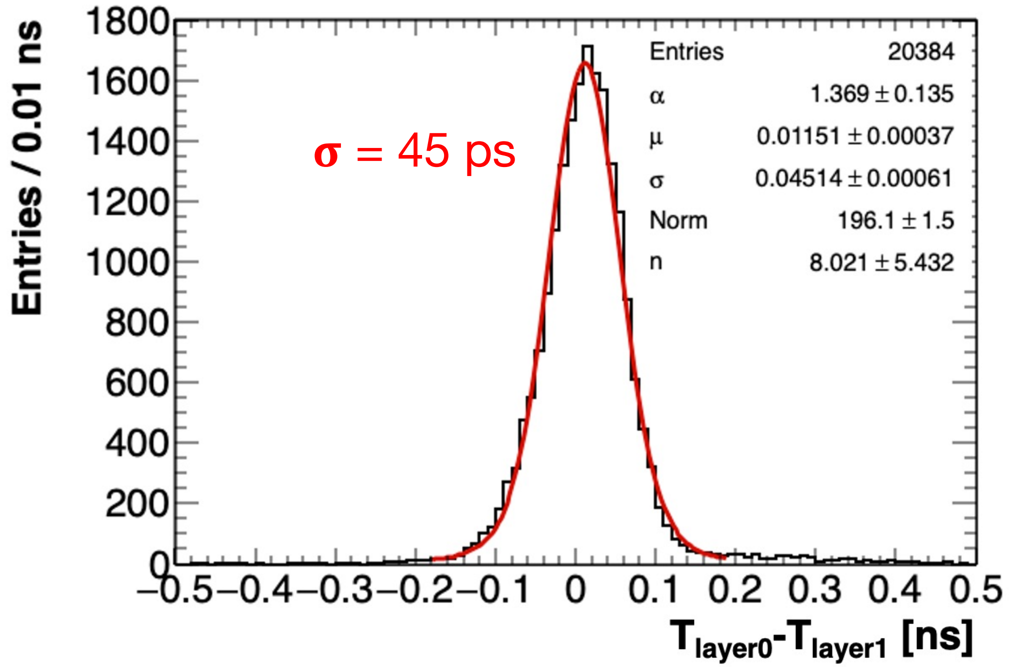


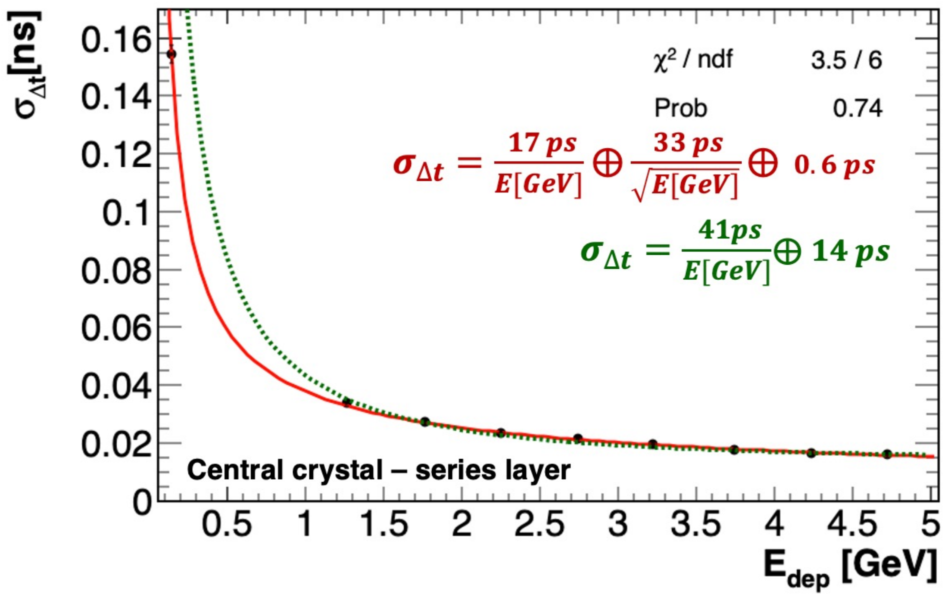


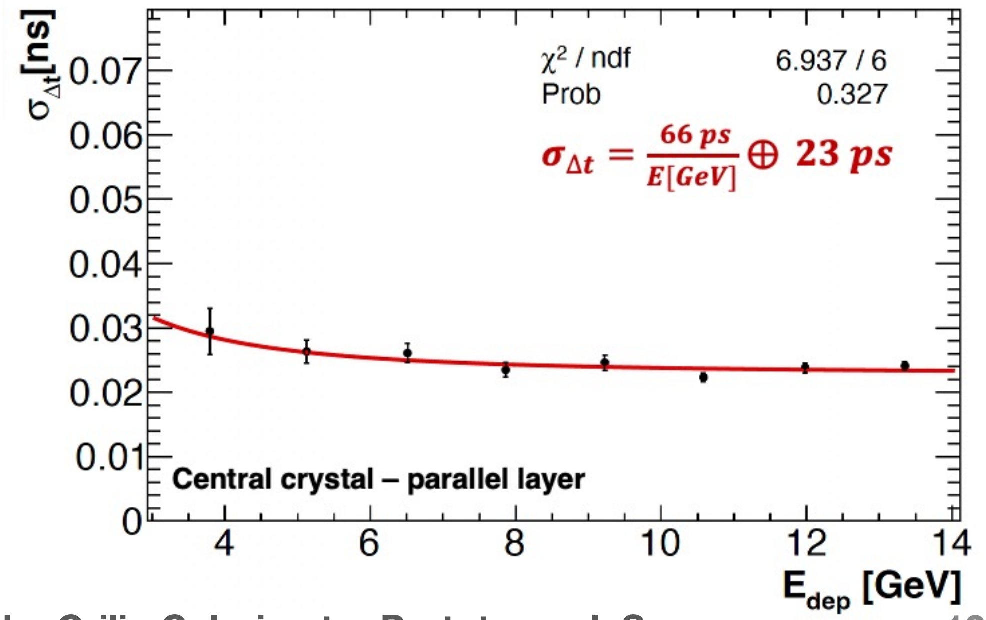
Beam test @ CERN: Timing

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



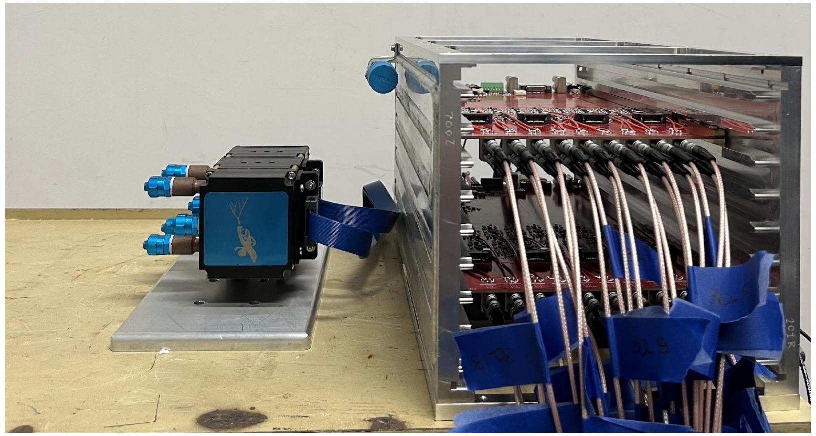


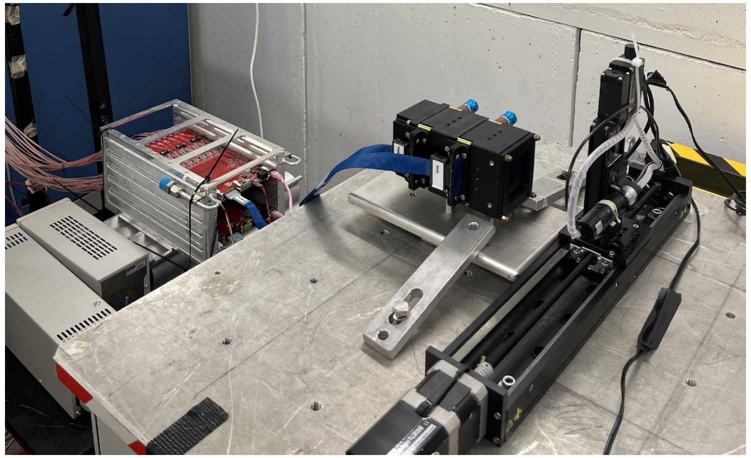


Beam test @ BTF

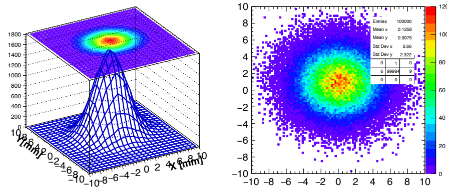
BTF, April 2024

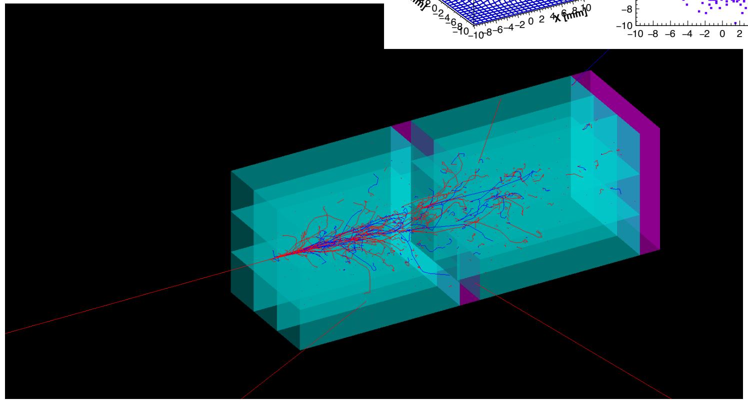
- Study of the LY loss of one layer of Proto-1 after Gamma ray irradiation
- Beam: 450 MeV electrons with multiplicity 1
- Beam centered on a different crystal at each run





Monte Carlo

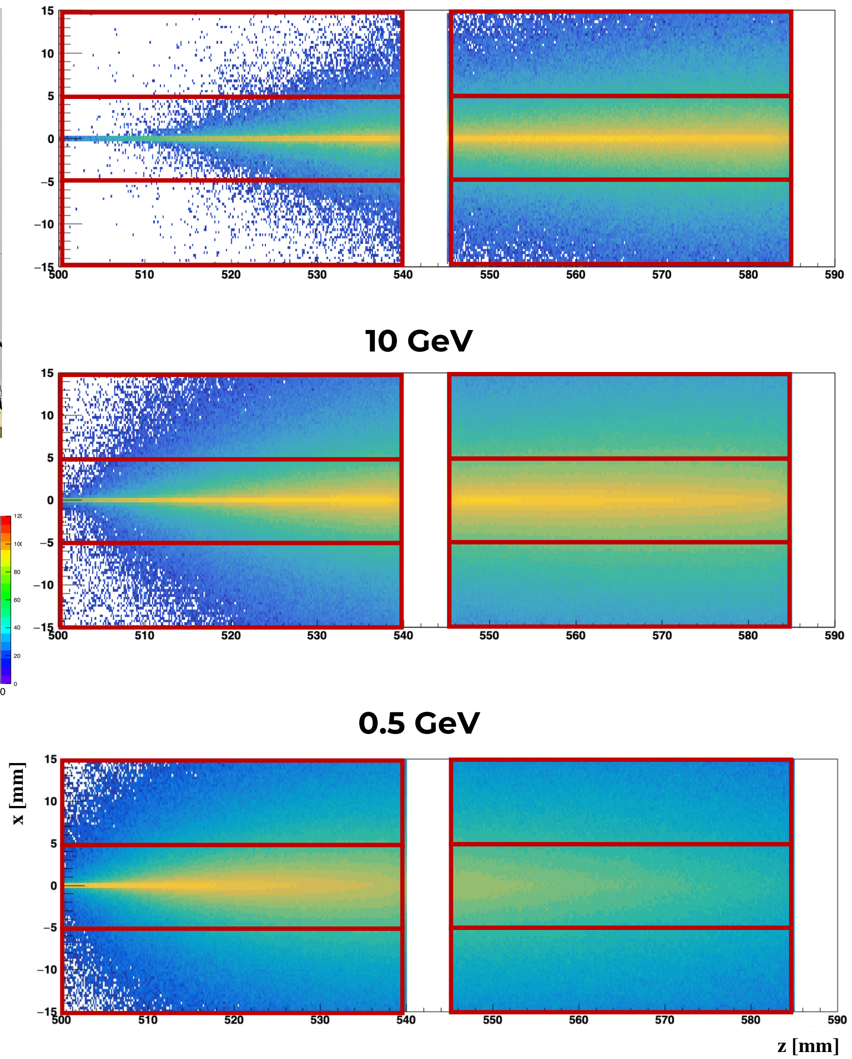




100 GeV

10 GeV

0.5 GeV

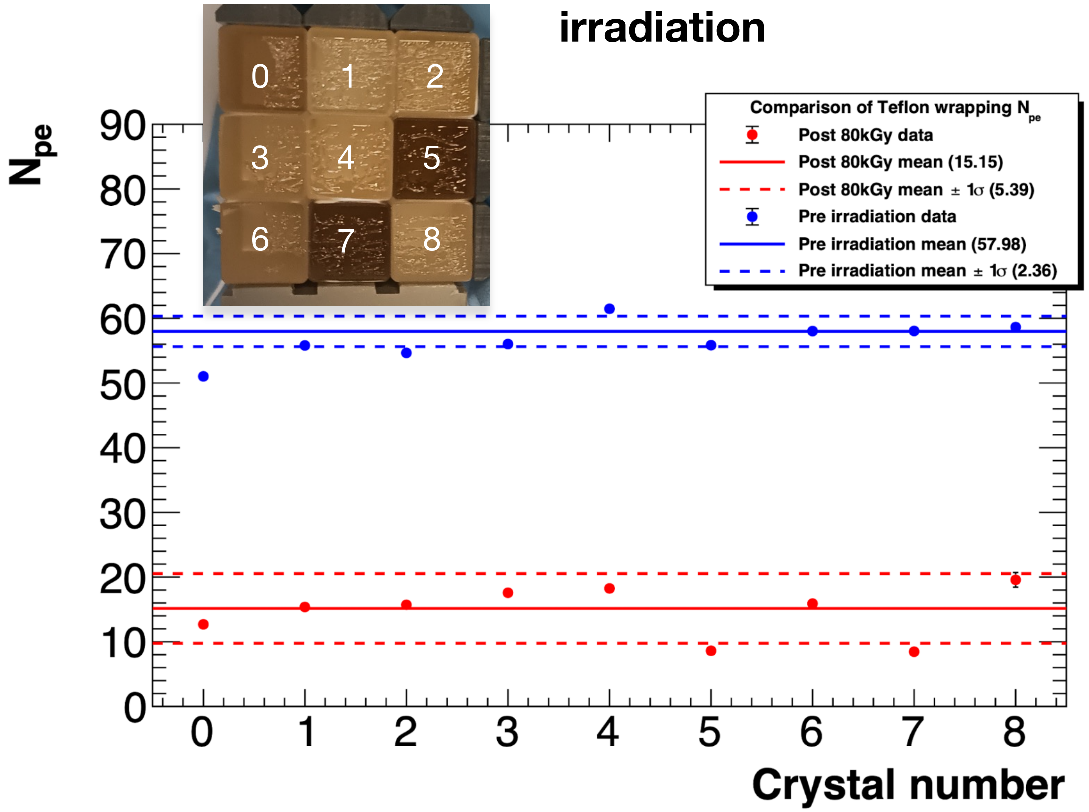


Beam test @ BTF: crystals

- Two different wrappings tested, Teflon and Mylar
- LY loss evaluated through variation in charge and number of photo-electrons

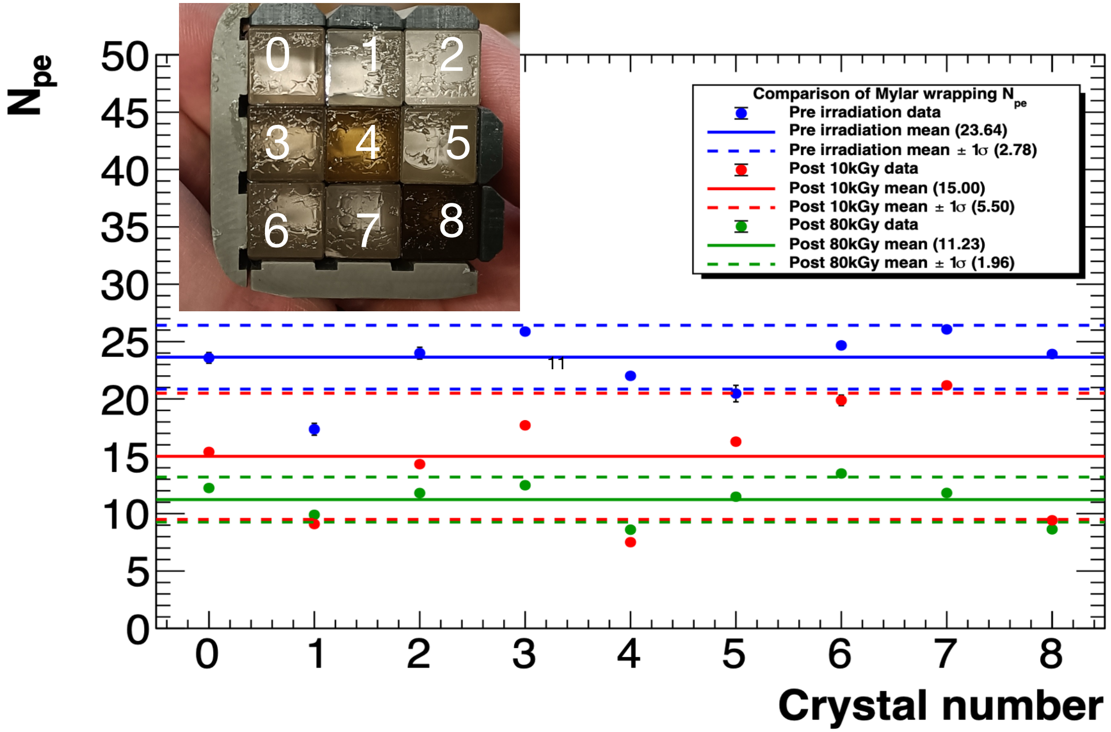
Telfon wrapping

Npe values of PbF_2 pre and post 80 kGy irradiation



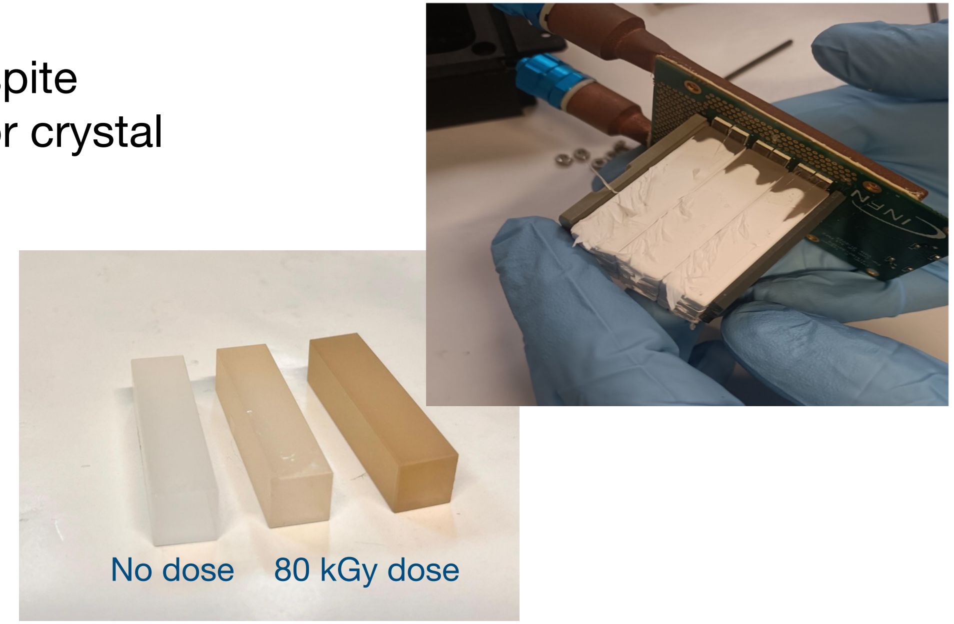
Mylar wrapping

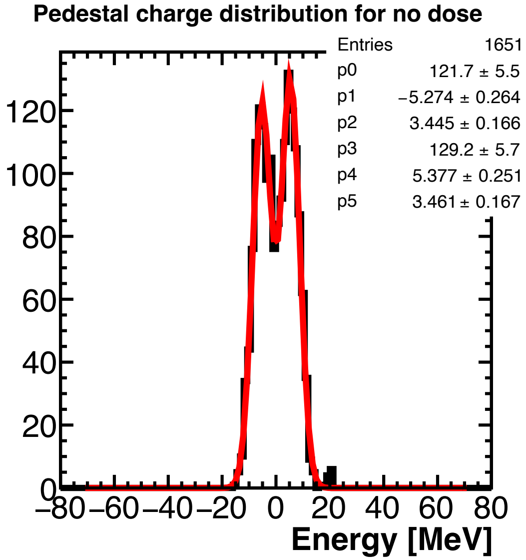
Npe values of PbF_2 pre, after 10 kGy and after 80 kGy irradiation

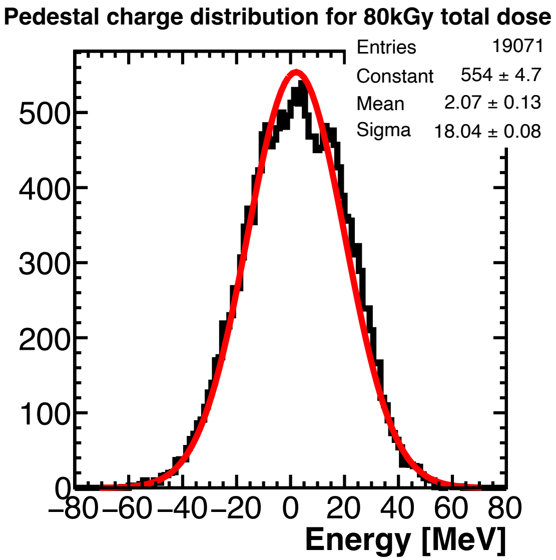


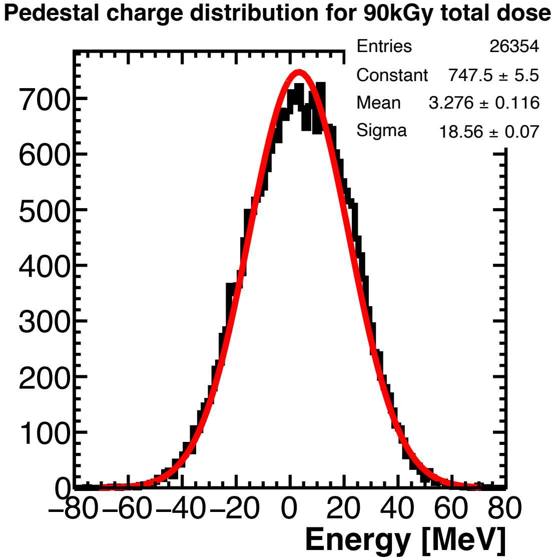
Beam test @ BTF: considerations

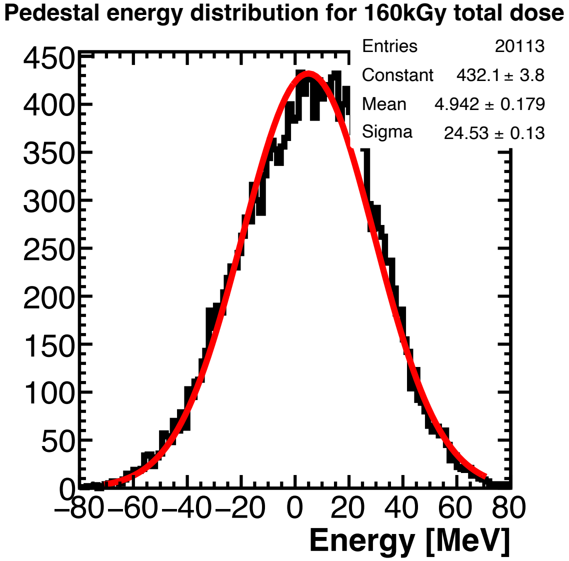
- Considerable variability in the crystals' response to radiation, despite SICCAS claiming the use of high-purity (>99.9%) PbF_2 powder for crystal growth
- Crystals evident loss of transparency
- Transparency loss was uniform length-wise in the crystals
- Teflon was damaged and brittle
- SiPM pedestal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











Summary

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

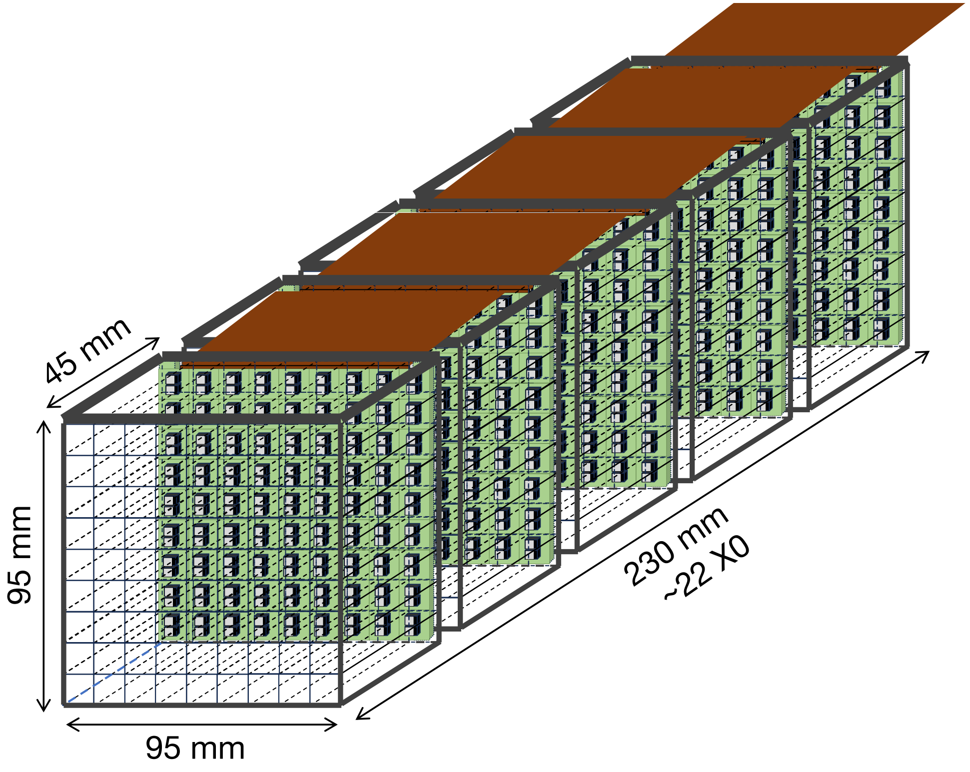
- *Use PbWO-UF in the first calorimeter layer.*
- *Conduct new irradiation tests and monitor Cherenkov light variations with a blue laser.*
- *Simultaneously test crystals with SiPMs and SiPMs alone.*

Next steps (2024 - 2025)

➢ We submitted and won an Italian grant for the project CALORHINO: *An innovative radiation-hard calorimeter proposal for a future Muon Collider Experiment.*
→ funds assigned for the development of a 5x5 x4(layers) Crilin prototype: 1 M_R – 16.8 X_0

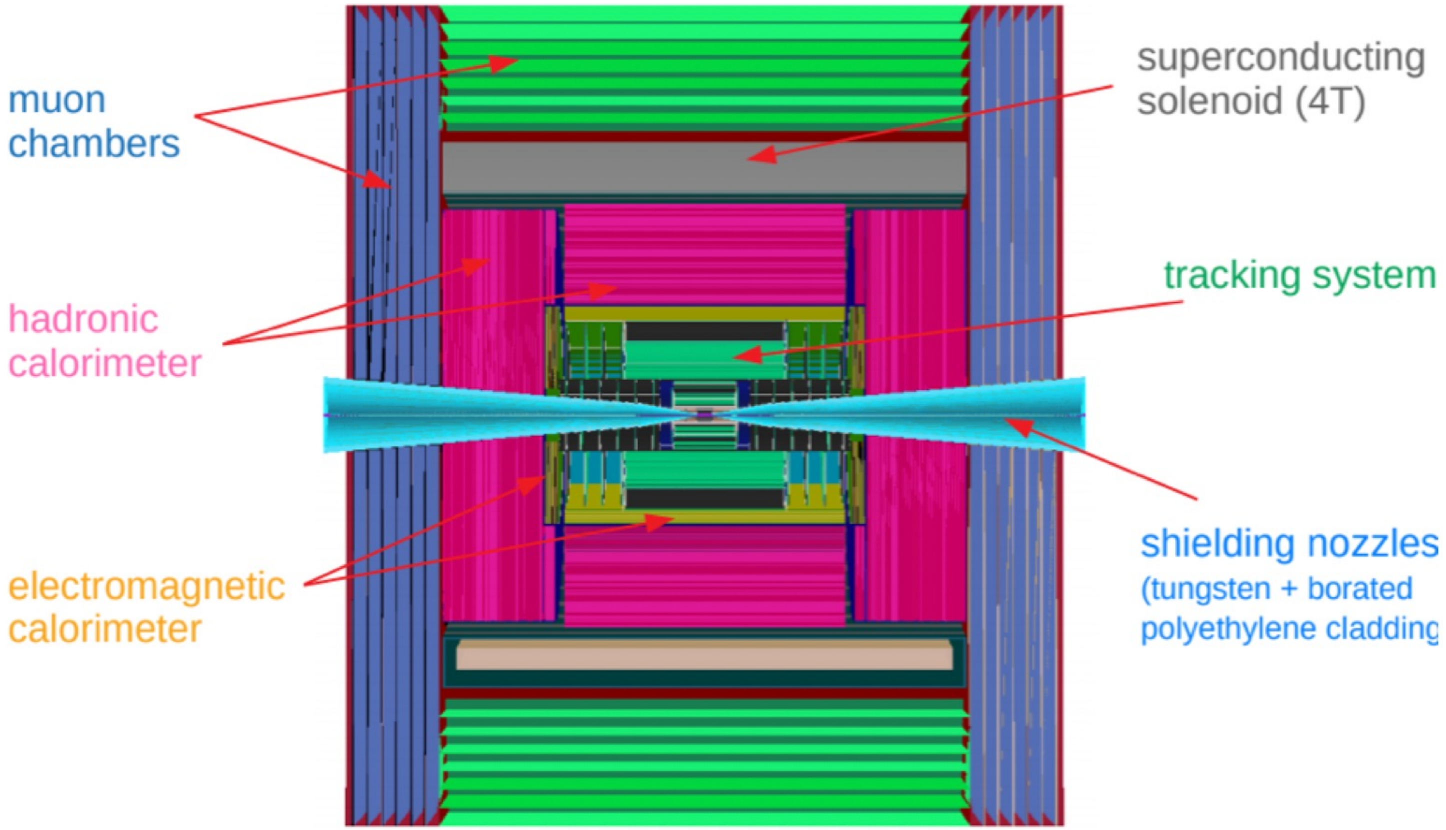
DRD6-WP3 from 2025

➢ Expanding upon the PRIN prototype to a 9x9 x5(layers) configuration, with a target of 2 M_R – 22 X_0.



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.

International MUON Collider Collaboration

The Crilin concept - in a few words

Introduction:
CRILIN, or Cristal Calorimeter with Longitudinal Information, represents a significant advancement in particle detection technology. Positioned strategically between homogeneous and sampling calorimeters, CRILIN offers a unique combination of capabilities that address key challenges in particle physics research.

Key Features:
At the heart of CRILIN's design are its outstanding energy and temporal resolution capabilities. This allows for precise measurements of particle energy deposits and their timing, essential for understanding particle interactions in detail. Moreover, CRILIN provides detailed longitudinal information, offering insights into the depth of particle interactions within the detector.

Differentiation:
What sets CRILIN apart is its ability to modulate energy deposition for each cell and adjust crystal size for tailored layers. Unlike segmented or high granularity calorimeters like those in the CALICE project, CRILIN offers unparalleled flexibility in optimizing energy detection while maintaining compactness.

Crystal Choice:
CRILIN relies on high-density crystals, carefully selected to balance the need for increased layer numbers with space constraints. These crystals also boast exceptional response speeds, ensuring accurate and timely particle detection.

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

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

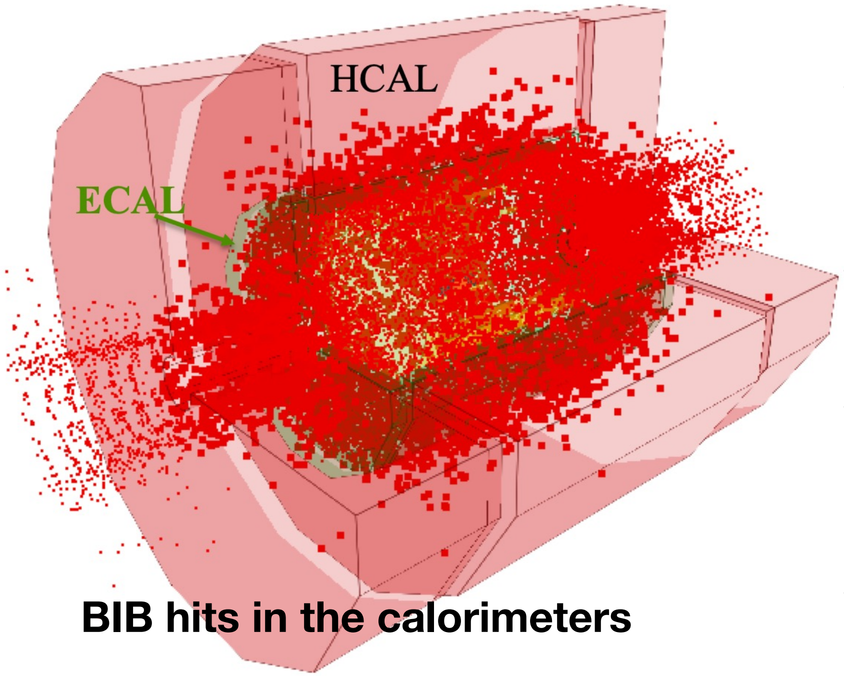
Fine granularity: reduce the hit density in a single cell and distinguish the BIB hits from the signal.

Good resistance to radiation: good reliability during the experiment

Crilin is particularly suited for the BIB mitigation strategy: having thicker layers, the BIB energy is integrated in large vo

Beam Induced Background

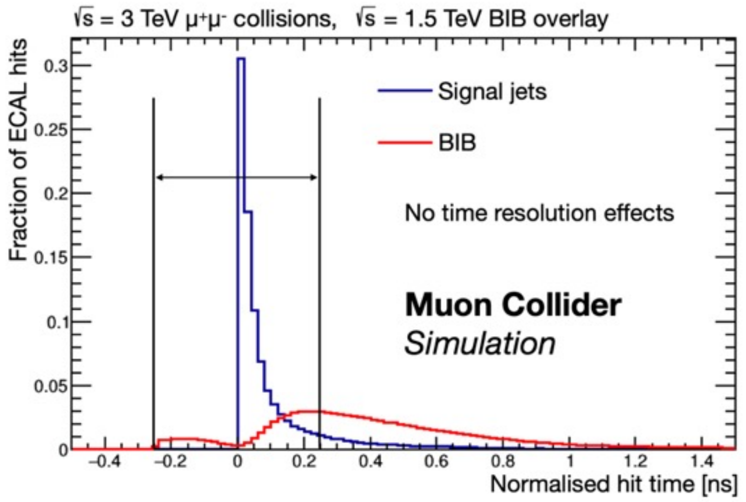
- **The beam-induced background (BIB)** poses the main challenge for the detector development at the Muon Collider
- Produced by muons decay in the beams, and subsequent interactions with the machine
- The BIB produces a flux of 300 particles per cm^2 through the ECAL surface
- 96% photons and 4% neutrons, average photon energy 1.7 MeV

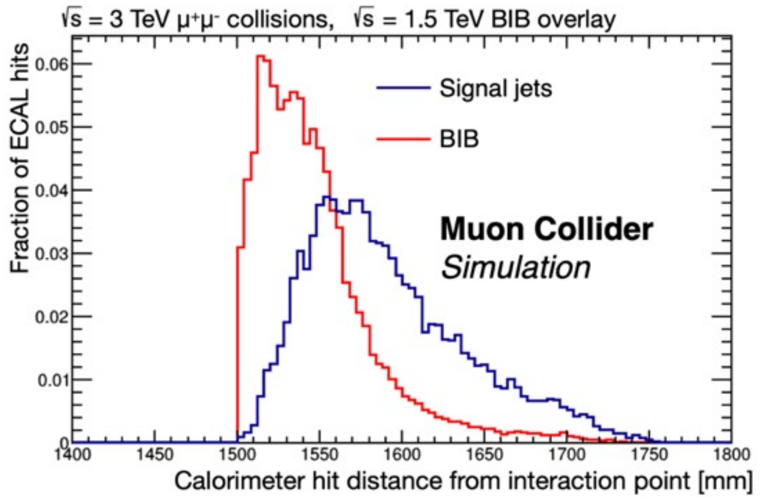


BIB hits in the calorimeters

Key features:

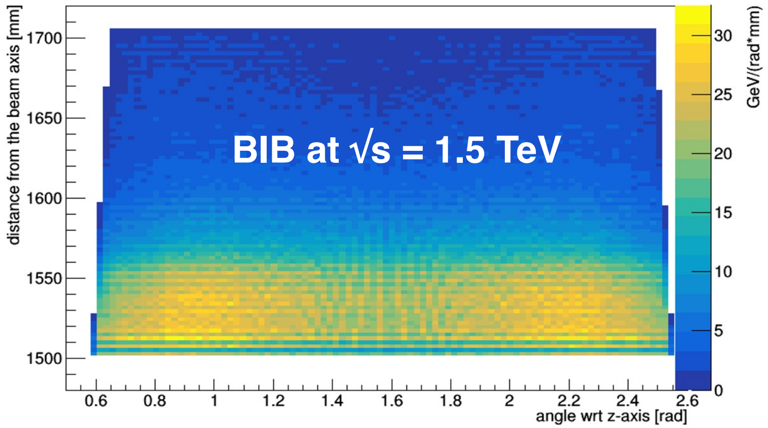
- **Timing**: BIB hits are out-of-time, a resolution in the order of 100 ps is needed
- **Longitudinal segmentation**: different profile for signal and BIB
- **Granularity**: helps in separating BIB particles from signal, avoiding overlaps in the same cell
- **Energy resolution:** target $\frac{\Delta E}{E} \simeq \frac{10\%}{\sqrt{E[\mathrm{GeV}]}}$



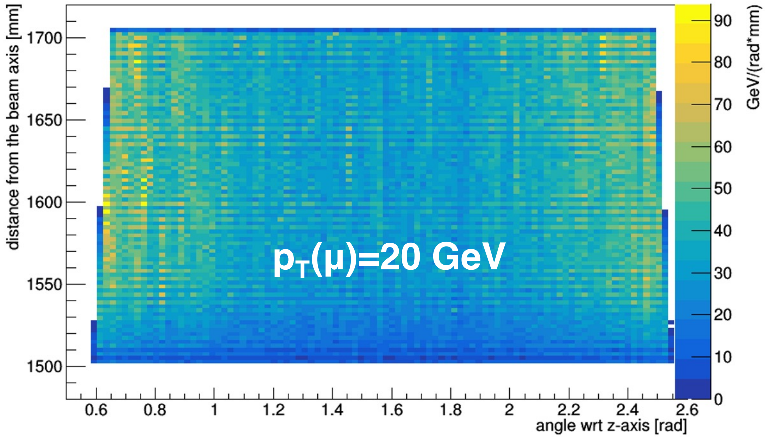


Beam Induced Background

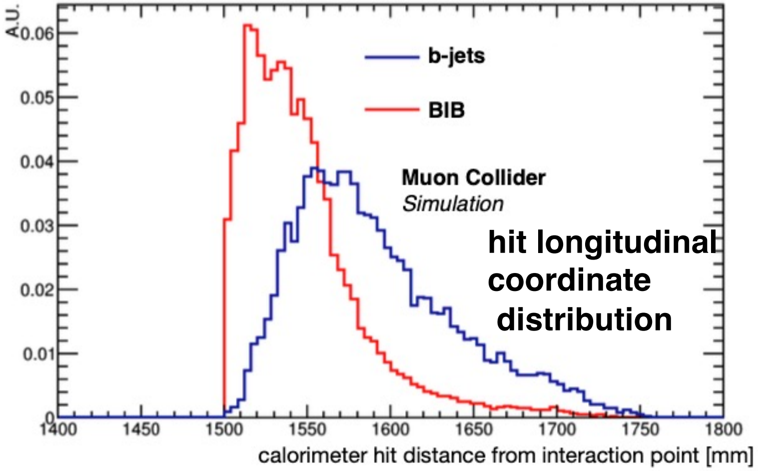
Energy released in ECAL barrel by one BIB bunch crossing

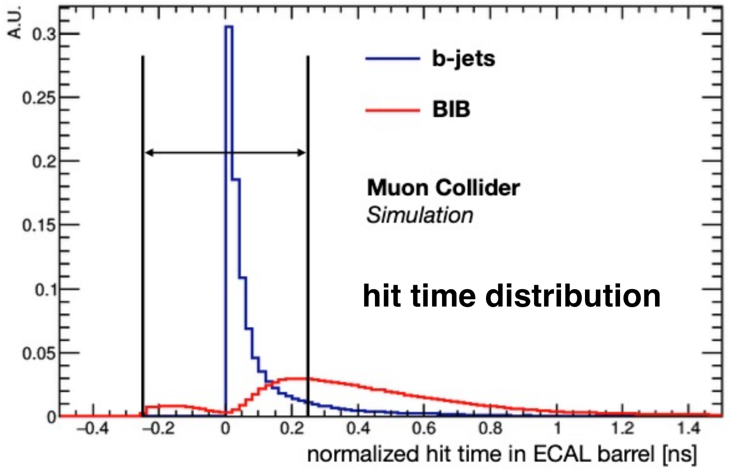


Energy released in ECAL barrel by uniformly distributed prompt muons in the (θ,ϕ) space



- Expected BIB on the ECAL barrel ~300 γ/cm^2 /events with E~1.7 MeV.
- BIB can be subtracted using information from energy releases in the ECAL.
- The BIB produces most of the hits in the first layers of the calorimeter while i.e. muons produce a constant density of hits after the first calorimeter layers.
- Since the BIB hits are out-of-time wrt the bunch crossing, a **measurement of the hit time performed cell-by-cell** can be used to **remove most of the BIB.**





The Crilin calorimeter - in a few words

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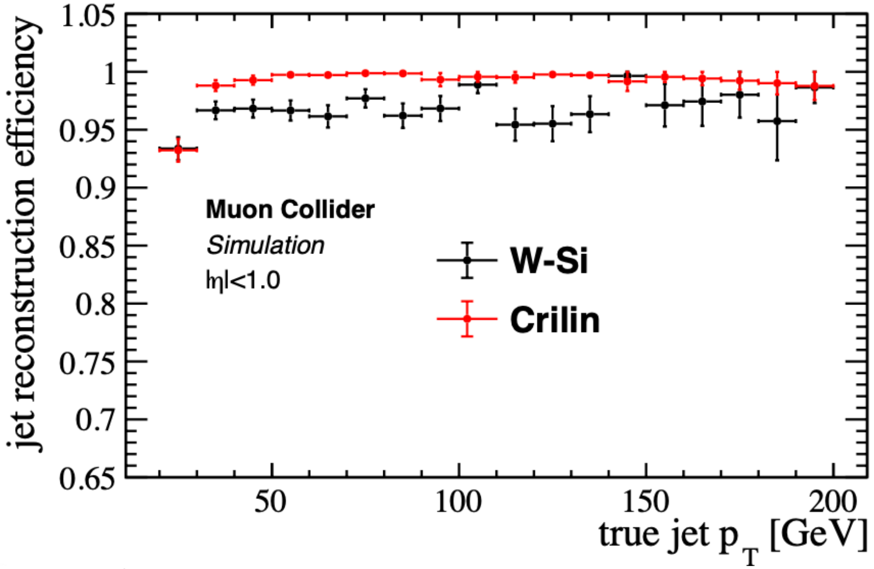
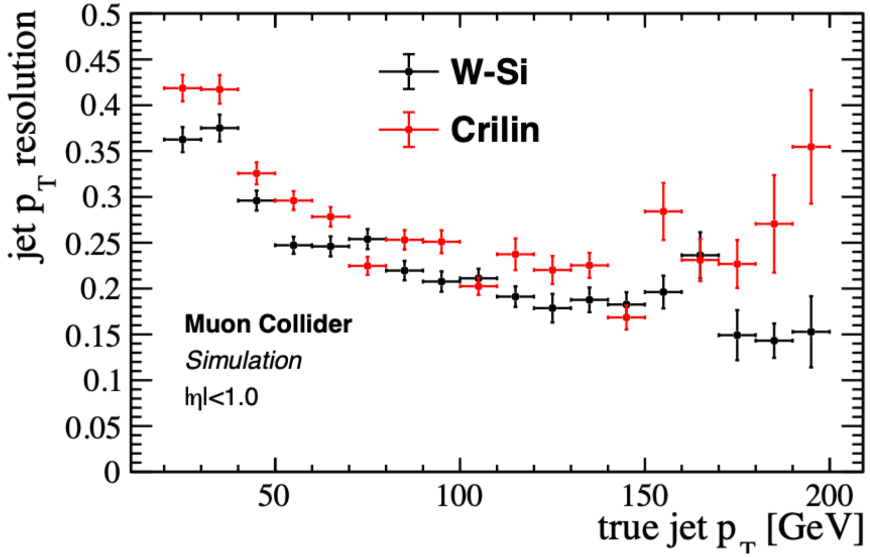
Fine granularity: reduce the hit density in a single cell and distinguish the BIB hits from the signal.

Good resistance to radiation: good reliability during the experiment

- The goal is to build a crystals calorimeter, fast, relative cheap, and with high granularity (both transversal and longitudinal) optimized for muon collider.
- Our proposed design, **Crilin**, is a **semi-homogeneous** electromagnetic calorimeter made of **Lead Fluoride Crystals** (PbF_2) matrices where each crystal is readout by 2 series of 2 UV-extended surface mount **SiPMs.**
- **It represents a valid and cheaper alternative to the W-Si Muon Collider ECAL**.





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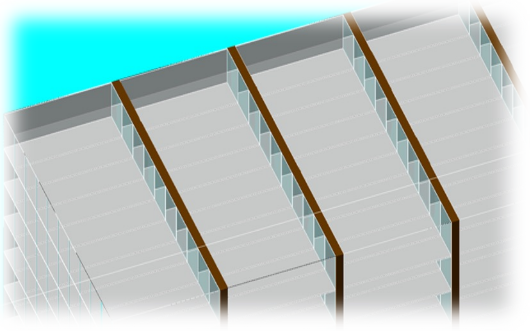
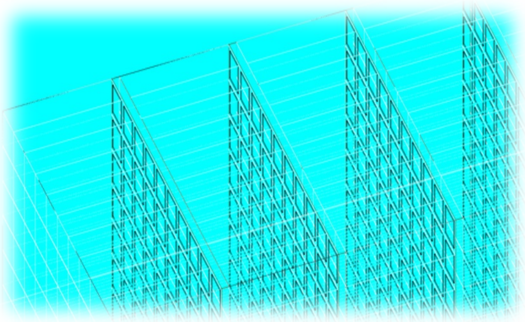
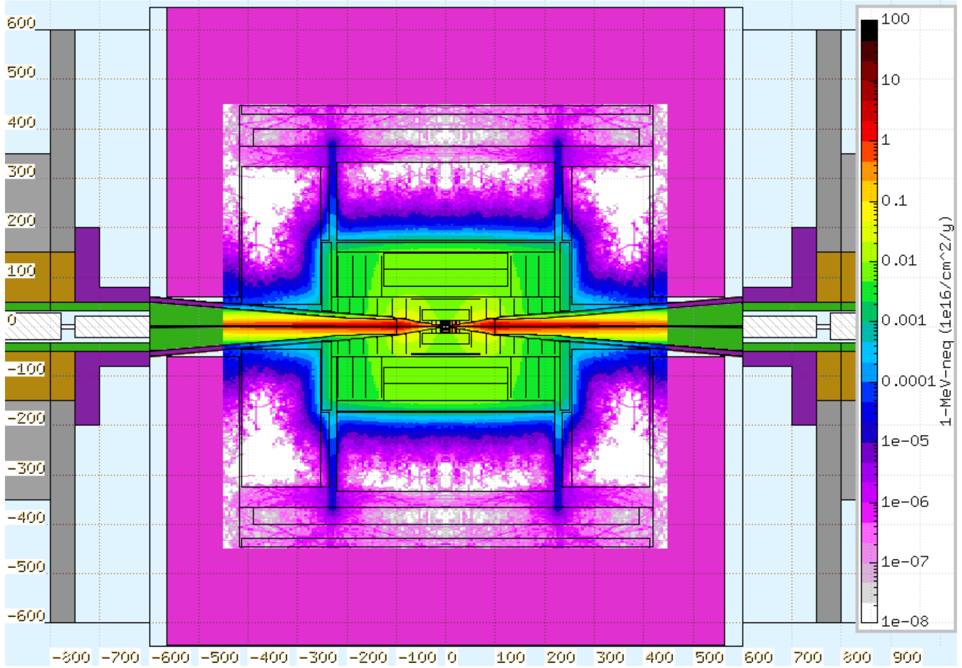
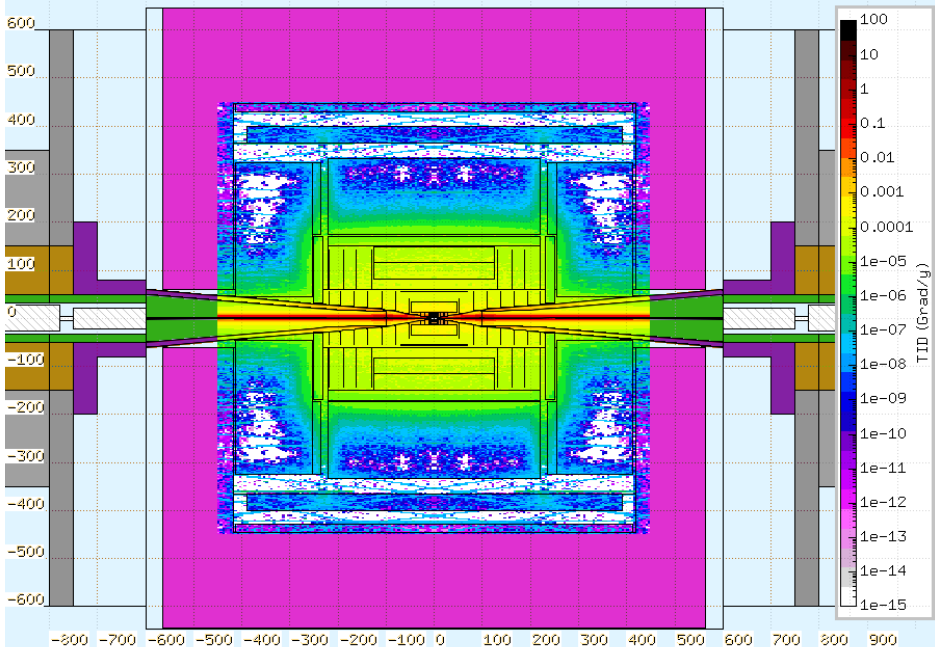




Radiation enviroment

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



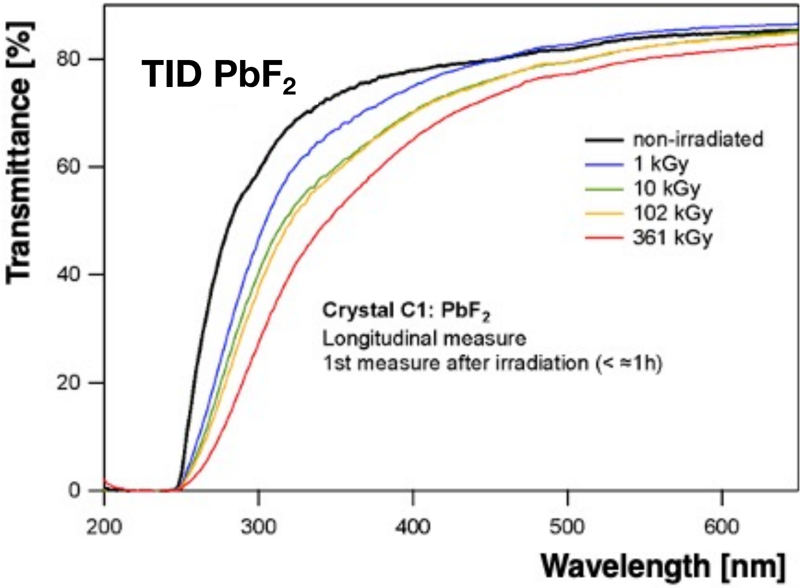


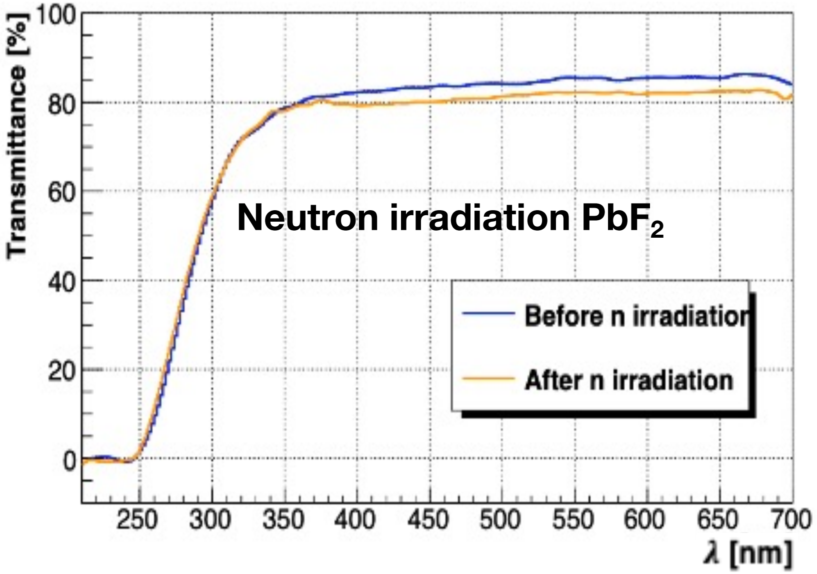
- **Neutron fluence** $\sim \mathbf{10^{14}}$ $n_{1MeVeq}/\boldsymbol{cm^2}$**year** on ECAL.
- **TID ~ 1 Mrad/year** on ECAL.

Radiation hardness tests

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

- **Crystals:** PbF_2 checked for TID (up to **1 MGy** @ Calliope, Enea Casaccia) and 14 MeV neutrons from ENEA-FNG, up to $\mathbf{10^{13}\ n/cm^2}$)
  - ➢ No significant loss in transmittance up to 350 kGy.
  - ➢ Good alternative (stable up to 2 MGy) is PWO-UF.





- **SiPMs:** 10 and 15 μm px-size SiPMs irradiated at ENEA-FNG up to $10^{14} n_{1MeVeq}/cm^2$
  - ➢ 10 μm px-size have a more manageable dark current increase

10 μm pixel-size SiPMs

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

Radiation hardness of PbF2 and PWO-UF

- Expected ECAL barrel ionizing radiation dose: 1 kGy/year (100 krad)
- Expected ECAL barrel neutron fluence: 10^{14} $n_{1MeVneq}/cm^2$ / year

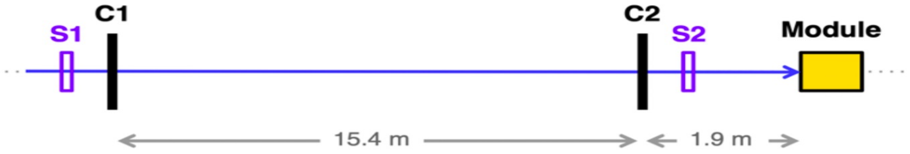
Preliminary conclusions:

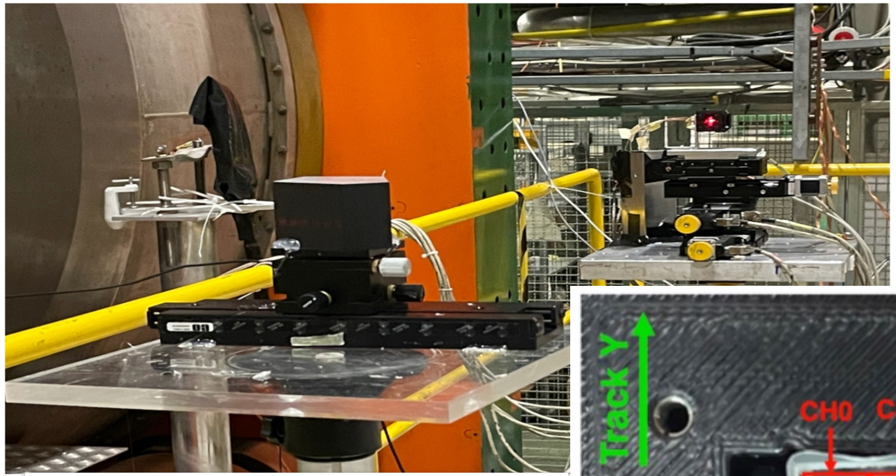
- PbF2 shows increased transmission threshold at low wavelength already at 10-100 kGy
- ~~Blue-green transparency for PbF2 can be recovered by exposure to blue light (e.g. natural light for several days)~~
- PWO-UF shows no shift in low-wavelength threshold and only ~2% loss of blue-green transparency even at 2 MGy!
- **Czochralski-grown** PWO (Crytur) is of high quality. Literature suggests that **Bridgeman-grown** PbF2 (SICCAS) may have inferior radiation hardness, requiring separate validation.

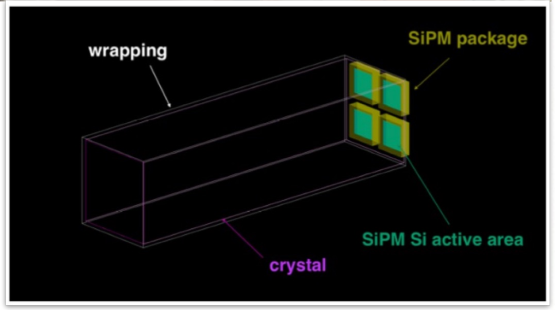
Proto-0: Single crystal beam test

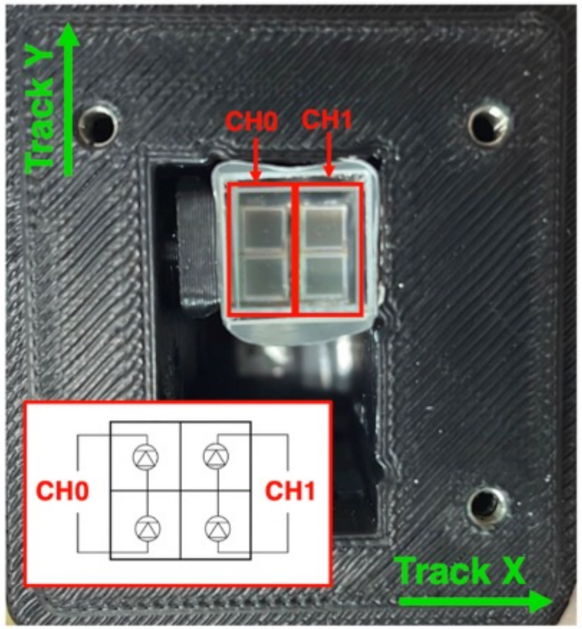
Beam test on Proto-0 in a single crystal configuration in fall 2022:

- $10 \times 10 \times 40$ mm^3 single crystal → 2 options: **PbF_2** (4.3 X_0) **$PbWO_4$-UF** (4.5 X_0).
- Four 3x3 mm^2, 10 μm pixel size SiPMs for two independent readout channels (SiPM pairs connected in series).
- Mylar wrapping - No optical grease.







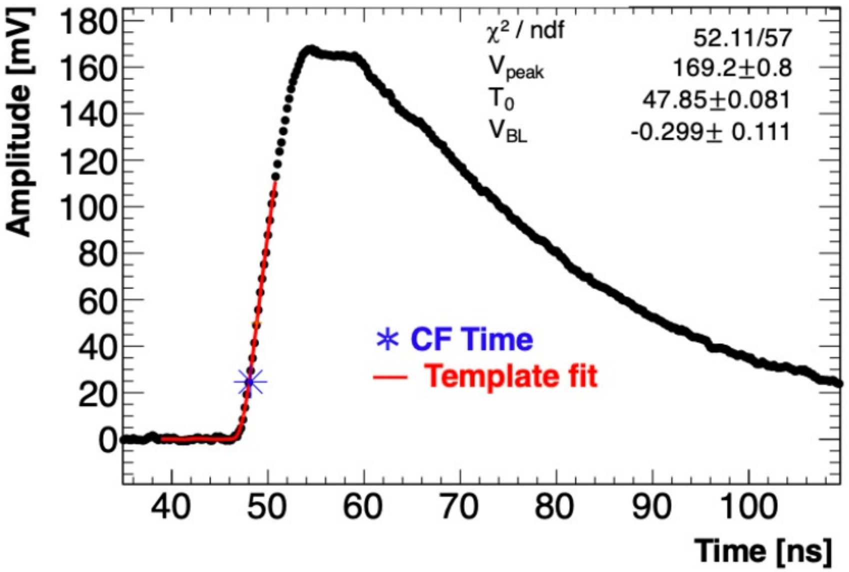


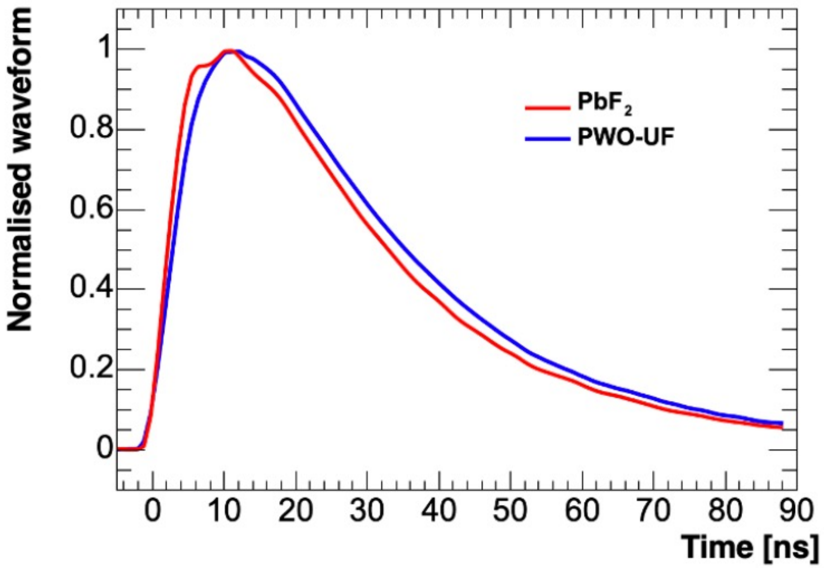
Aim:

- Validate CRILIN new readout electronics and readout scheme.
- Study systematics of light collection in small crystals with high *n.*
- Measure time resolution achievable with different crystal choices.

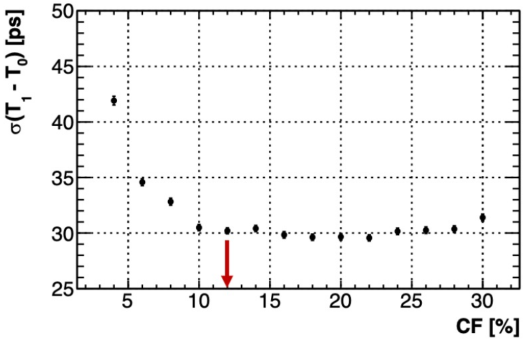
Waveform recontruction

- Template fit for WF reconstruction
- Timing extraction using CF method

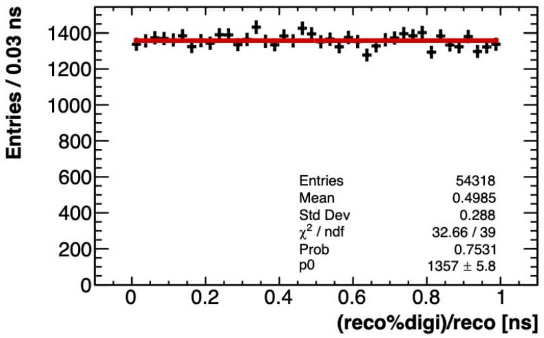




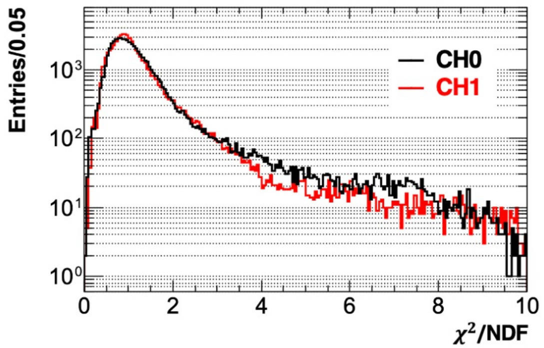
CF optim



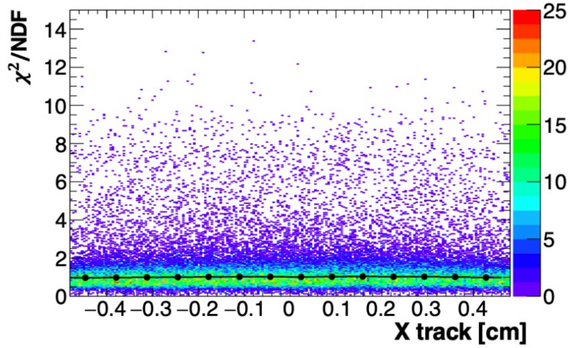
bias check



fit chi2s



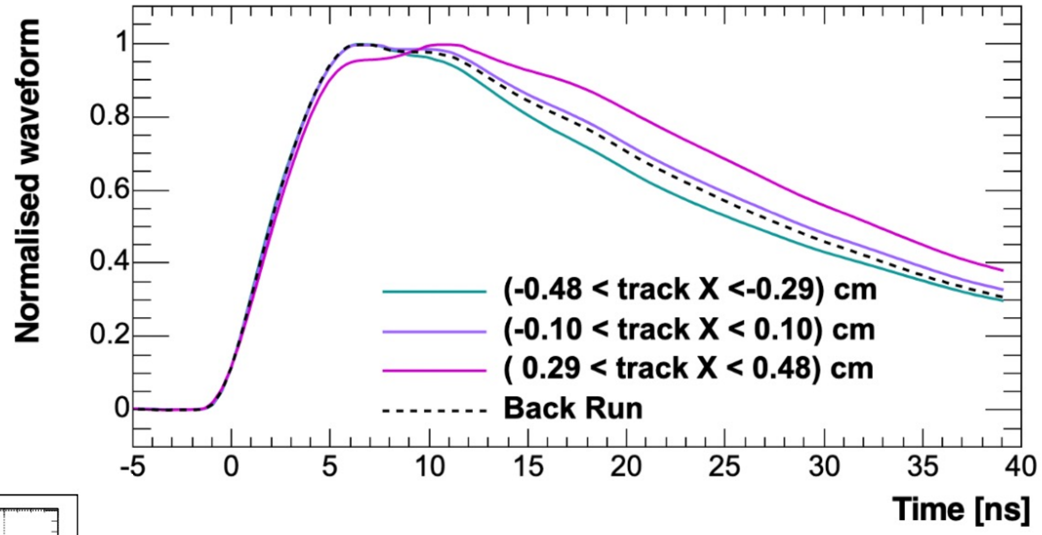
chi2:pos

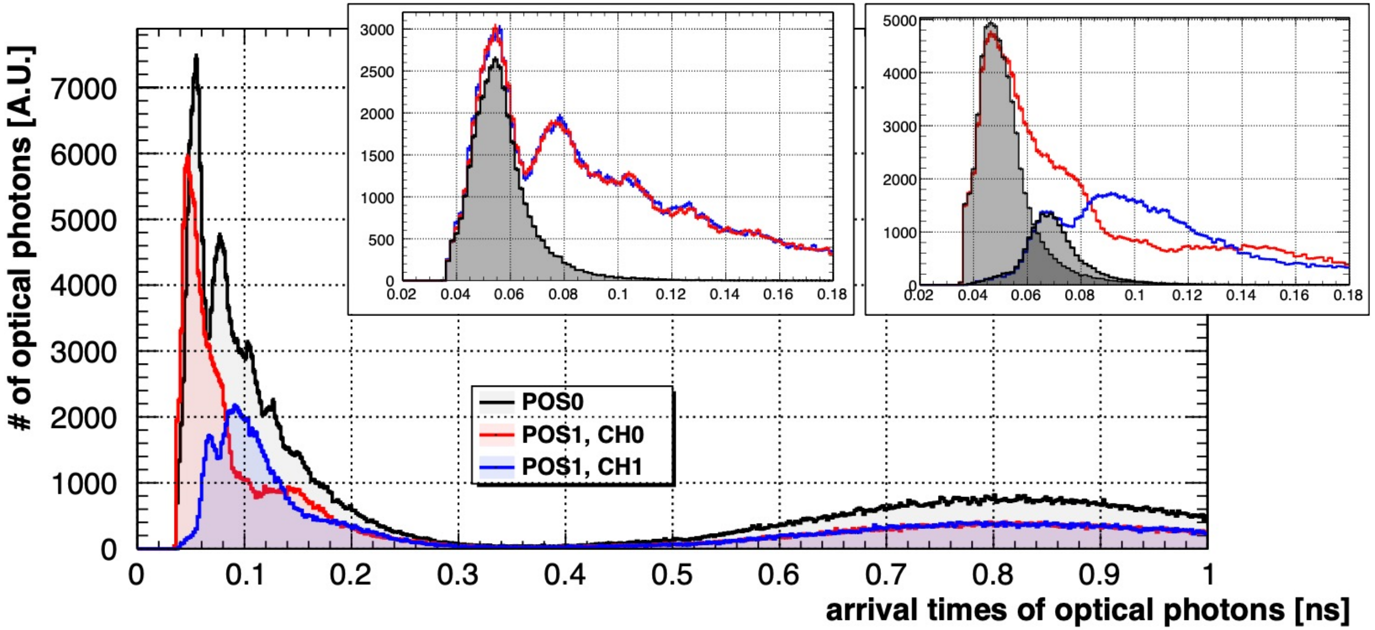


Positional effects: waveshapes

Effects on waveforms (data)

- Pulse shape modification as a function of impact position selected with different fiducial cuts
- Green → particle incident directly on SiPM pair giving signal
- Magenta → particle incident on opposite SiPM pair
- Purple → particle incident between SiPM pairs
- Dashed line → signal shape for back runs

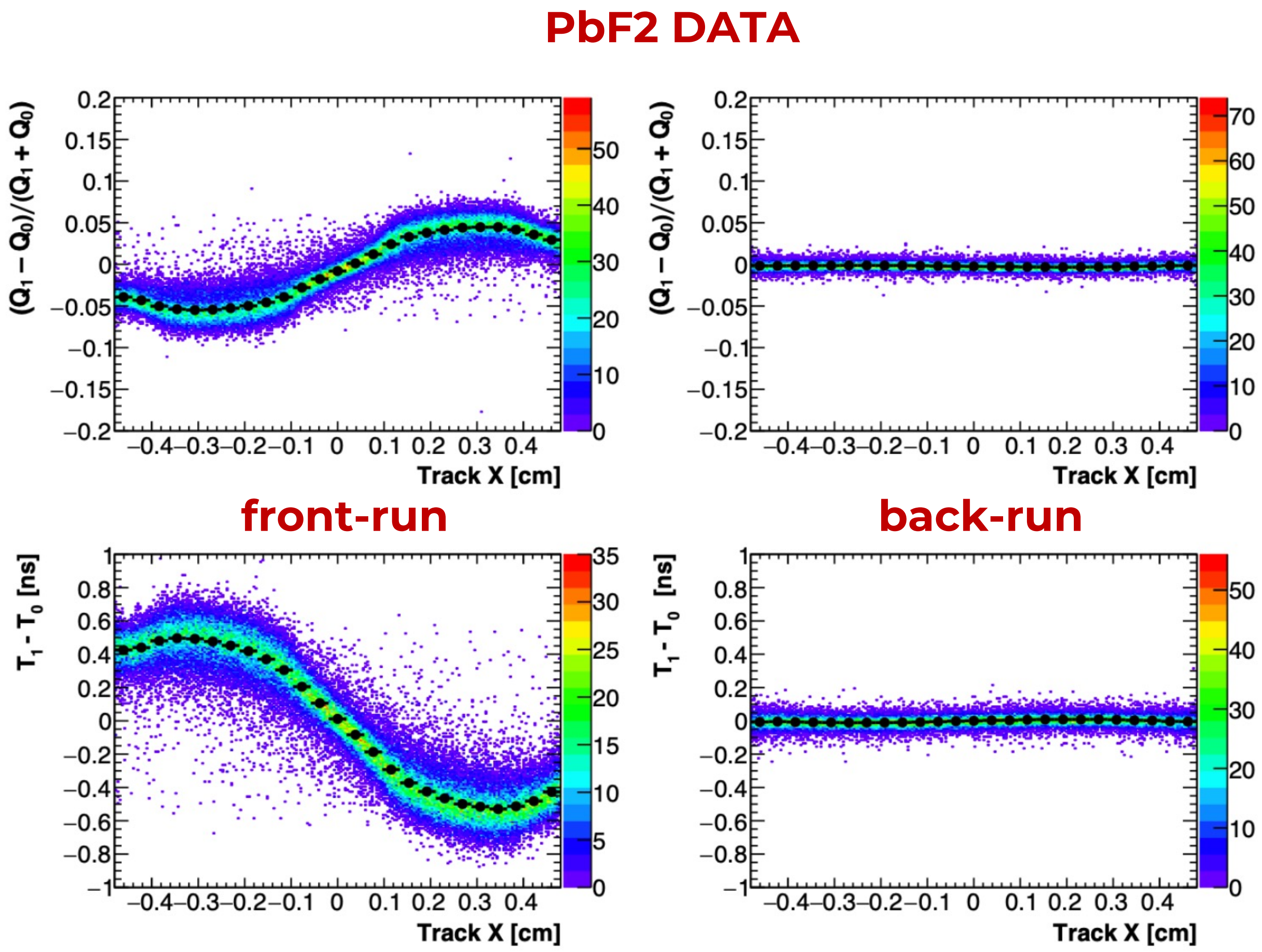




Optical simulation

- Simulated time distributions for optical photons arrival on the photosensors, for two beam positions
- POS0: centred beam the crystal
- POS1: 3 mm beam offset (towards CH0)
- shaded areas → contributions due to light reaching the photosensors directly (i.e., with zero or one reflections)

Positional effects: charge and timing



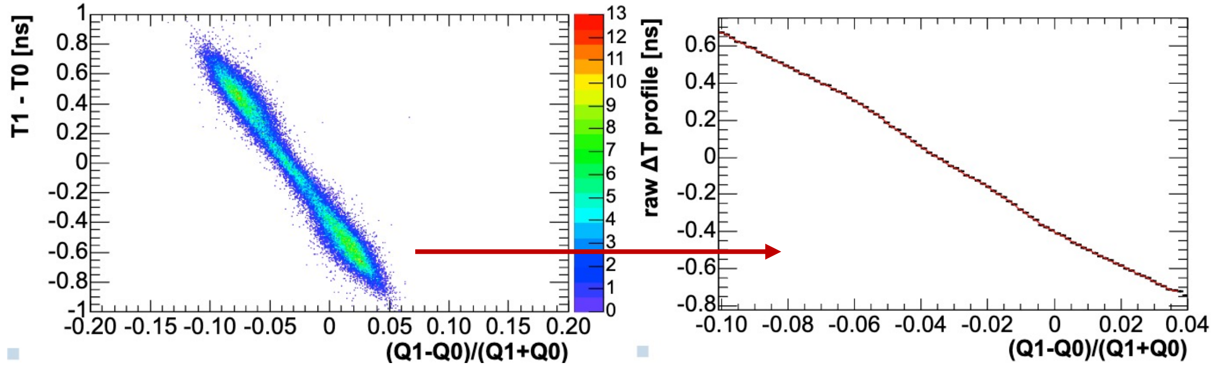
- +/- 10 % maximum imbalance in light collection
- anticorrelated effect on timing (T1-T0)

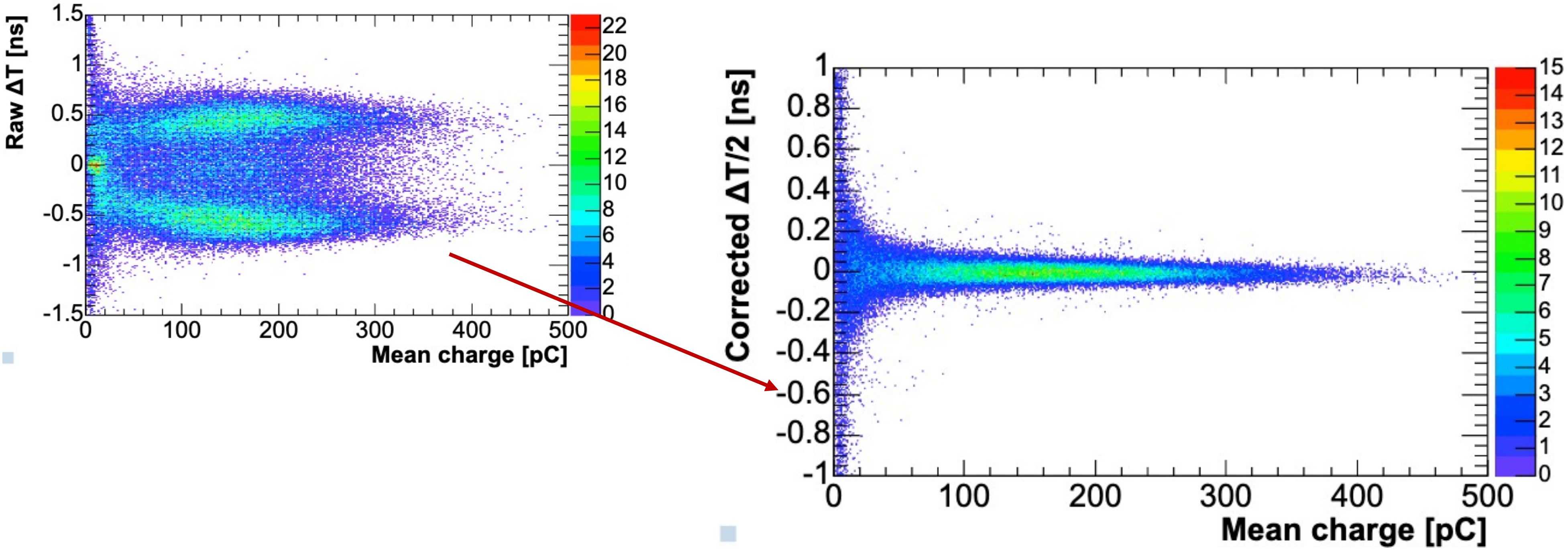
- No significant effects for back-runs
- Similar effects for PbWO4-UF

- Light propagated indirectly is more strongly attenuated due to the longer total path length traversed and the multiple reflections
- earlier arrival times for photons arriving directly

Correction process

- The front mode shows a peculiar distribution both in time time difference and charge sharing:
  - ➢ the relationship between this two quantities can be used as correction function
  - ➢ Negligible effect in back runs





MC validation: optical simulation

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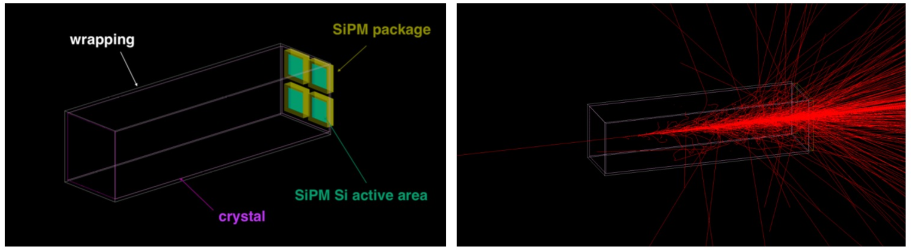
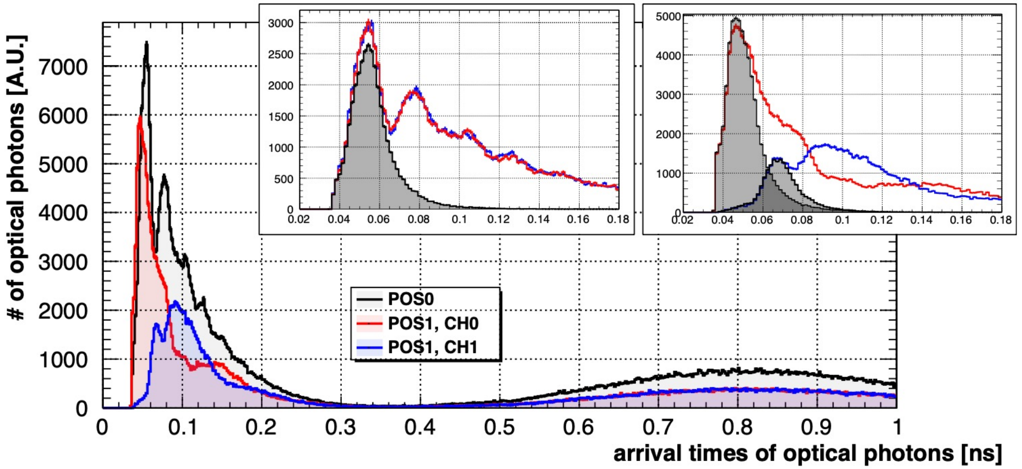
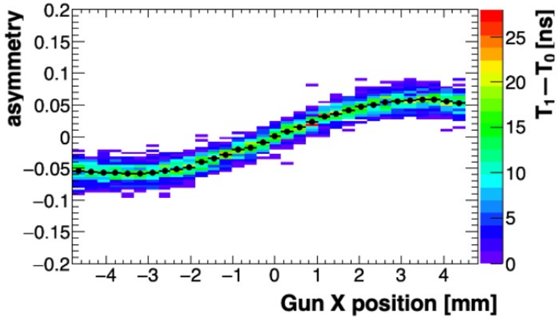
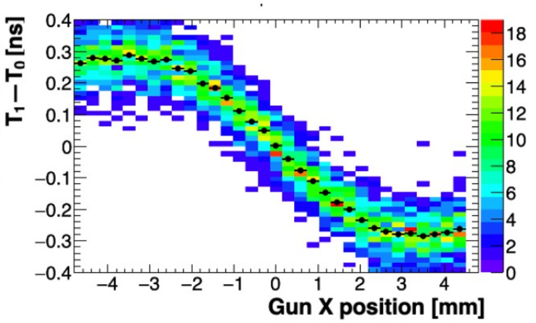
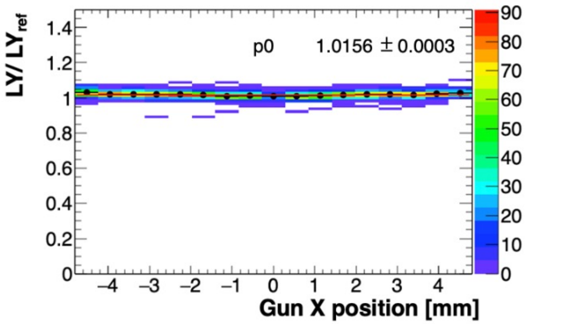
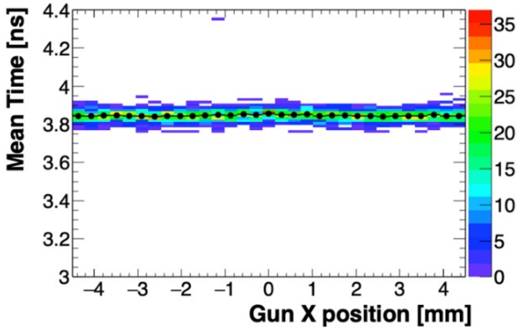












- Confirmation of the positional effects
- Charge asymmetry matched within 20 %
- Smaller timing offsets in simulation wrt data
- mean-time and mean-energy information are always well behaved

Results

Two different orientation were tested → **FRONT** and **BACK:**

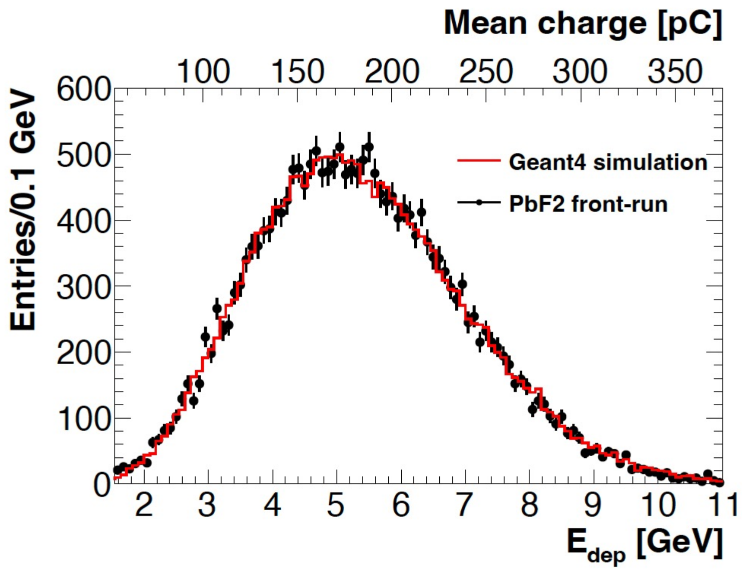
- The BACK run time resolution is better, even after correction, for both crystals.
- PbF_2 outperforms $PbWO_4$-UF despite its higher light output (purely Cherenkov)
- **PbF_2 →** σ_{MT} < 25 ps worst-case for E_{dep} > 3 GeV
- **$PbWO_4$-UF →** σ_{MT} < 45 ps worst-case for E_{dep} > 3 GeV

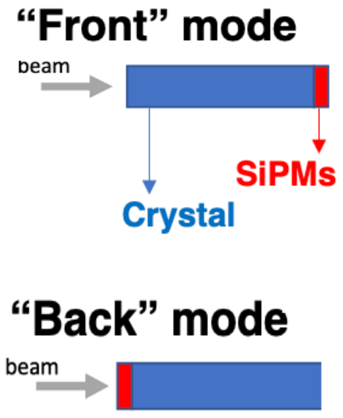
PbF_2

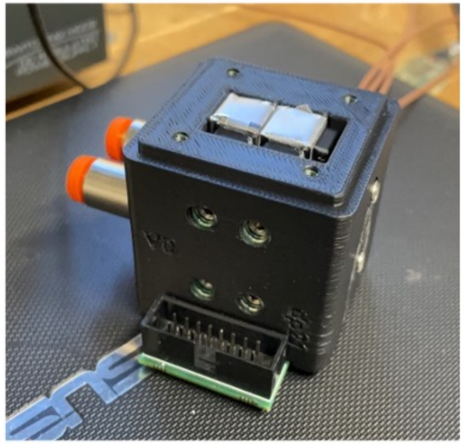
	back-run	front-run
E_{dep} MPV [GeV]	4.26 ± 0.01	4.81 ± 0.03
E_{dep} sigma [GeV]	1.35 ± 0.01	1.46 ± 0.02
pC/GeV	~29.3	~35.6
NPE/MeV	~0.30	~0.30

PWO-UF

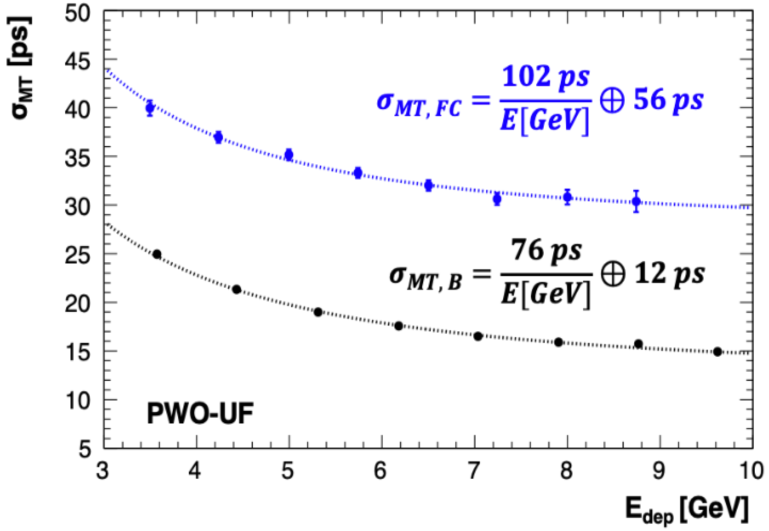
	back-run	front-run
E_{dep} MPV [GeV]	6.39 ± 0.01	6.88 ± 0.01
E_{dep} sigma [GeV]	1.83 ± 0.01	1.99 ± 0.01
pC/GeV	~66.7	~76.9
NPE/MeV	~0.11	~0.13

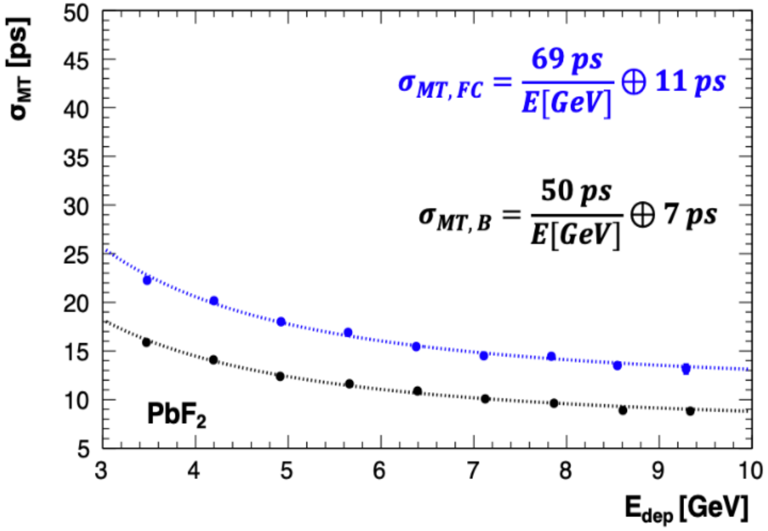






Proto-0





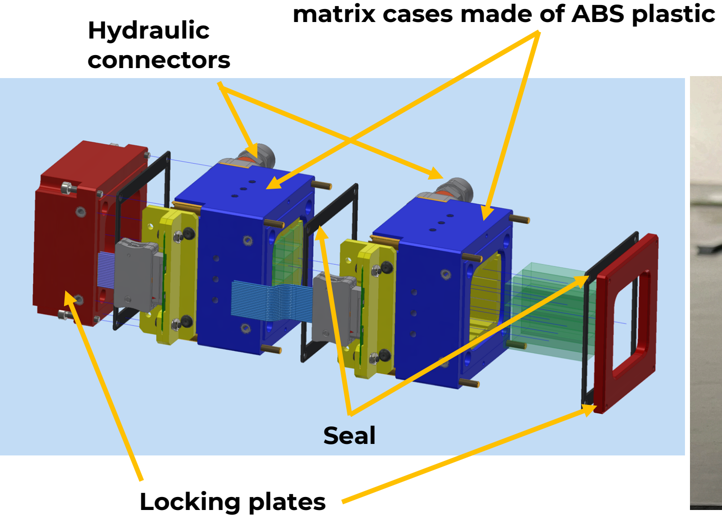
Proto-1

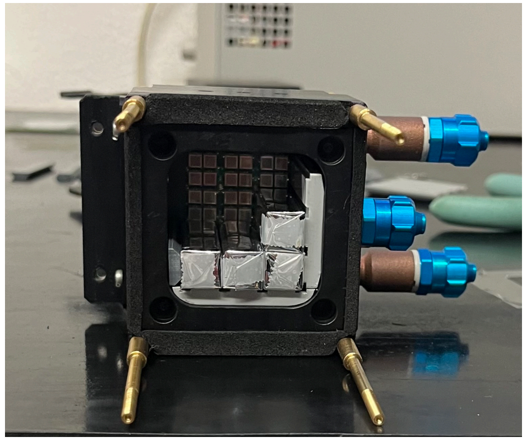
Two stackable and interchangeable submodules assembled by bolting, each composed **of 3x3 crystals+36 SiPMs** (2 channels per crystal)

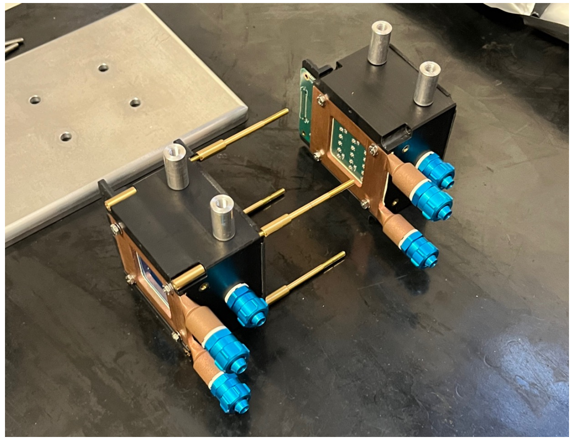
- light-tight case which also embeds the front-end electronic boards and the heat exchanger needed to cool down the SiPMs.

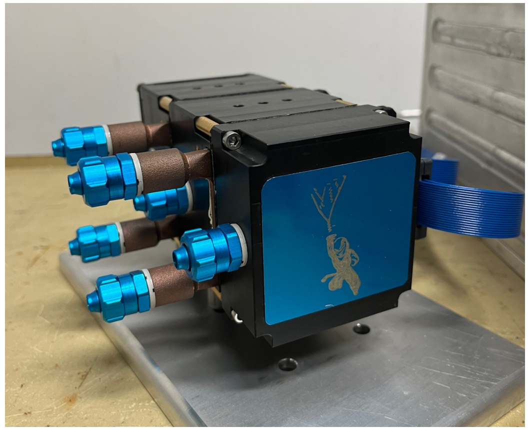
Cooling system:

- Total heat load estimated: **350 mW per crystal** (two readout channels)
- Cold plate heat **exchanger** made of copper mounted over the electronic board.
- **Glycol based water solution** passing through the deep drilled channels.









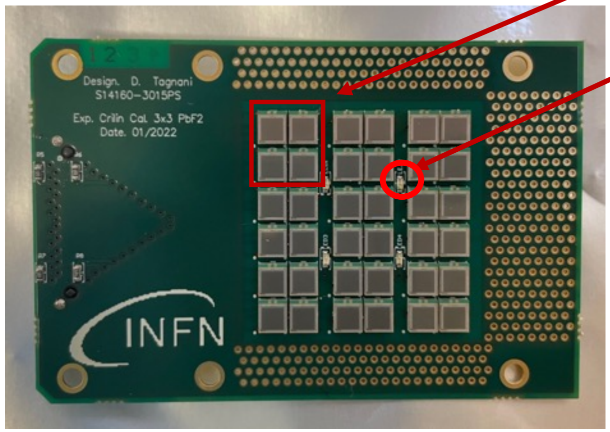
Proto-1: Electronics

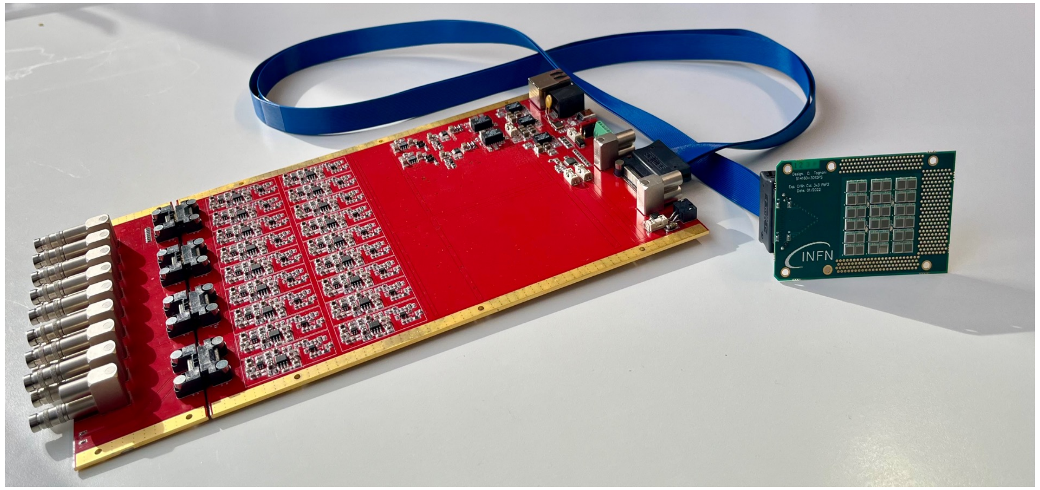
The **SiPMs board** is made of:

- **36 10 μm Hamamatsu SiPMs** →each crystal has **two separate readout channels connected in series**.
- Four SMD blue LEDs nested between the photosensor packages.

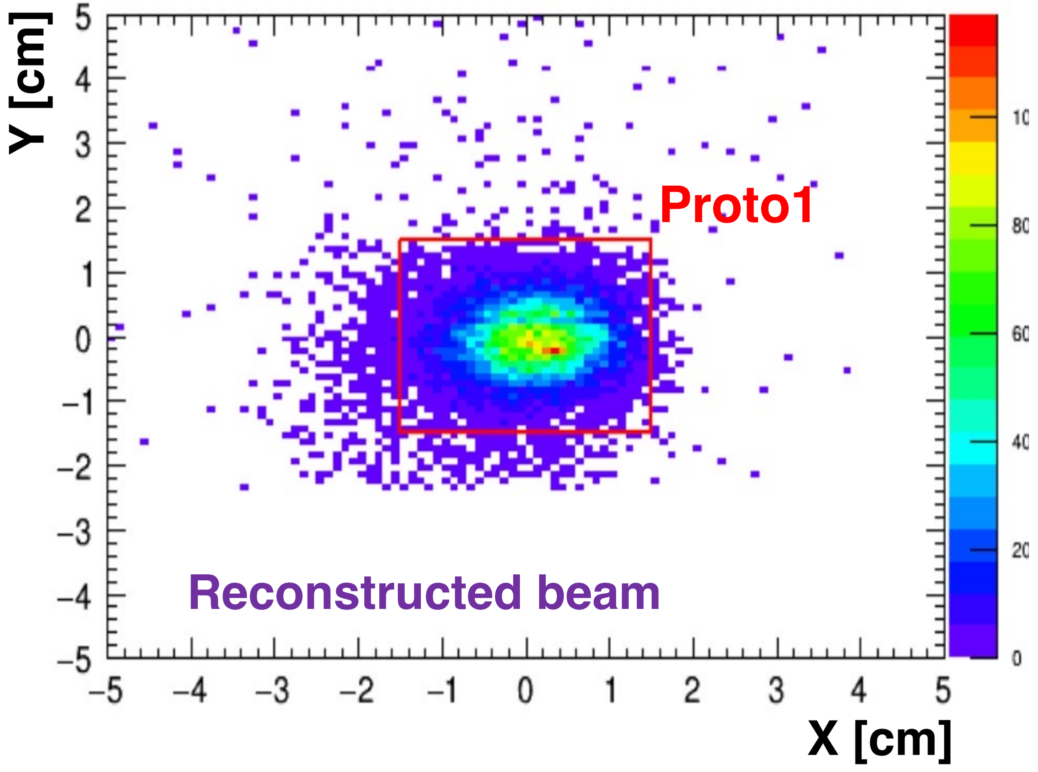
The **Mezzanine Board** for 18 readout channels:

1. Pole-zero compensator and high speed non-inverting stages;
2. 12-bit DACs controlling HV linear regulators for SiPMs biasing.
3. 12-bit ADC channels;
4. Cortex M4 LPC407x Processors.

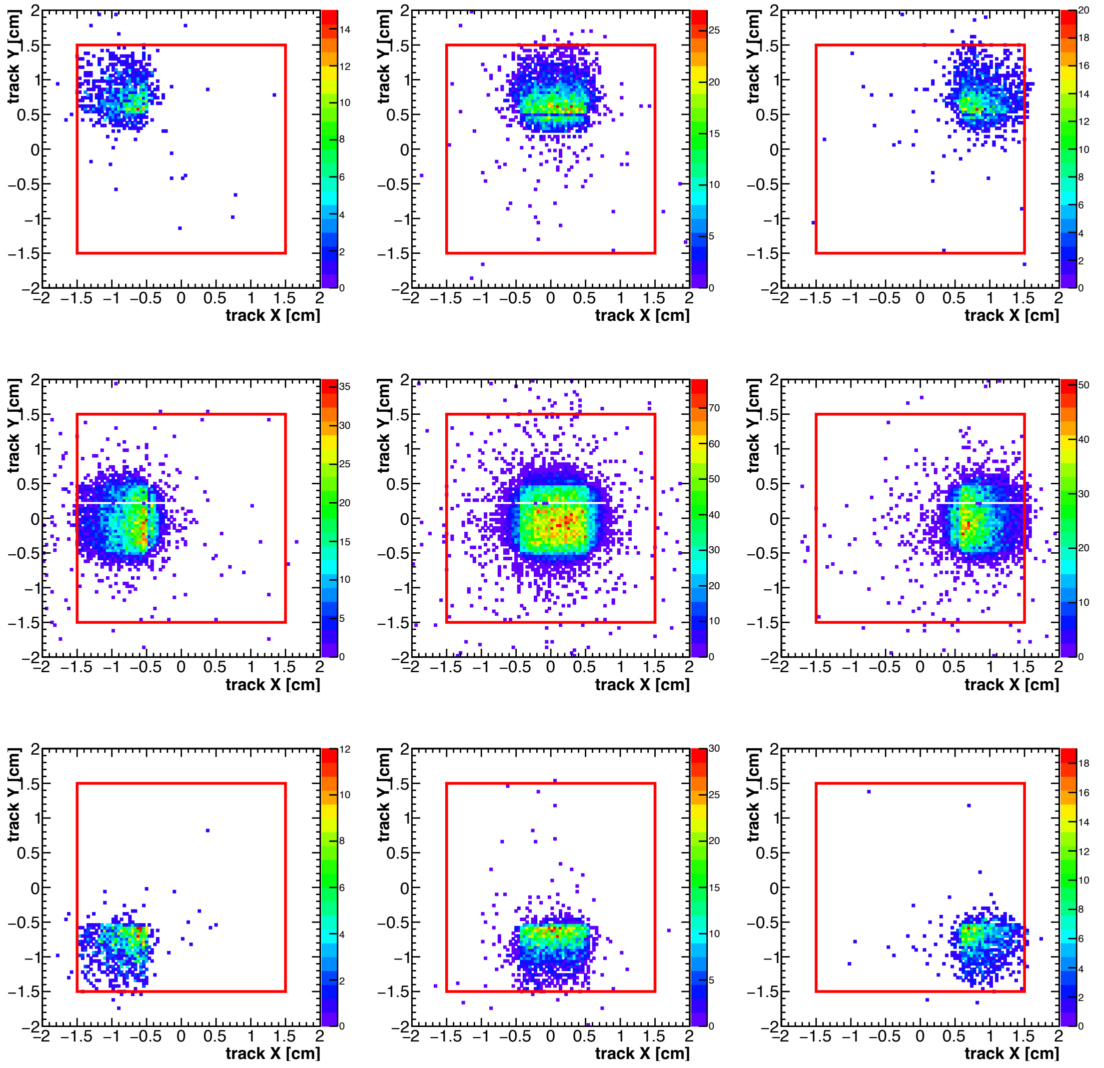




Beam test @ CERN – 2 –



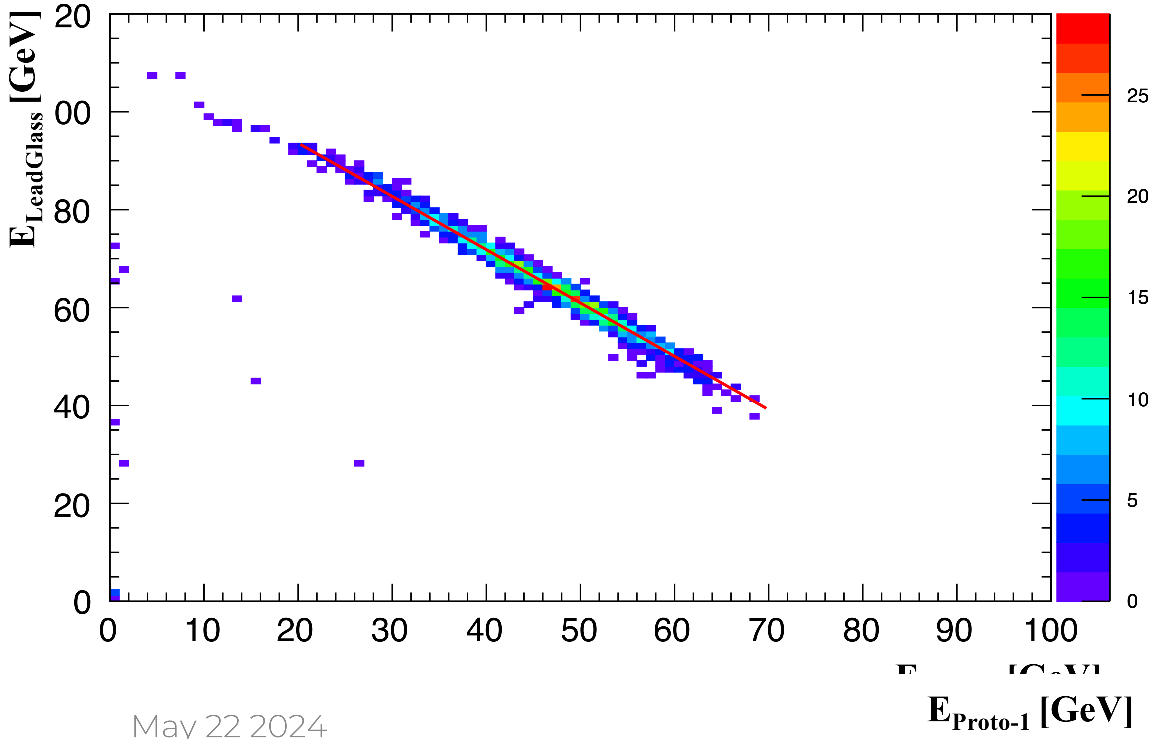
Reconstructed beam on 1st layer crystals

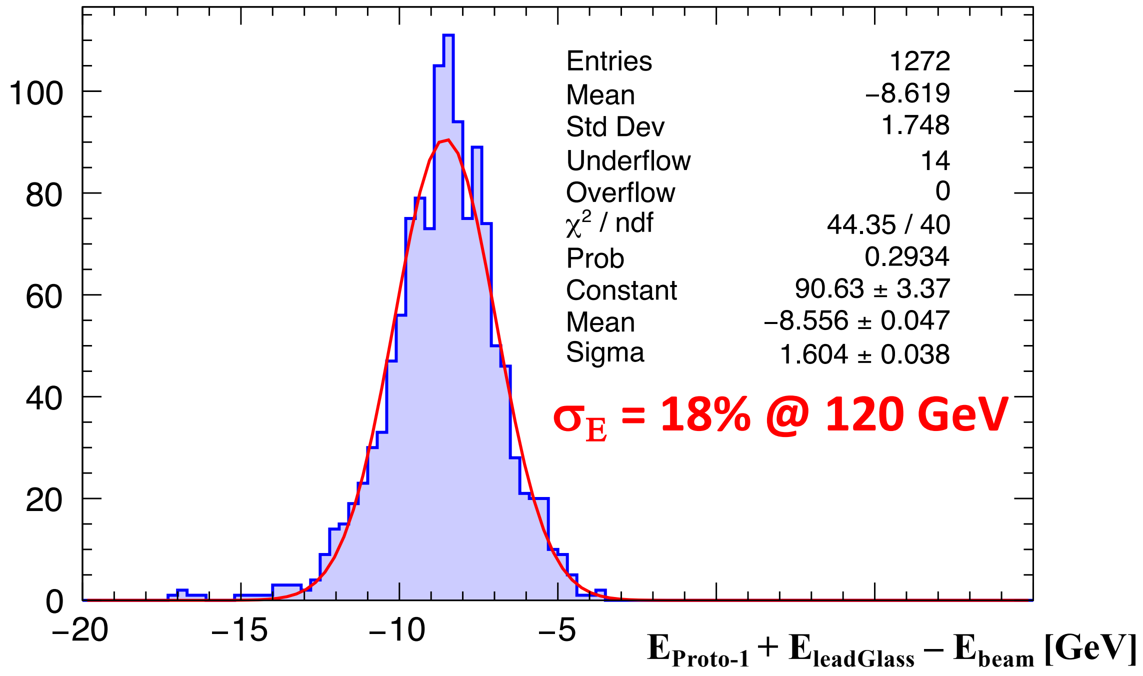


Beam test @ CERN – Proto-1 + Lead Glass –

Energy resolution is dominated by leakage

- ➢ Used 24 X_0, ~2 M_R, lead glass crystal + PMT to recover the longitudinal leakage
- ➢ We obtained about the lead glass measured energy resolution @ 120 GeV → Proto-1 apport is negligible → good indication for the future large-scale prototypes

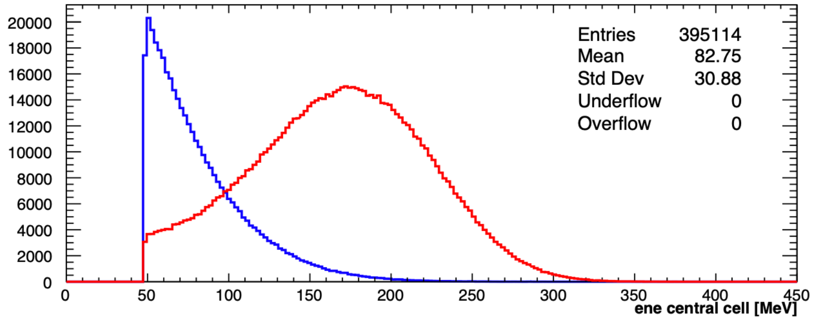




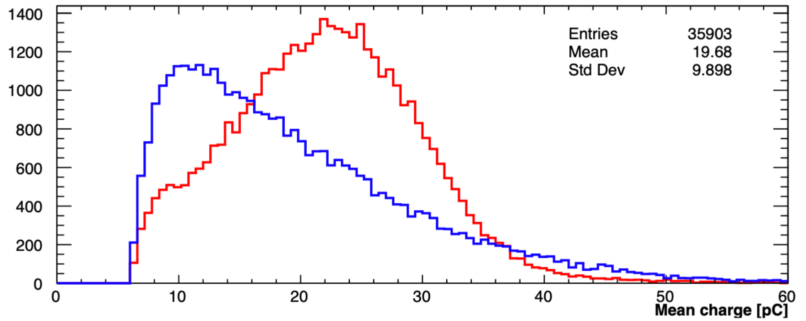
Beam test @ BTF: Result

Threshold a 6 pC → 50 MeV

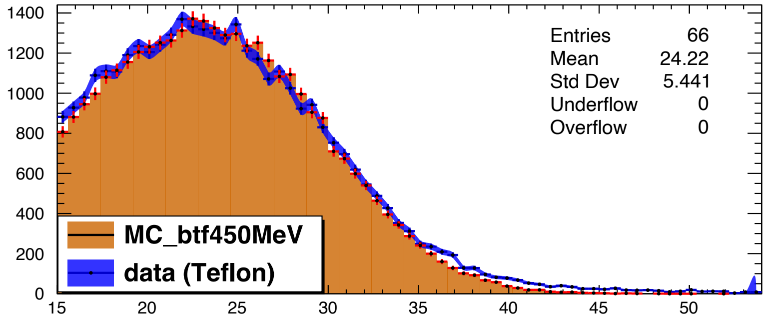
MC

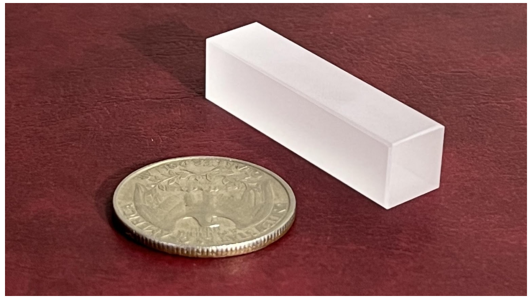


DATA



Equalization data-MC

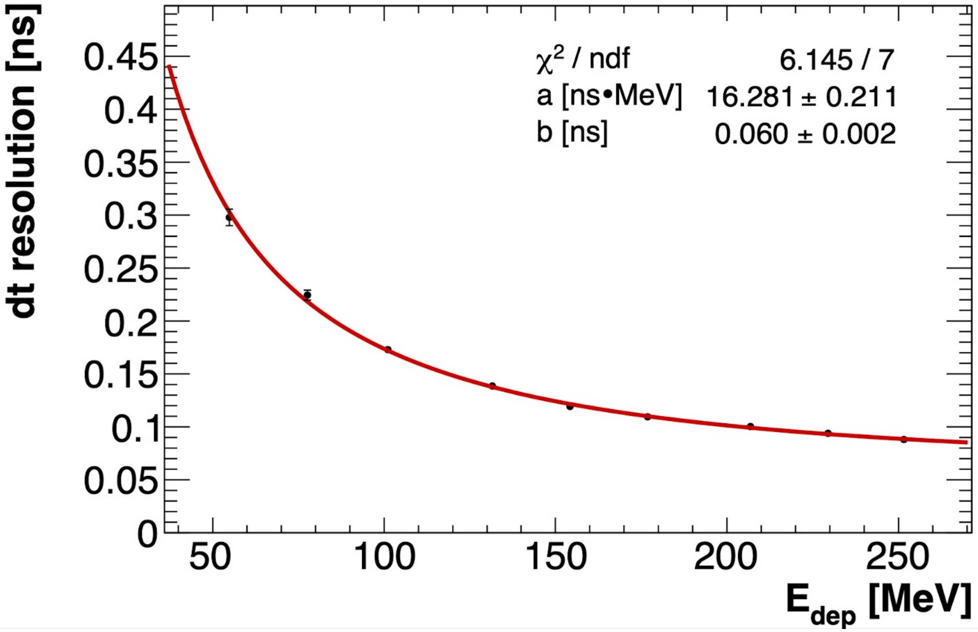




~ 0.13 pC/MeV response (Teflon)

~ 0.32 PE/MeV @ Vop +2 (Teflon)

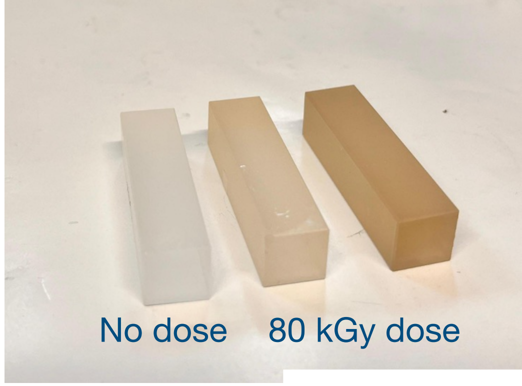
~ 0.25 PE/MEV @ Vop +2 (Mylar)

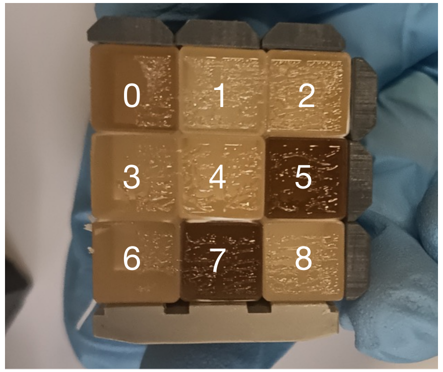


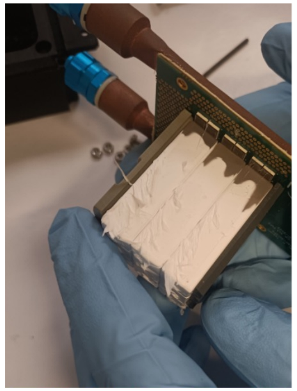
Beam test @ BTF: Teflon wrapping

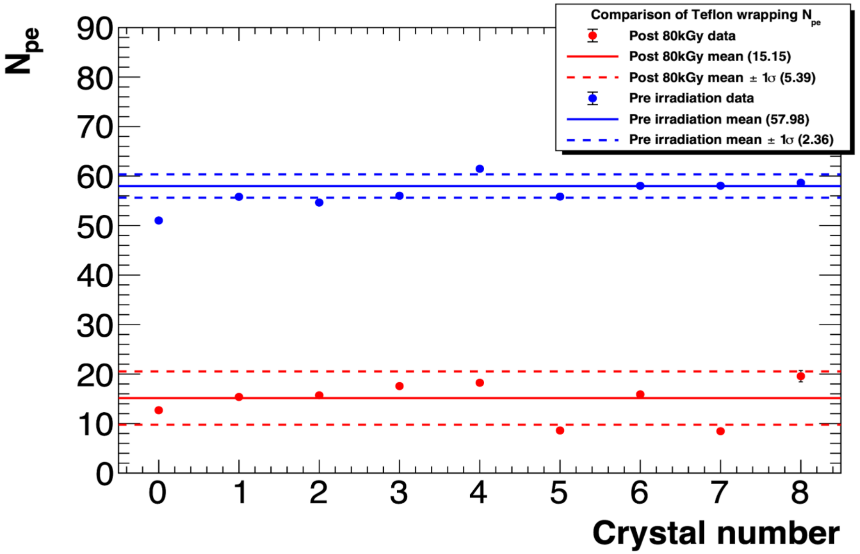
After 80 kGy (8 Mrad) irradiation

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

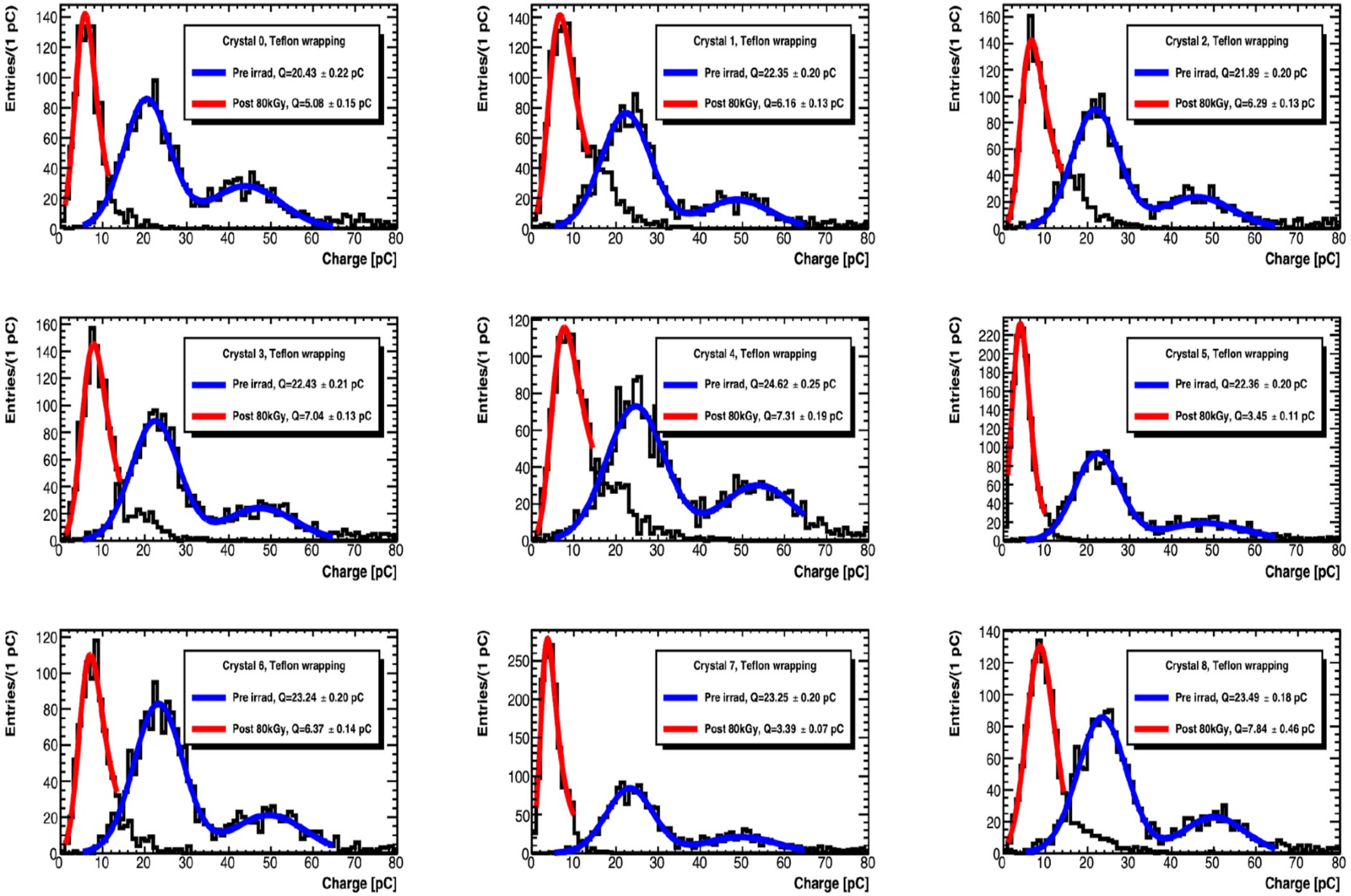






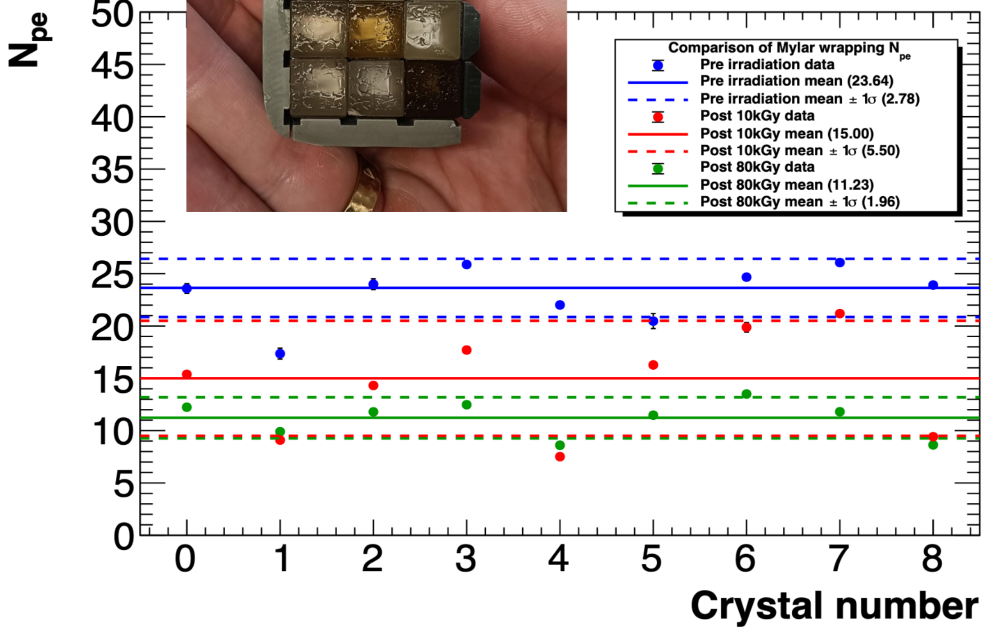


Charge distribution of PbF_2 pre and post irradiation

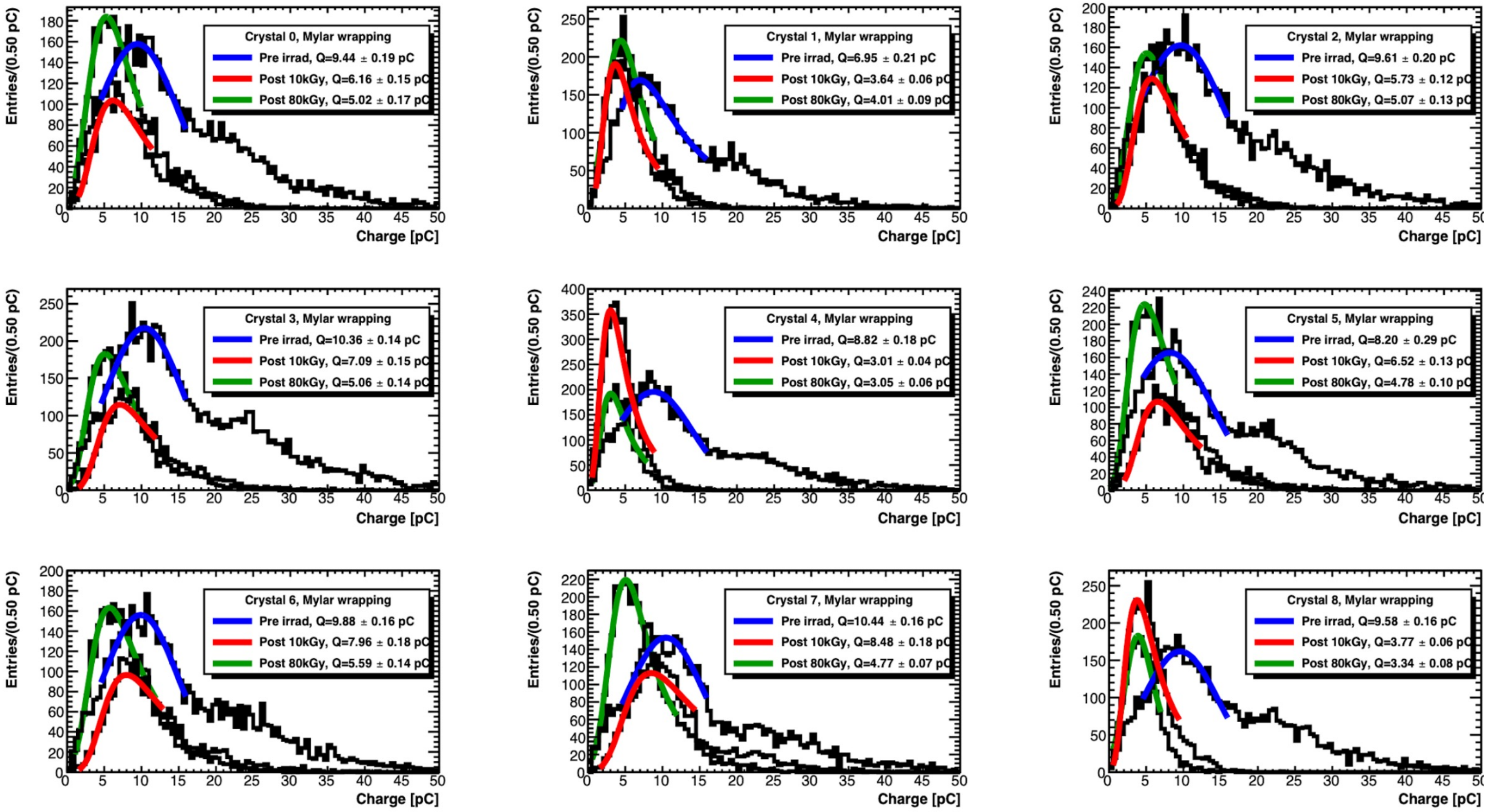


Beam test @ BTF: Mylar wrapping

- 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

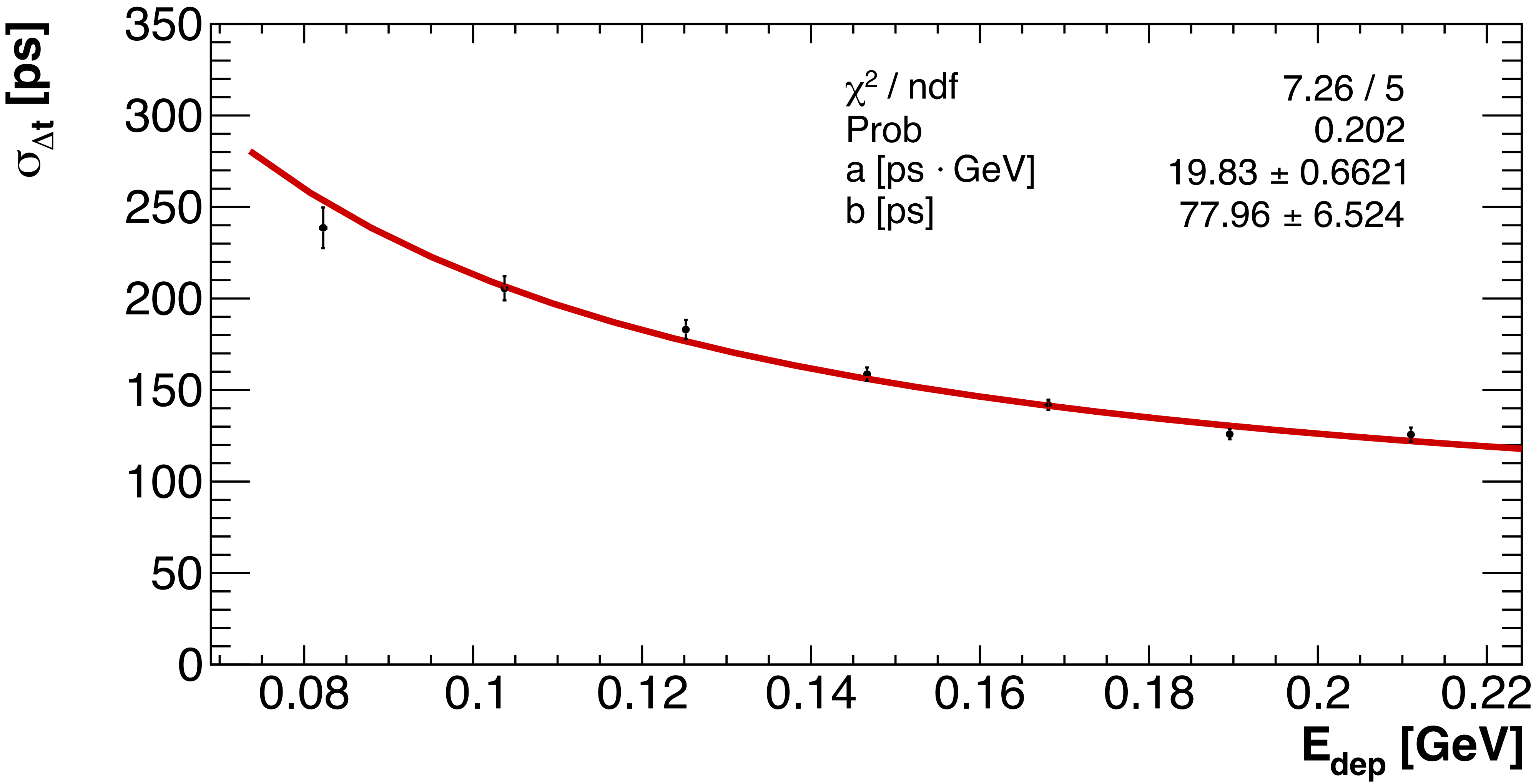


Charge distribution of PbF_2 pre, after 10 kGy and after 80 kGy irradiation



Beam test @ BTF: time resolution

Time resolution for crystal 3 with Teflon wrapping pre irradiation



Crilin Module Prototype

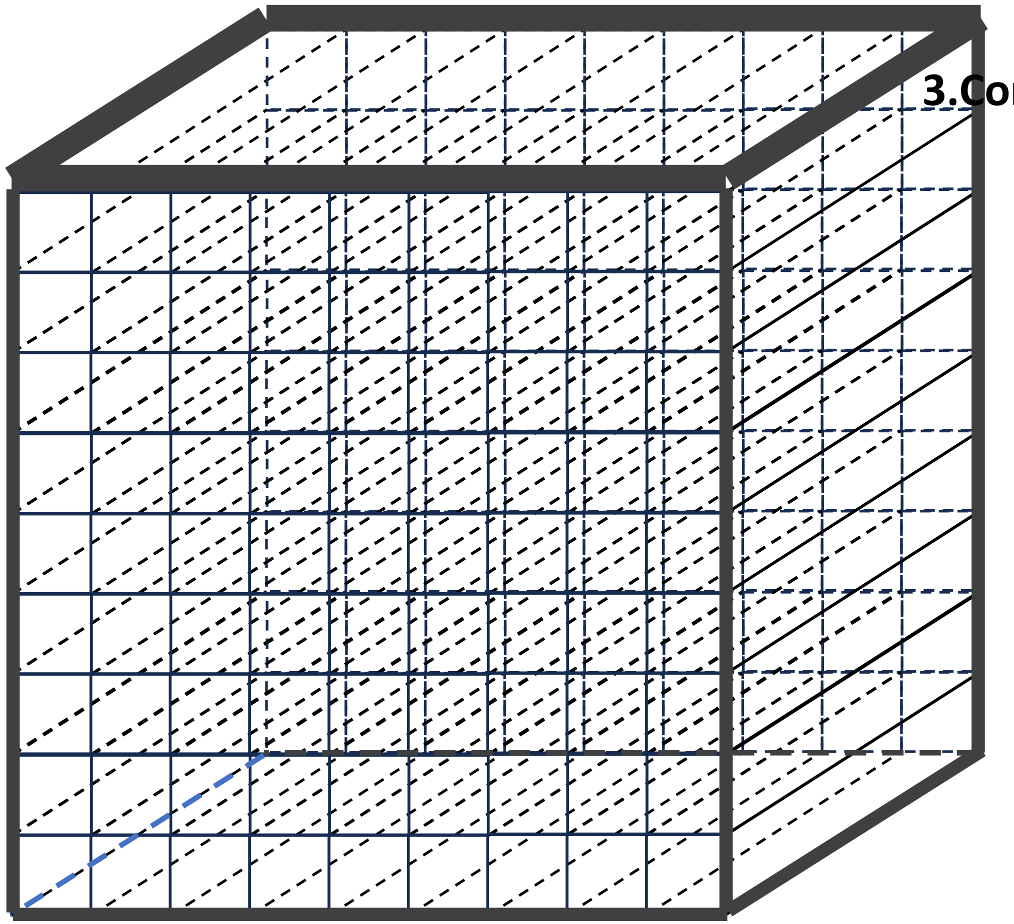
1.Aluminum matrix to hold the crystals:

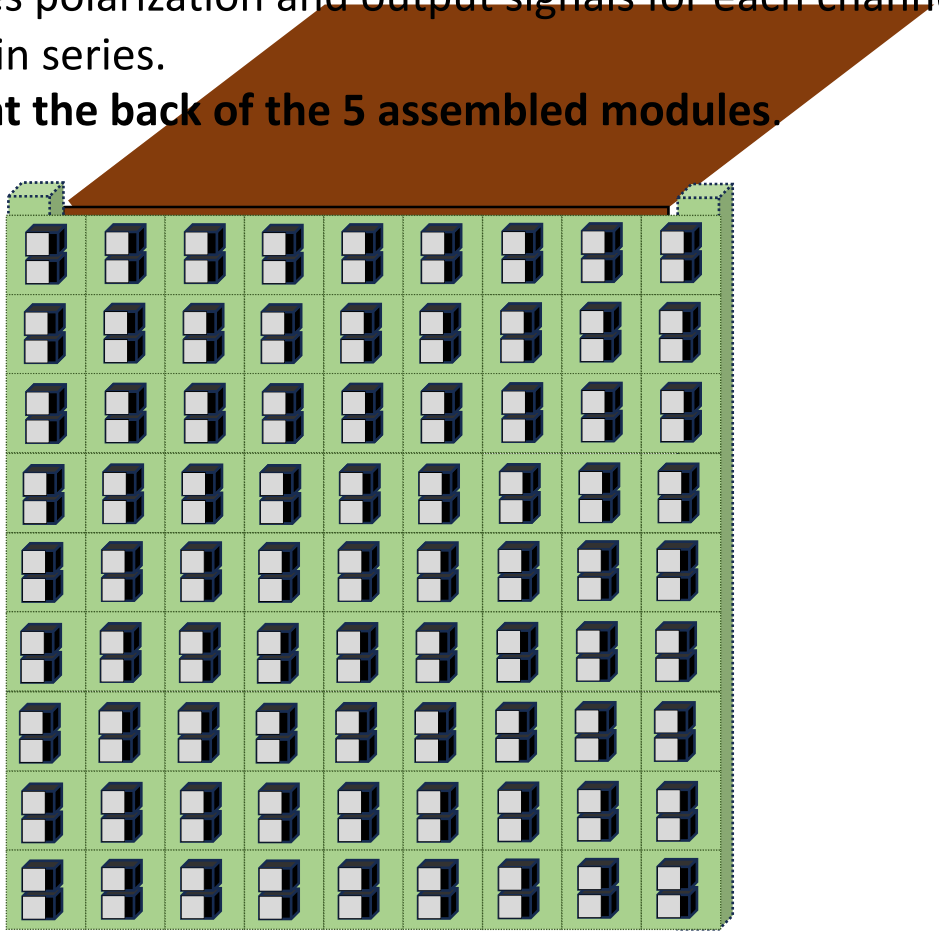
1. 50 µm thickness between crystals
2. Thicker (~ 2mm) in the external envelope with channels for cooling

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.



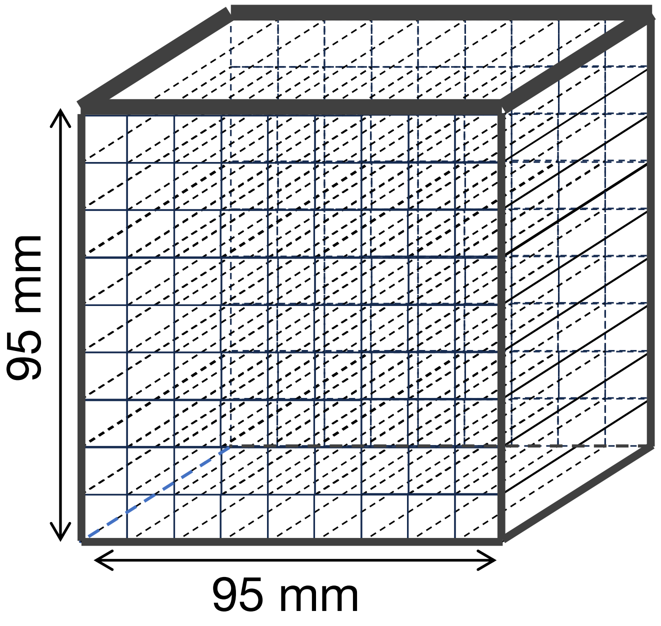


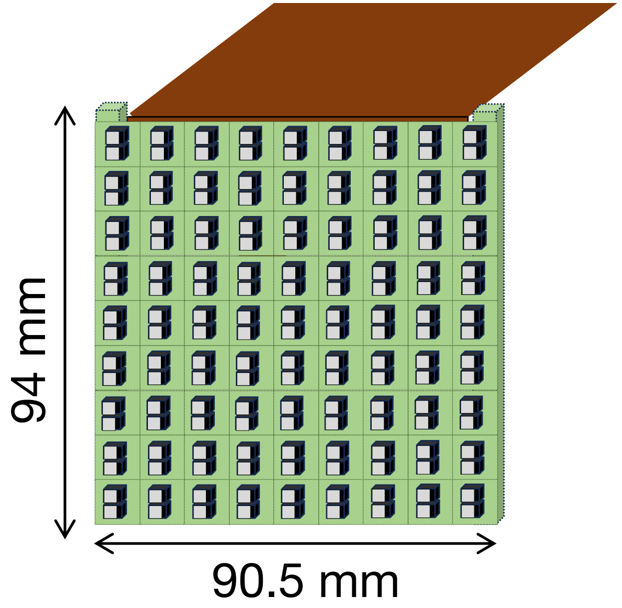
Crilin Module Prototype

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.





Crilin Module Prototype