ICHEP 2024

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

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Crilin and the Muon Collider

Crilin (CRYstal calorimeter with Longitudinal INformation):

- ECAL R&D for the future Muon Collider: an option for a next-gen facility (see US P5)
  - Physics and detector studies for 3 and 10 TeV Muon Collider designs are ongoing

Muon Collider pros:

- **$m_\mu >> m_e$** (no synchrotron radiation)
- **point-like particle:** all energy is available in collisions
- **Higgs** boson studies
- **direct search of heavy states**

Muon Collider cons:

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

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

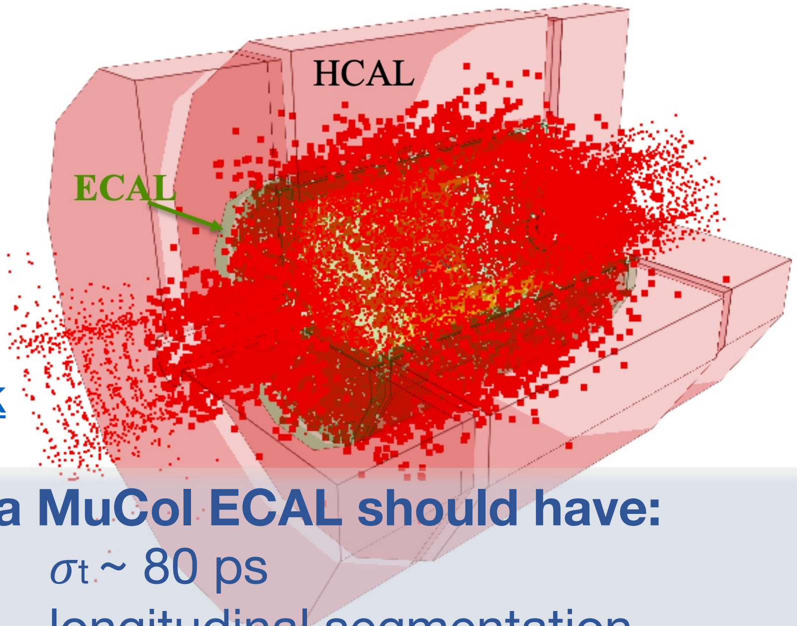
Muon Collider requirements

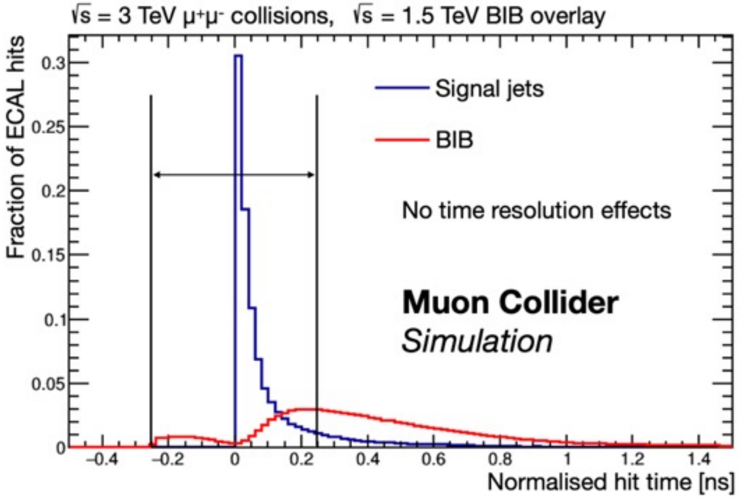
BIB in the ECAL region (after nozzles and tracking system):

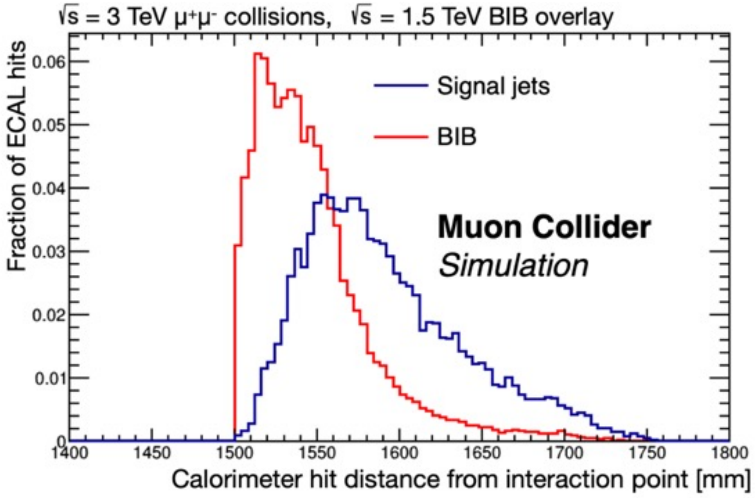
- Flux of 300 particles per cm^2 through the ECAL surface:
    - mainly γ (96%) and n (4%): average photon energy 1.7 MeV
- **Time of arrival flatter** than physics signals → most of BIB excluded with a clustering window of ~240 ps
- Different **longitudinal hit profile** wrt signal
- **Total Ionising Dose**: ~1 kGy/year
- **Neutron fluence**: 10^{14} n_{1MeVeq}/cm^2 / year

See M.Casarsa's talk

BIB hits in the calorimeters







a MuCol ECAL should have:

- σ_t ~ 80 ps
- longitudinal segmentation
- fine granularity
- proper radiation resistance
- $\sigma_E/E \sim 10\%/\sqrt{E}$

→ CALICE-like W-Si sampling calorimeter initially considered as the primary candidate

Now Crilin is the baseline choice

The Crilin calorimeter

- **Semi-homogeneous** ECAL made of **crystal matrices** interspaced and readout by **SiPMs**
- Each crystal independently read by 2 channels, each consisting of 2 SiPMs in series.

Key factors for BIB handling:

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

Longitudinal segmentation: allows to recognize fake showers from the BIB

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

Good resistance to radiation: reliability during the experiment to resist BIB TID and neutrons

Crystal choice motivation:

High-density: allows to build a compact system to fulfil space constraints

Fast response: Cherenkov/fast crystals, to have excellent timing and fast rise times

→ **PbF_2 (Cherenkov only)**
$PbWO_4$-UltraFast
LYSO (to be tested)

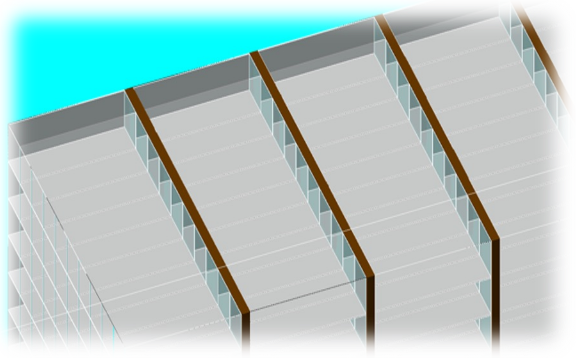
*S. Ceravolo et al 2022 JINST **17** P09033*

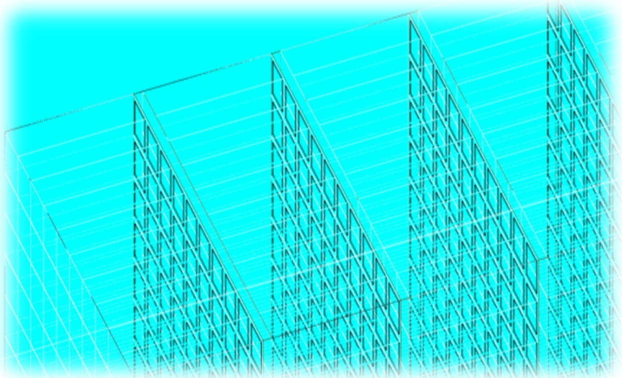
Distinctive features:

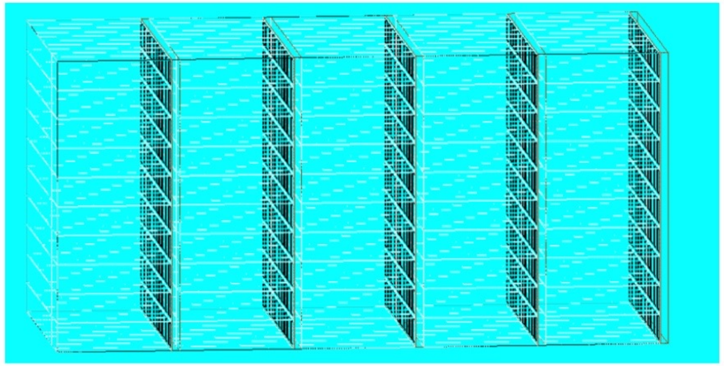
Semi-homogeneous : *unique* hybrid between homogeneous and sampling calorimeters → exploit the strengths of both

Flexibility: able to adjust crystal and layers size for tailored solutions

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

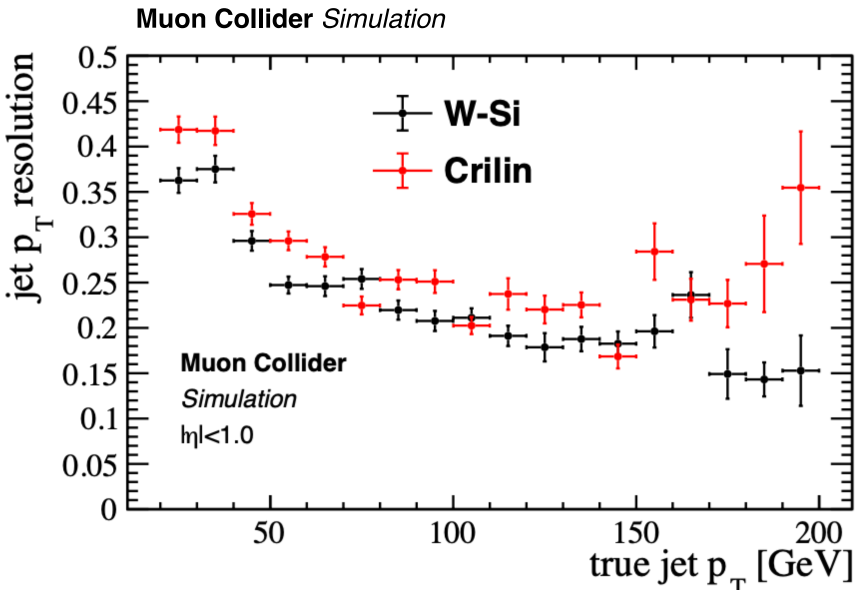


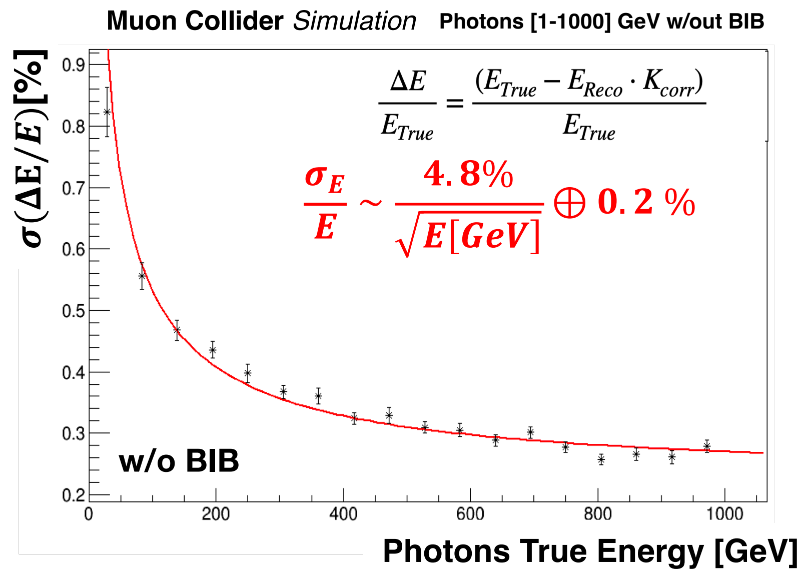


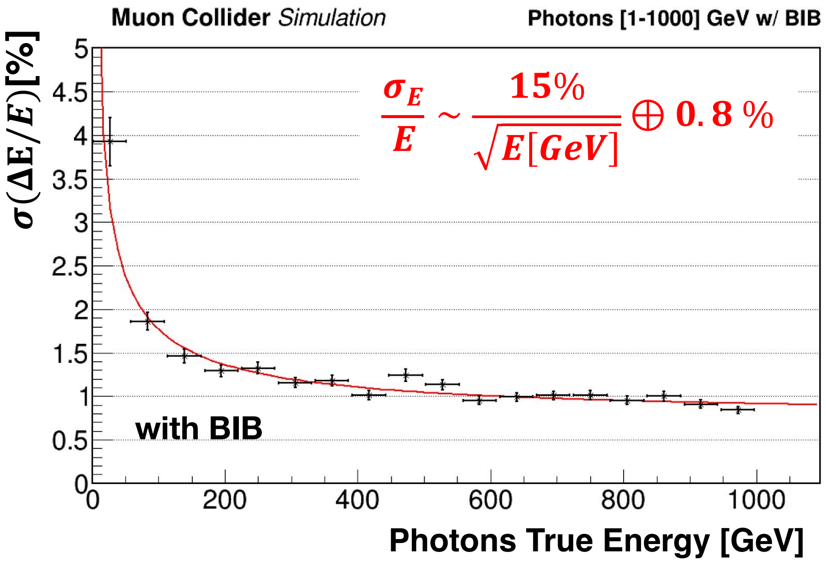


Simulated performances

- ECAL barrel with Crilin technology implemented in the Muon Collider simulation framework
  - Including **digitization** from real test-beam waveforms + BIB rejection with timing and longitudinal hit position
  - 5 layers with 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: with 4.5 cm layers, BIB energy is integrated in large volumes → reduced statistical fluctuations of the BIB energy deposit
- Crilin 5 layers competitive wrt W-Si 40 layers → **factor 10 less in cost** (6 vs 64 Mchannels)







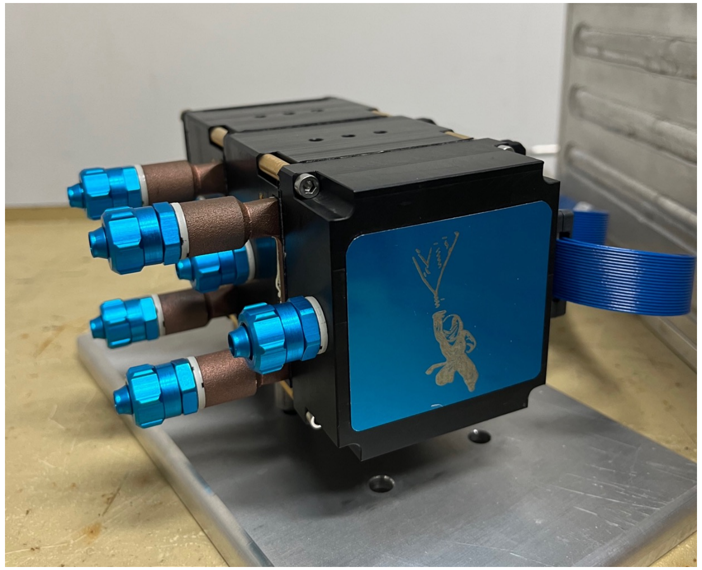
R&D status

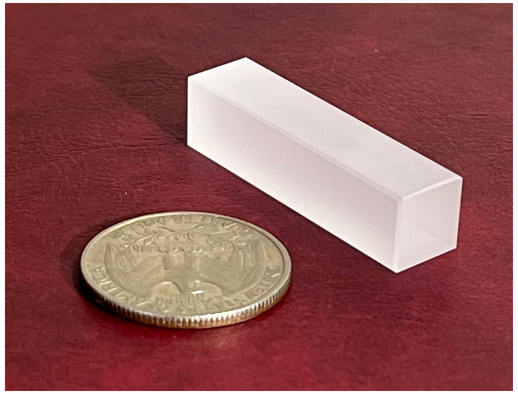
Prototype versions
- Proto-0 (2 crystals → 4 channels)
- Proto-1 (3x3 crystals x 2 layers → 36 channels)

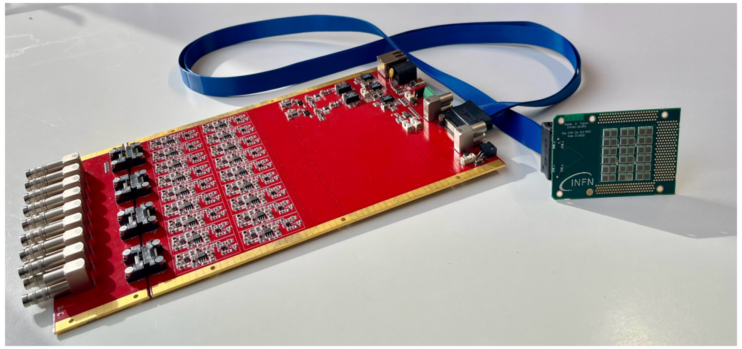
Front-end electronics
- Design completed
- Production and QC completed

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)

- **Radiation hardness campaigns**
  - Both with Neutrons and Gamma rays



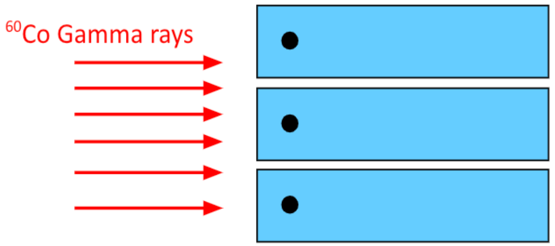




Crystals radiation hardness

Tests of two **PbF_2** and **$PbWO_4$-UF** crystals (both 10x10x40 mm³), for:

- TID (Co-60) @ Calliope, Enea
- Neutrons (14 MeV) @ FNG, Enea

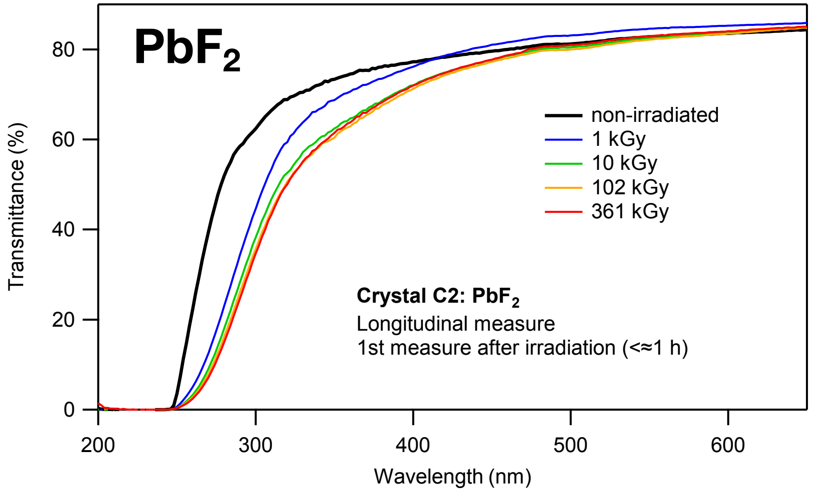


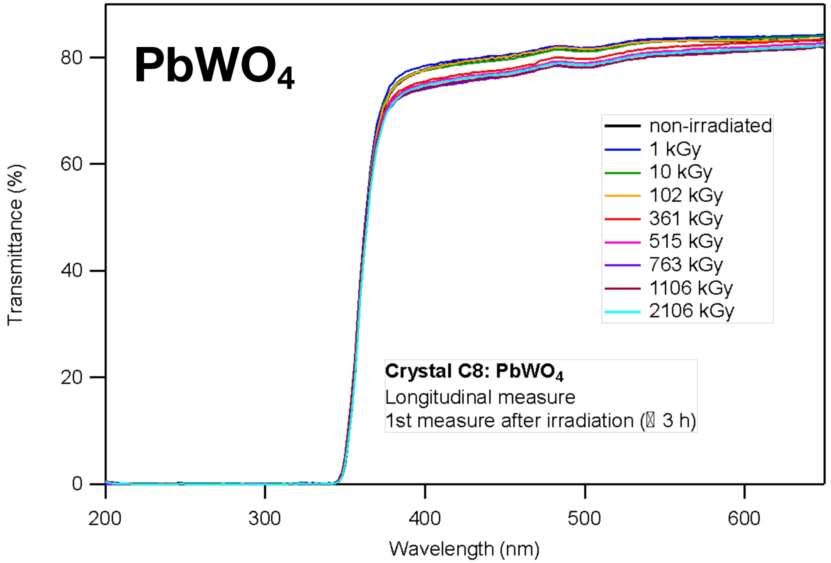
Crystal	PbF_2	PWO-UF
Density [g/cm³]	7.77	8.27
Radiation length [cm]	0.93	0.89
Molière radius [cm]	2.2	2.0
Decay constant [ns]	-	0.64
Refractive index at 450 nm	1.8	2.2
Manufacturer	SICCAS	Crytur

- **For PbF_2 no significant decrease** in transmittance after:
  - **TID < 360 kGy**
  - 10^{13} n/cm² neutrons

- **For $PbWO_4$-UF no significant decrease** in transmittance after:
  - **TID < 2 MGy**

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





SiPMs radiation hardness

Neutrons irradiation tests: 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)

From I-V curves extrapolation at 3 different temperatures:

- Currents at different operational voltages
- Breakdown voltages

15 μm pixel-size

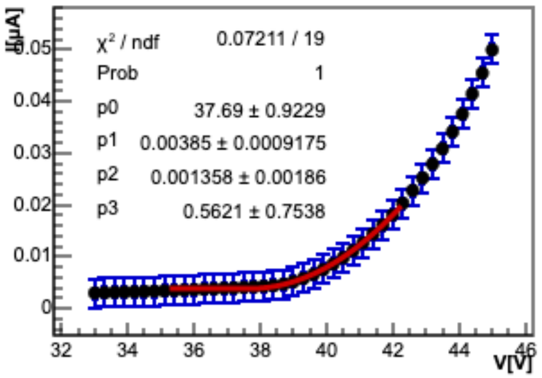
T [°C]	V_{br} [V]	$I(V_{br}+4V)$ [mA]	$I(V_{br}+6V)$ [mA]	$I(V_{br}+8V)$ [mA]
-10 ± 1	75.29 ± 0.01	12.56 ± 0.01	30.45 ± 0.01	46.76 ± 0.01
-5 ± 1	75.81 ± 0.01	14.89 ± 0.01	32.12 ± 0.01	46.77 ± 0.01
0 ± 1	76.27 ± 0.01	17.38 ± 0.01	33.93 ± 0.01	47.47 ± 0.01

10 μm pixel-size

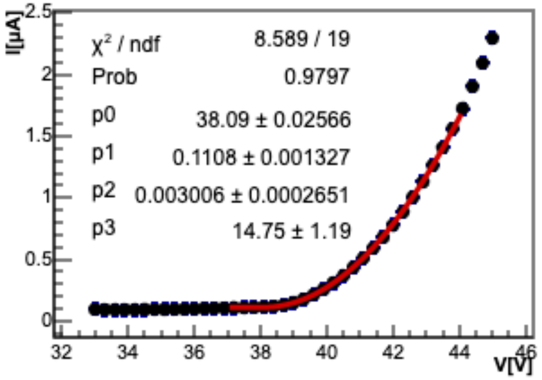
T [°C]	V_{br} [V]	$I(V_{br}+4V)$ [mA]	$I(V_{br}+6V)$ [mA]	$I(V_{br}+8V)$ [mA]
-10 ± 1	76.76 ± 0.01	1.84 ± 0.01	6.82 ± 0.01	29.91 ± 0.01
-5 ± 1	77.23 ± 0.01	2.53 ± 0.01	9.66 ± 0.01	37.51 ± 0.01
0 ± 1	77.49 ± 0.01	2.99 ± 0.01	11.59 ± 0.01	38.48 ± 0.01

Dark I @ V_{op} 1.8 vs 13 mA for 10/15 micron pixels

10 μm pixel-size
Pre 10kGy



10 μm pixel-size
Post 10kGy



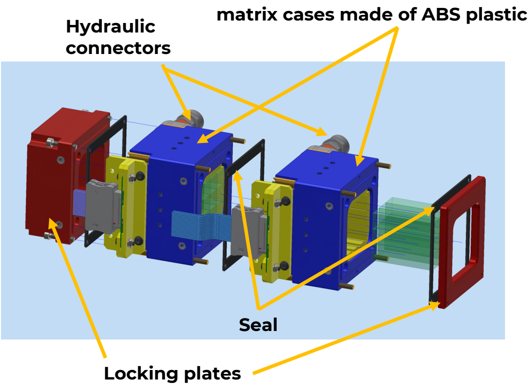
For the expected radiation level, **the best SiPMs choice are the 10 μm ones** for their minor dark current contribution.

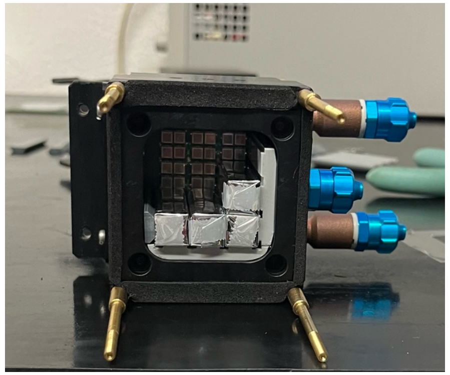
Dark I @ V_{op} goes from 12 nA to 600 nA after 10 kGy

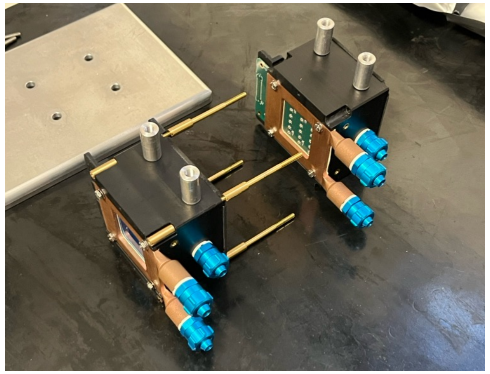
Proto-1: Mechanics and Electronics

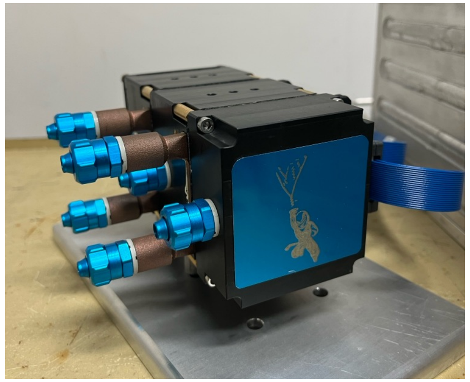
Mechanics:
- Two stackable and interchangeable submodules, each composed of 3x3 crystals+36 SiPMs (2 channel per crystal)

- Light-tight case embedding front-end electronic boards and heat exchanger cooling SiPMs

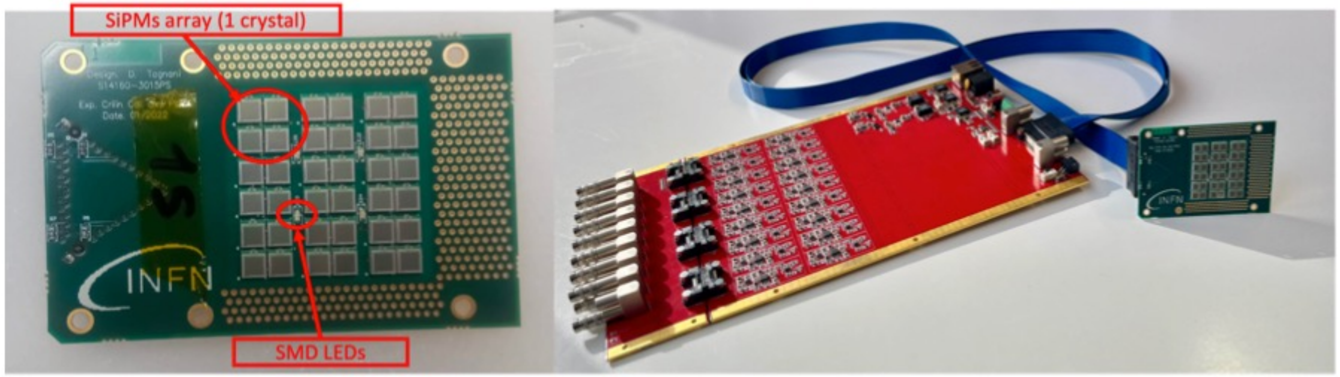






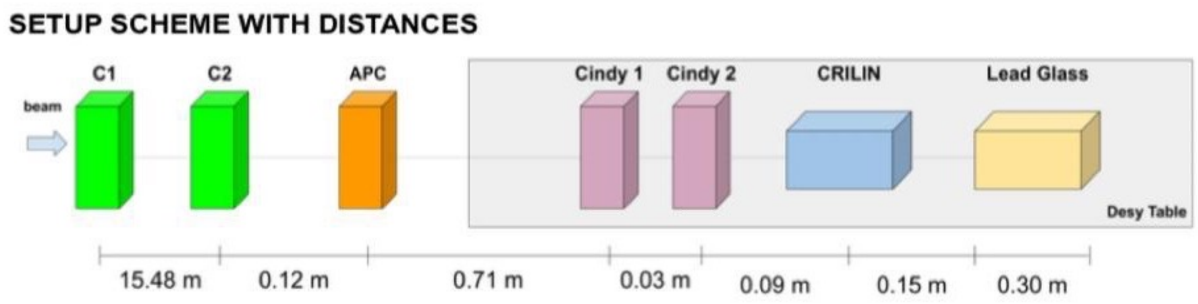


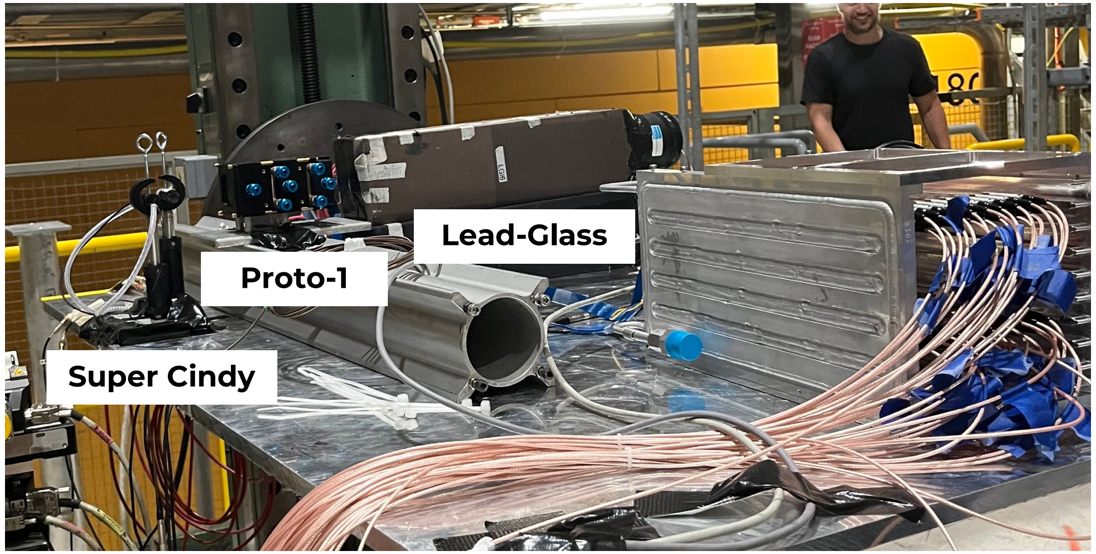
Electronics:
- **SiPMs board:** custom SiPM array board 36x10 μm Hamamatsu SMD SiPMs
- **Mezzanine board:** 18x readout channels → amplification, shaping and individual bias regulation, slow control routines



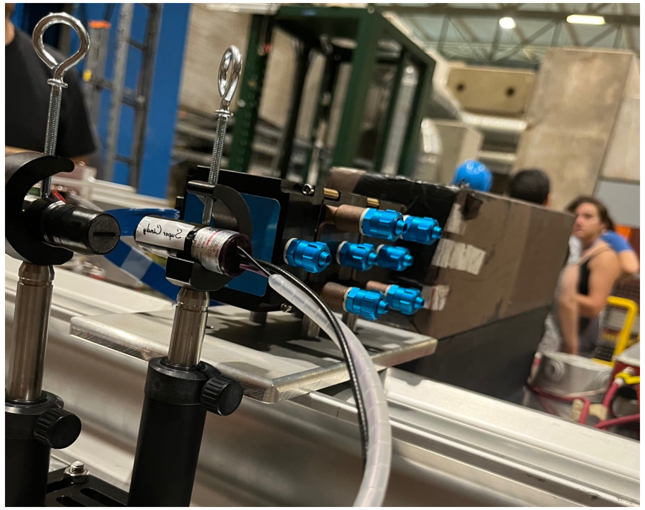
Beam test @ CERN

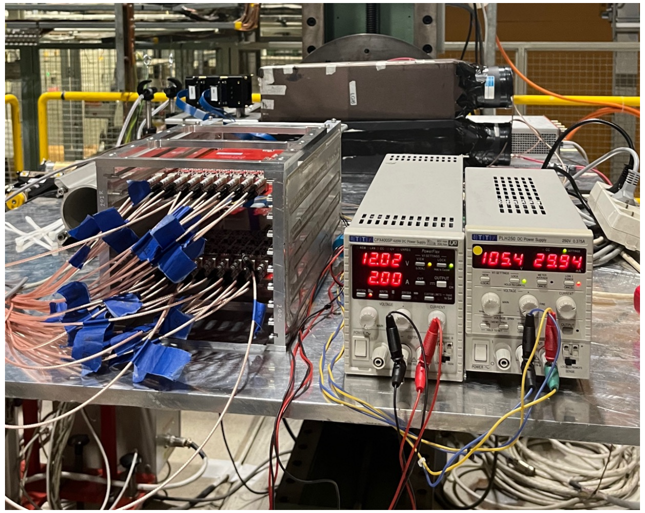
H2-SPS-CERN, August 2023





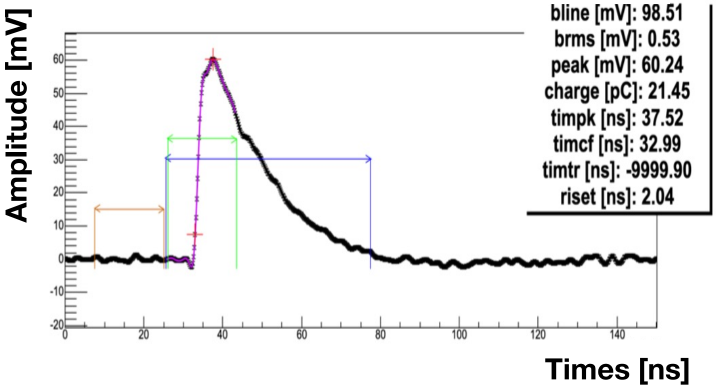
- Electron beam from 40 GeV up to 150 GeV
- Beam reconstructed with 2 silicon strip telescopes
- Data acquisition with 2 CAEN V1742 (32 ch each) modified @ 2 Vpp
- 5 Gs/s sampling rate



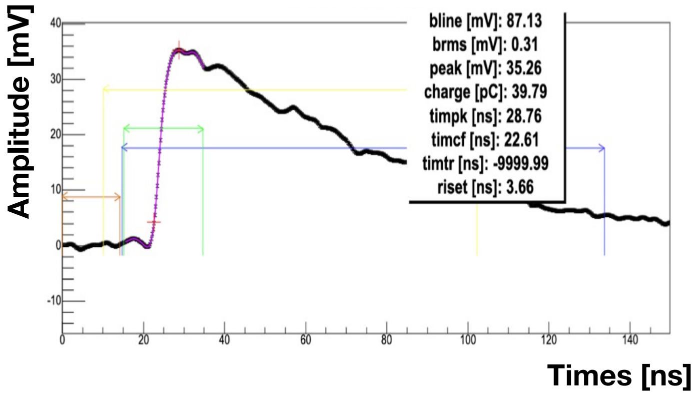


Beam test @ CERN: Configuration

1st layer: SiPMs series

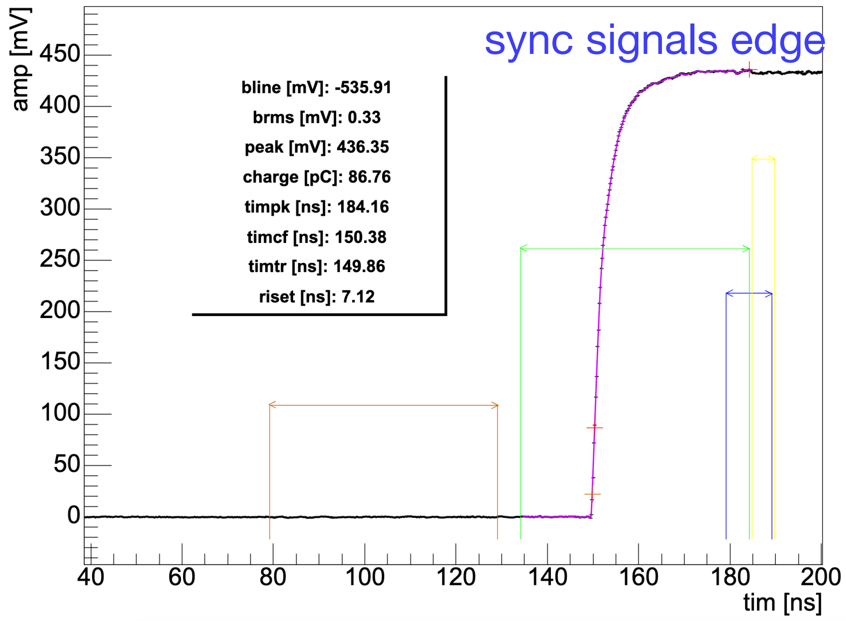


2nd layer: SiPMs parallel



Synchronisation pulses reconstruction:

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

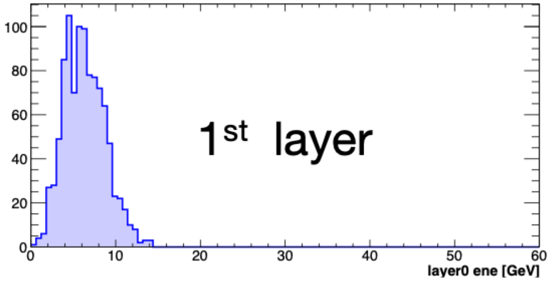


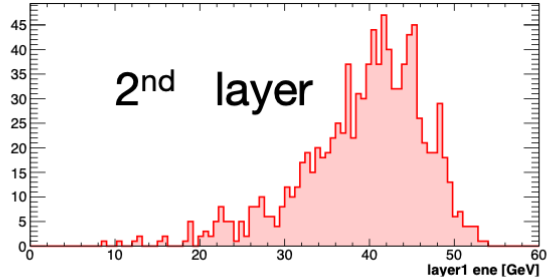
- **Two different SIPMs connection in the two layers for testing purposes:** series and parallel
- Timing resolution dominated by synchronisation jitter
- Energy resolution dominated by longitudinal leakage (8 X_0 only)

Beam test @ CERN: Energy

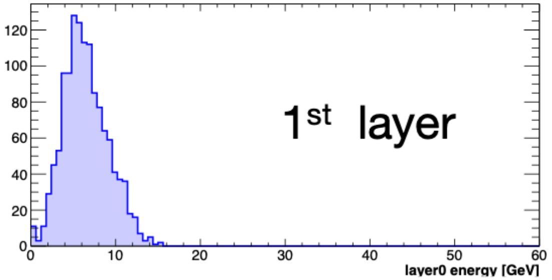
Good agreement between data e MC

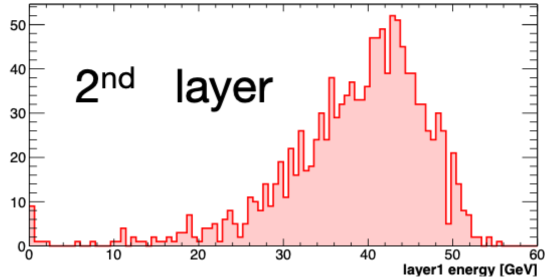
MC
120 GeV e^-



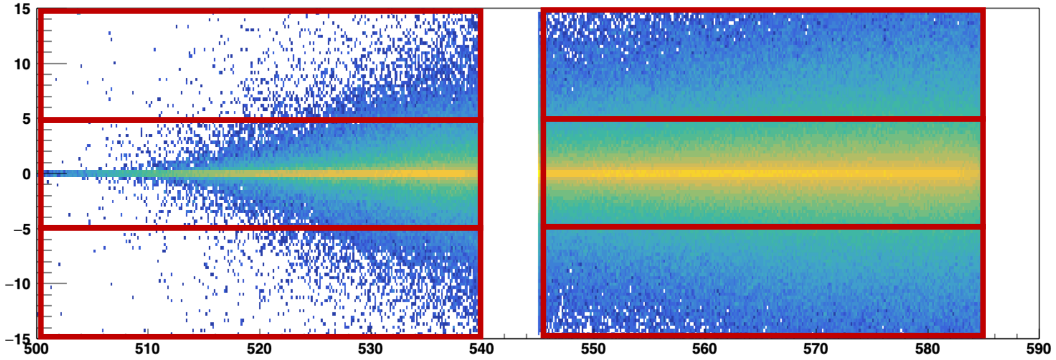


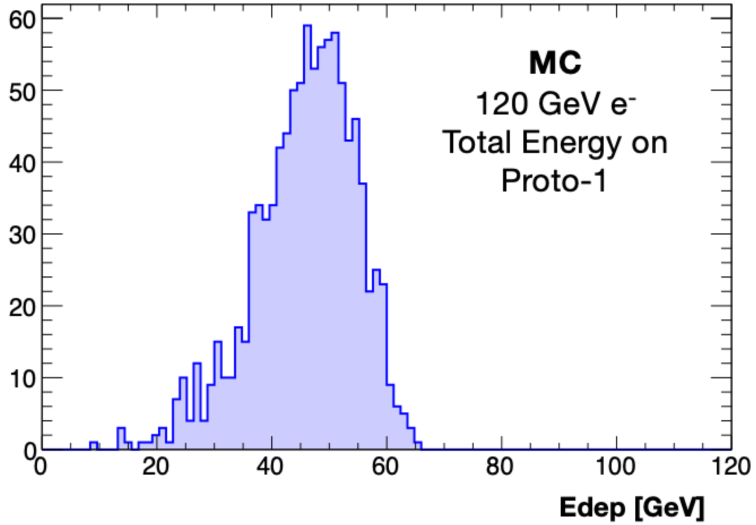
DATA
120 GeV e^-

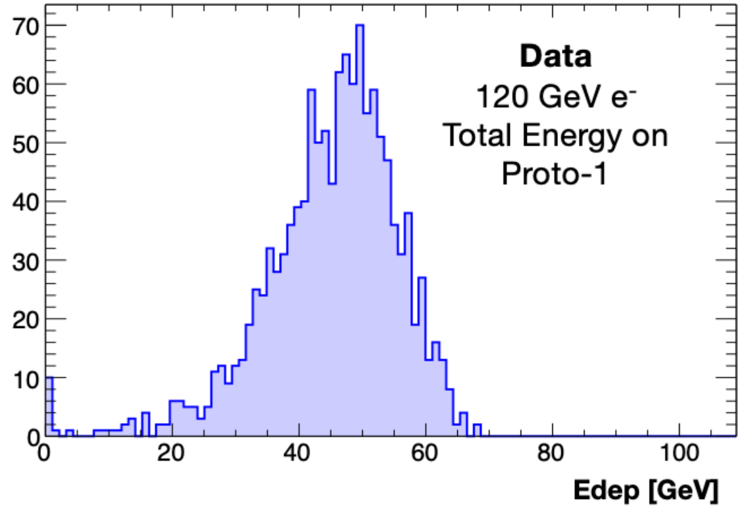




MC
120 GeV e^-



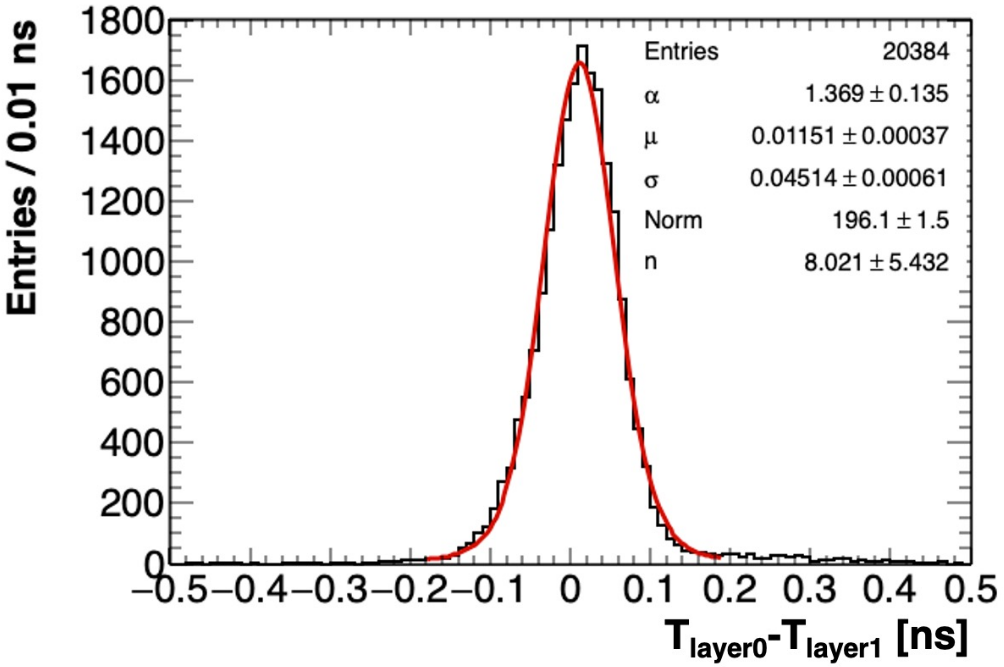


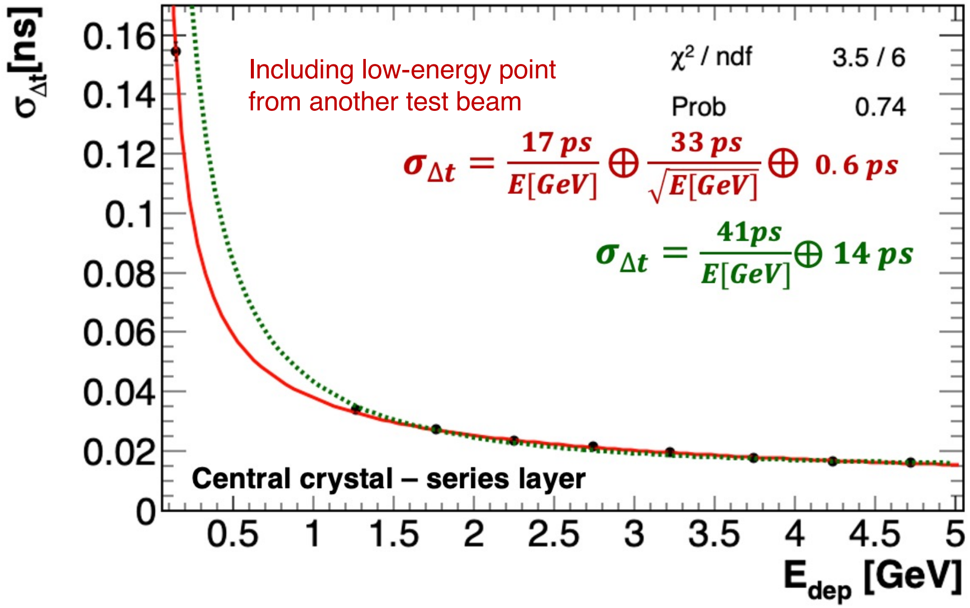


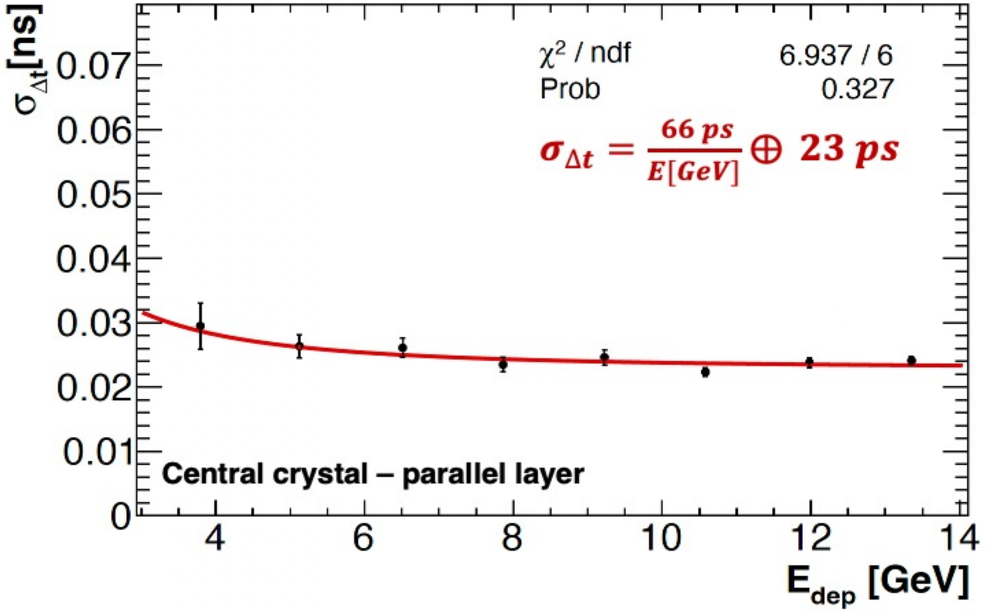
Beam test @ CERN: Timing

- 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 central crystals of different layers. **Time resolution dominated by the 2 boards synchronisation jitter** O(32ps)



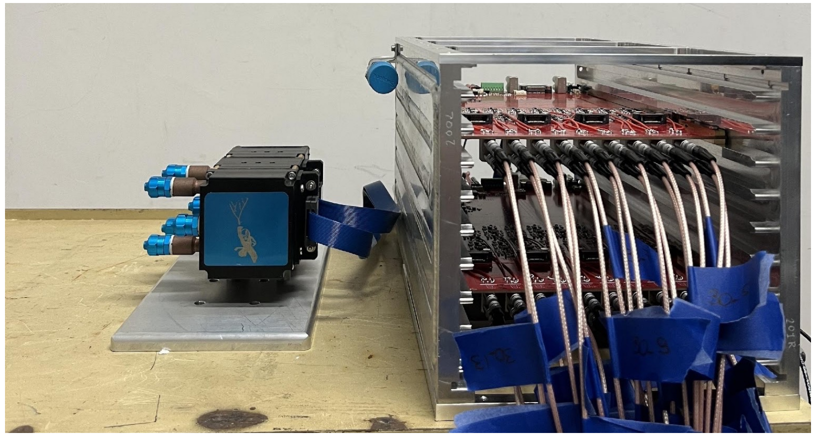


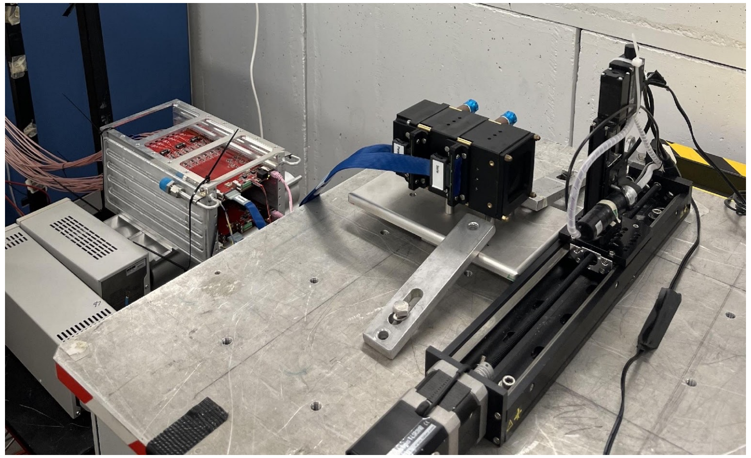


Beam test @ BTF

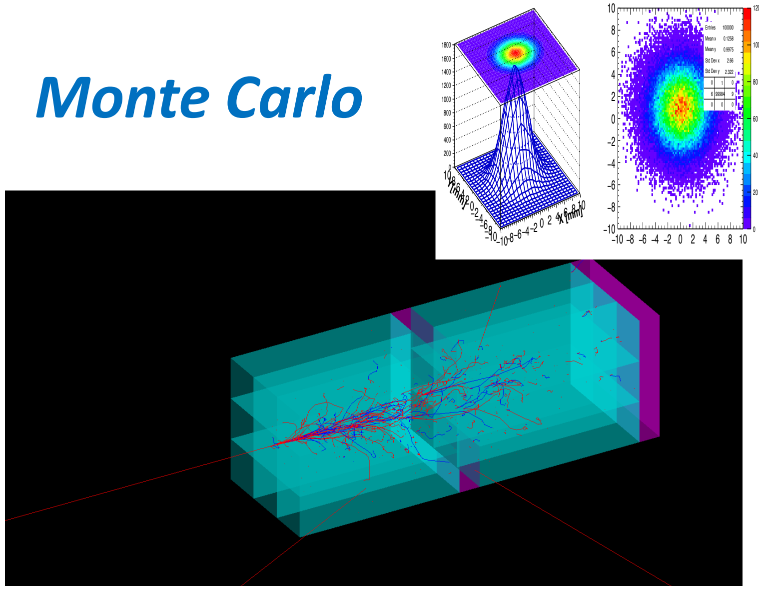
BTF, April 2024

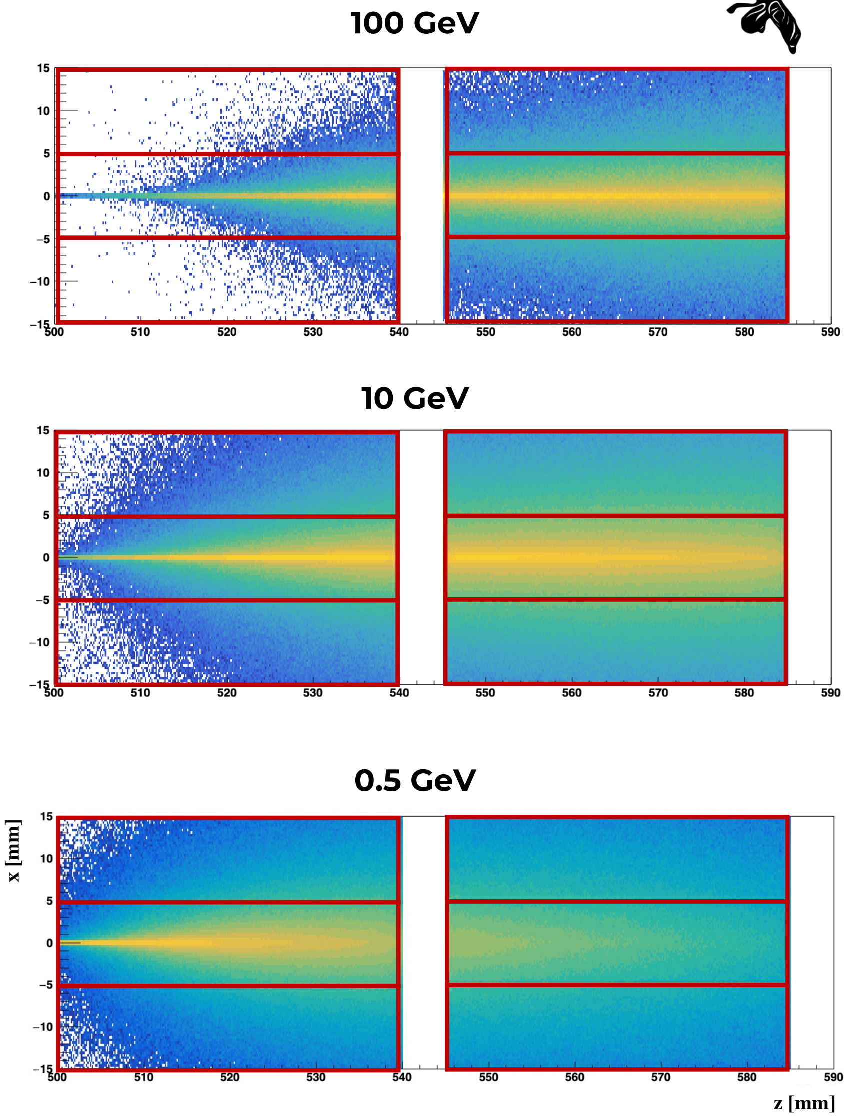
- Study of the LY loss of one layer of Proto-1 after Gamma ray irradiation
- Beam: 450 MeV electrons with multiplicity 1
- Beam centered on a different crystal at each run





Monte Carlo



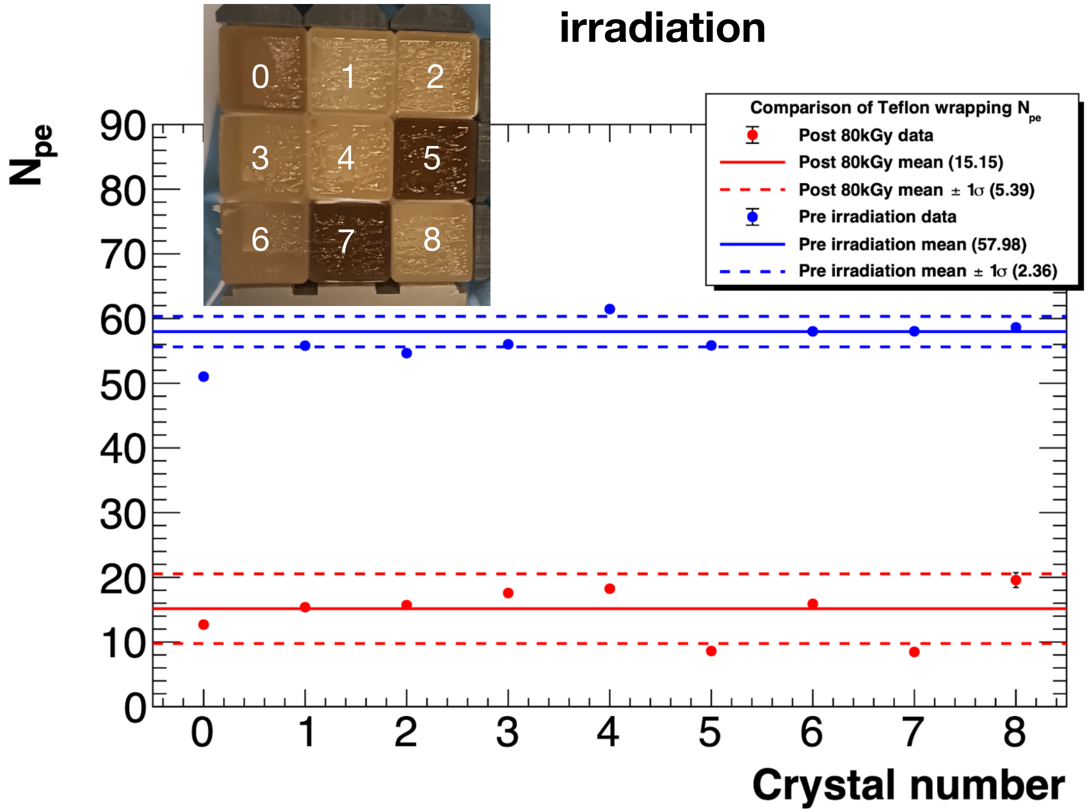


Beam test @ BTF: crystals

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

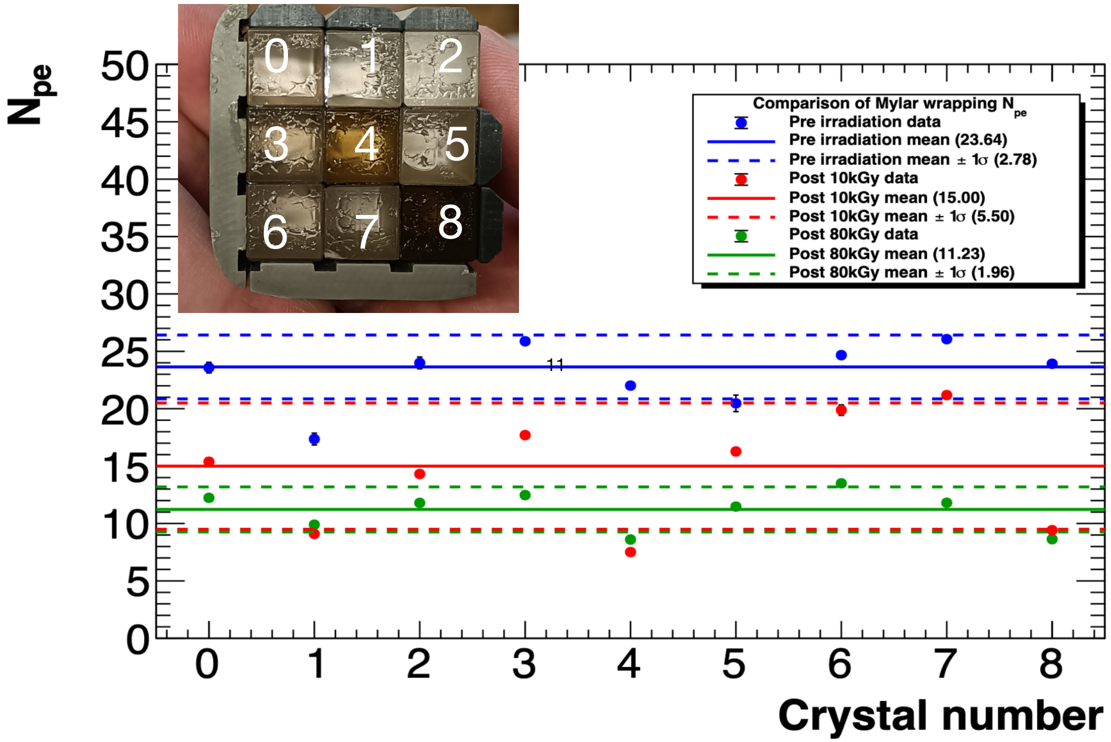
Teflon wrapping

Mean Npe values of PbF_2 pre and post 80 kGy irradiation



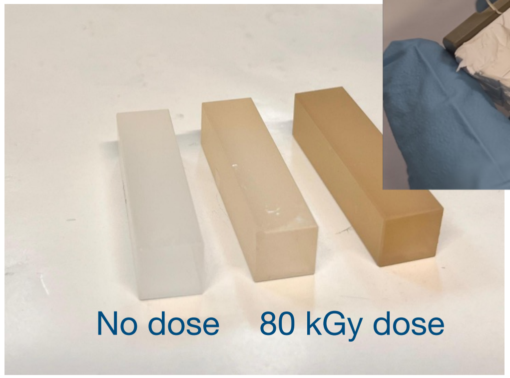
Mylar wrapping

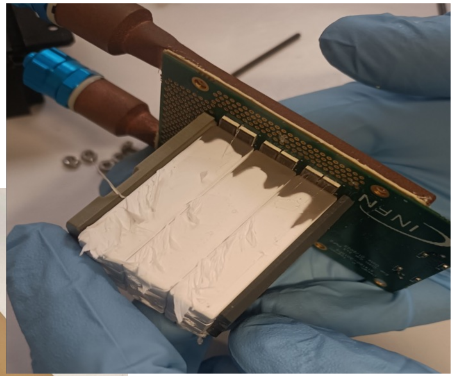
Mean Npe values of PbF_2 pre, after 10 kGy and after 80 kGy irradiation

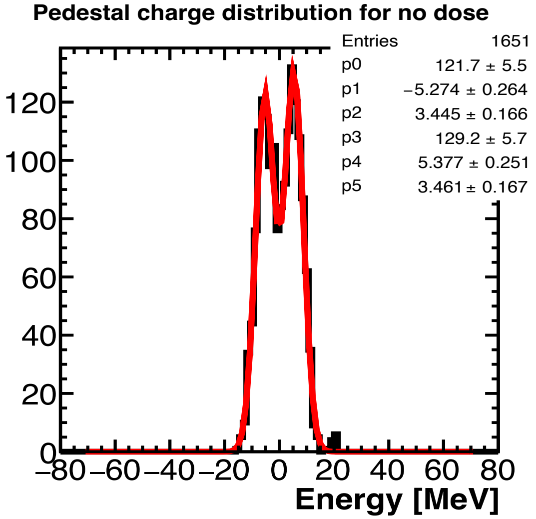


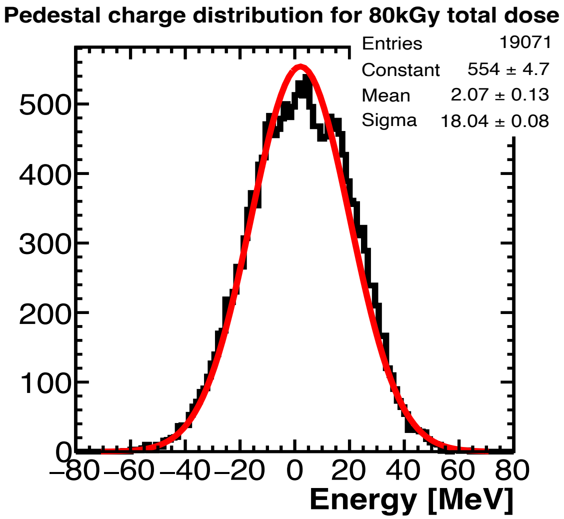
Beam test @ BTF: considerations

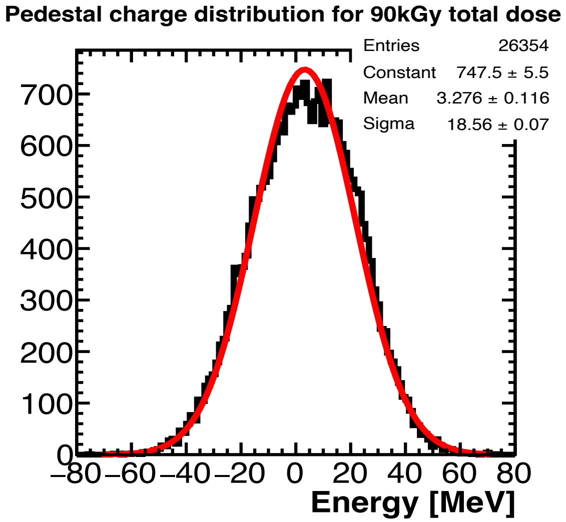
- Considerable variability in crystals' response to radiation, despite SICCAS claiming use of high-purity (>99.9%) PbF_2 powder for crystal growth
- Transparency loss was uniform length-wise in the crystals
- Teflon was damaged and brittle
- SiPM dark counts increases significantly with the absorbed dose
- Good operation after extreme TID (16 times MuCol) at low energies :)
- New tests planned to evaluate SiPMs PDE loss and optical grease degradation to disentangle LY losses due to crystals / SiPM

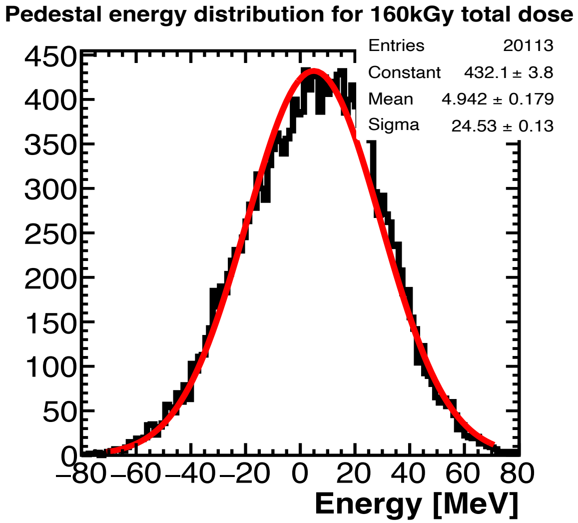












Summary

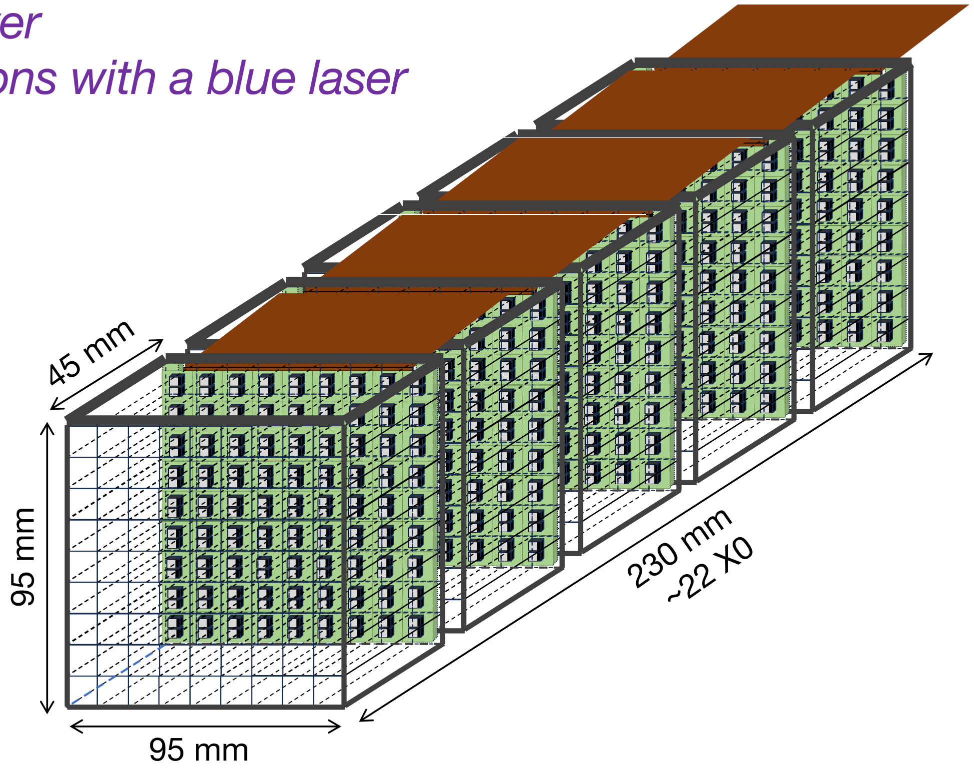
- **Time resolution**: < 40 ps for single crystals, for E_{dep} > 1 GeV
- **Radiation resistance:** PbF_2($PbWO_4$-UF) robust to > 350(2000) kGy and SiPMs validated up to 10^{14} n_{1MeV}/cm^2 fluences – good operation after irradiation shown at low-energies

- *Crilin fulfills requirements -> baseline choice for MuCol, but we can improve:*
- *Use LYSO or PbWO-UF in the first calorimeter layer*
- *Conduct new irradiation tests and monitor variations with a blue laser*

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 5x5 x4(layers) Crilin prototype: 1 M_R – 16.8 X_0



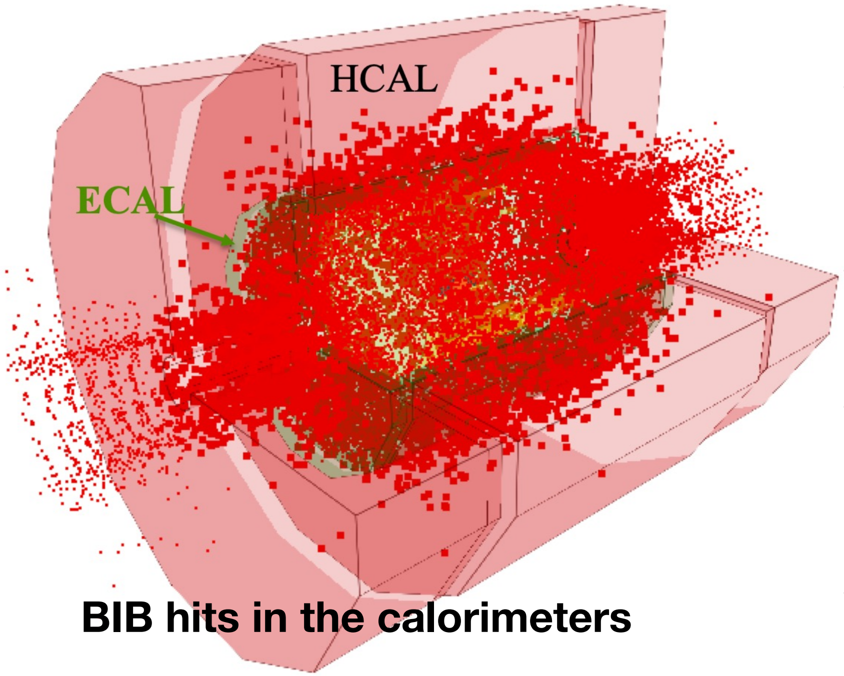
DRD6-WP3 from 2025 – proposal submitted

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

Backup slides

Beam Induced Background

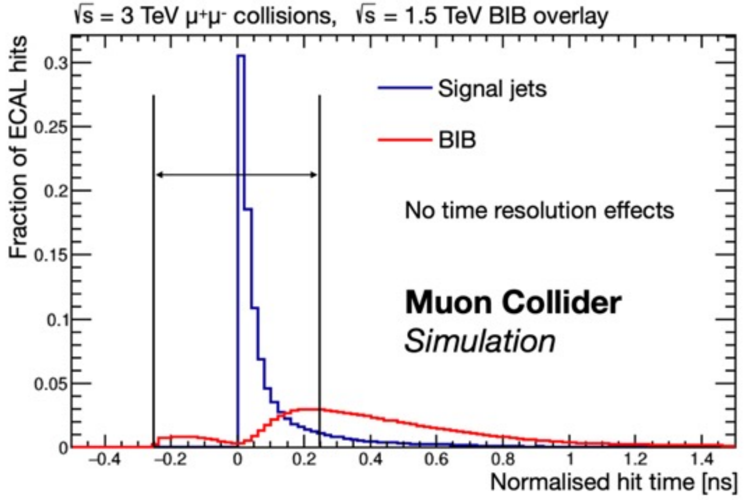
- **The beam-induced background (BIB)** poses the main challenge for the detector development at the Muon Collider
- Produced by muons decay in the beams, and subsequent interactions with the machine
- The BIB produces a flux of 300 particles per cm^2 through the ECAL surface
- 96% photons and 4% neutrons,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

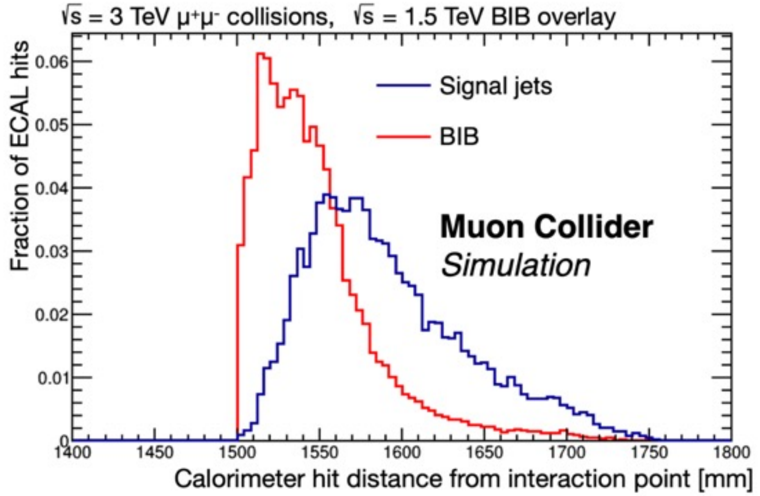


BIB hits in the calorimeters

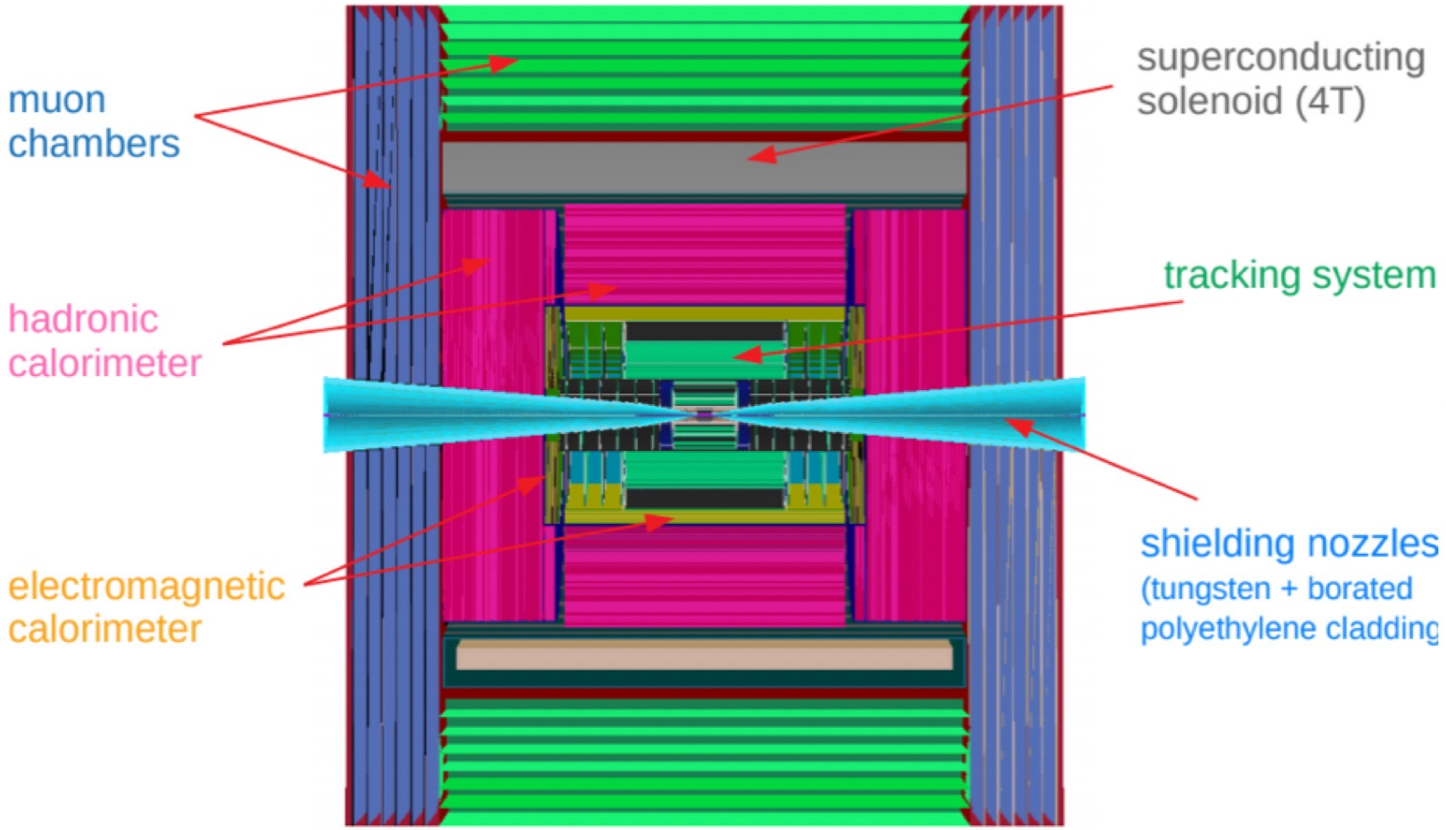
Key features:

- **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 $\frac{\Delta E}{E} \simeq \frac{10\%}{\sqrt{E[\mathrm{GeV}]}}$





Muon Collider



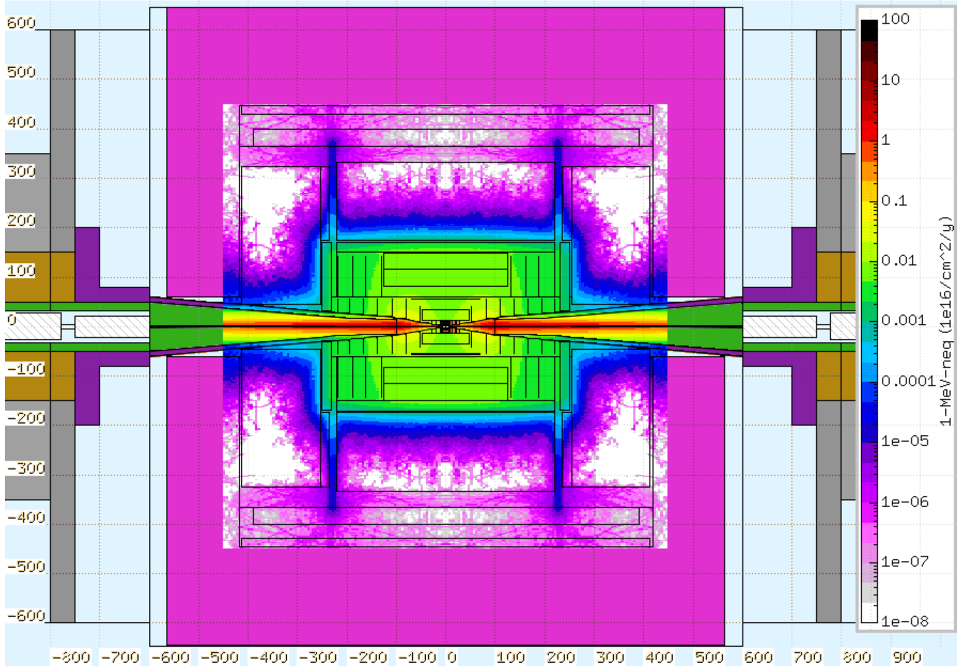
Main issues: BIB and radiation damage

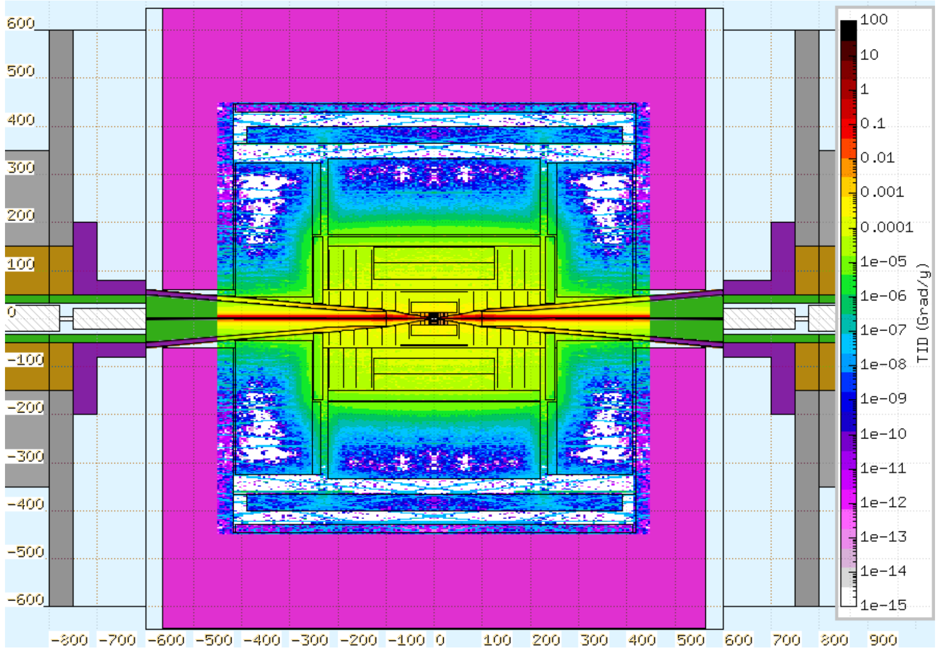
Optimized detector interface:

- 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



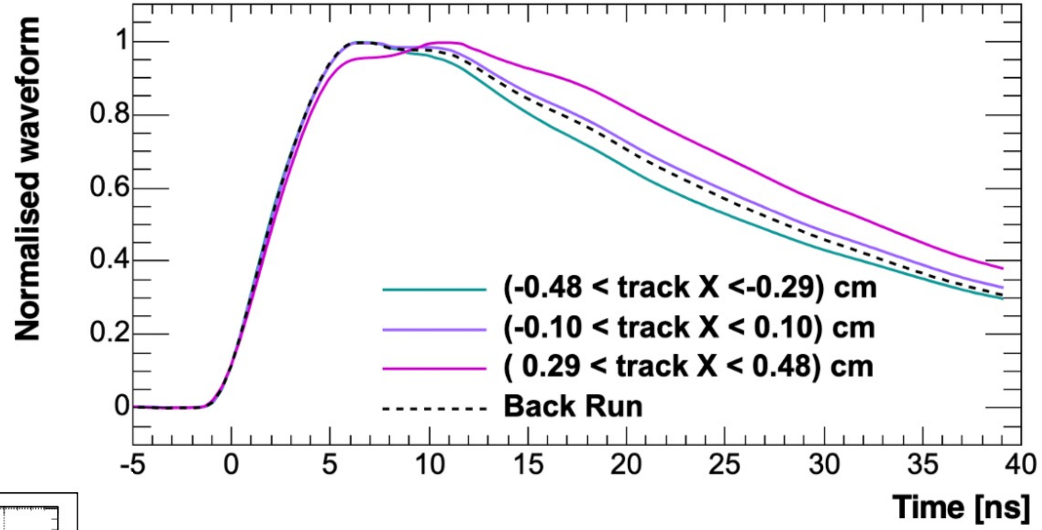


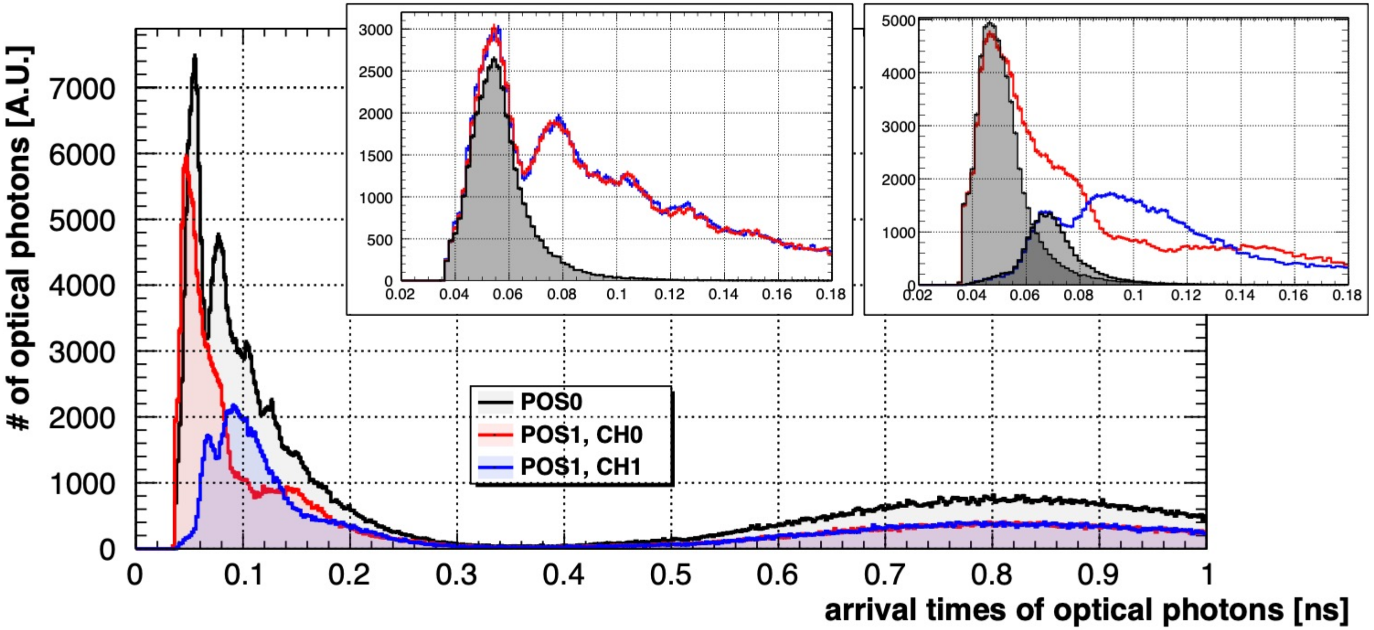
- **Neutron fluence** $\sim 10^{14}$$n_{1MeVeq}/cm^2$**year** on ECAL.
- **TID ~ 1 kGy/year** on ECAL.

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



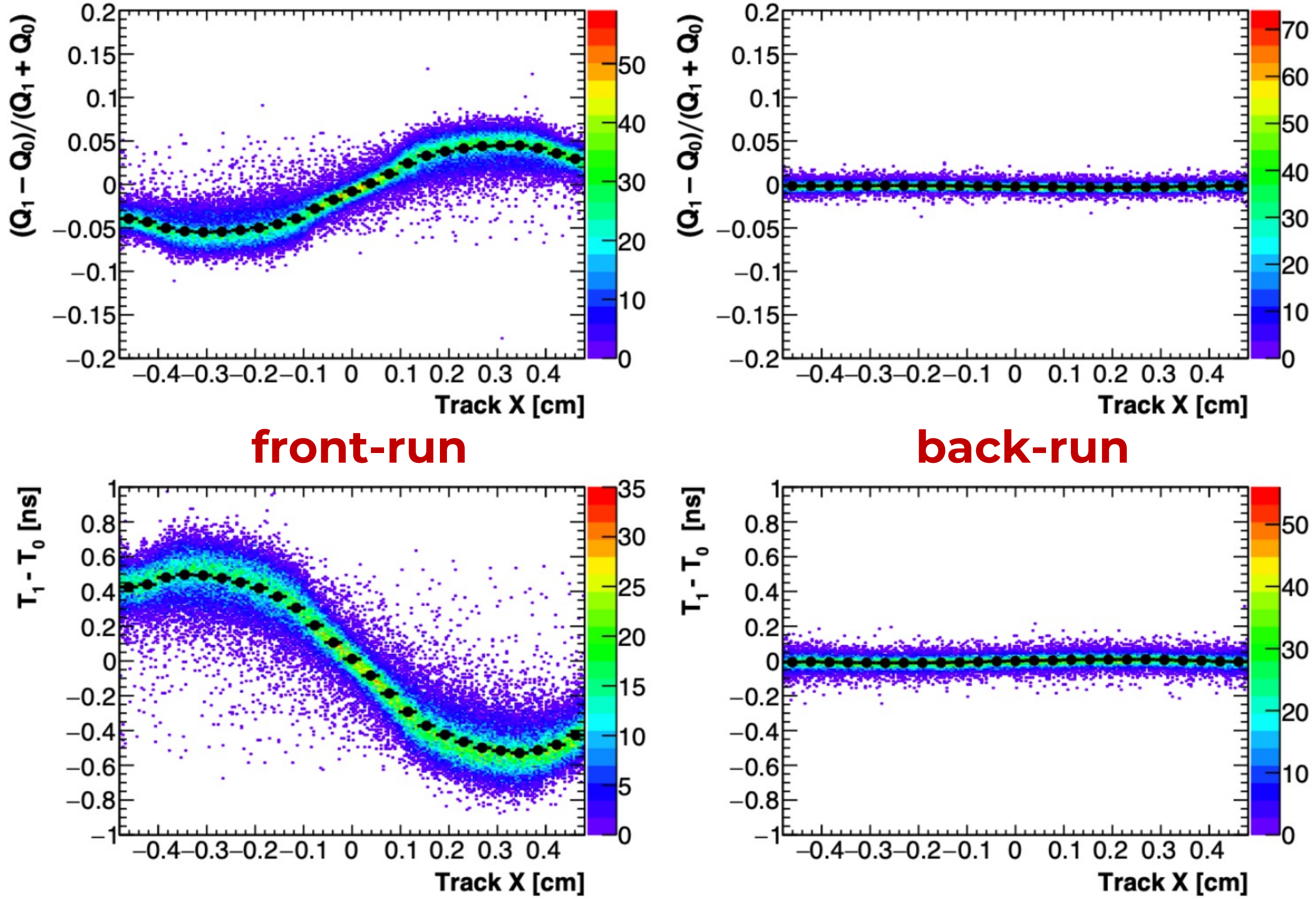


Optical simulation

- 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

PbF2 DATA



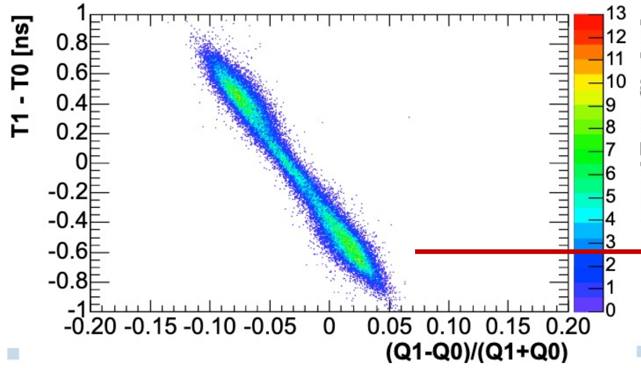
- +/- 10 % maximum imbalance in light collection
- anticorrelated effect on timing (T1-T0)

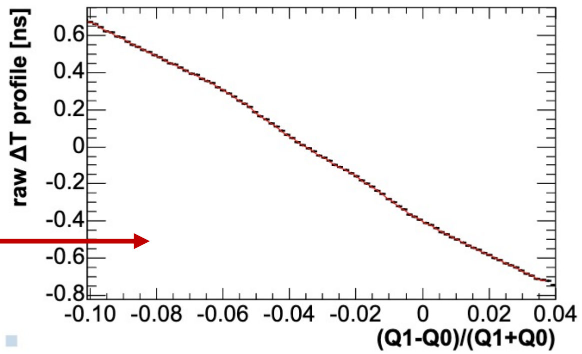
- No significant effects for back-runs
- Similar effects for PbWO4-UF

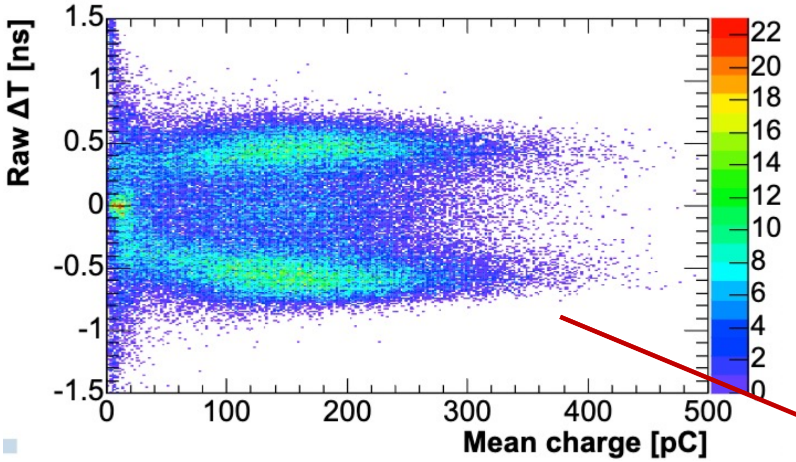
- Light propagated indirectly is more strongly attenuated due to the longer total path length traversed and the multiple reflections
- earlier arrival times for photons arriving directly

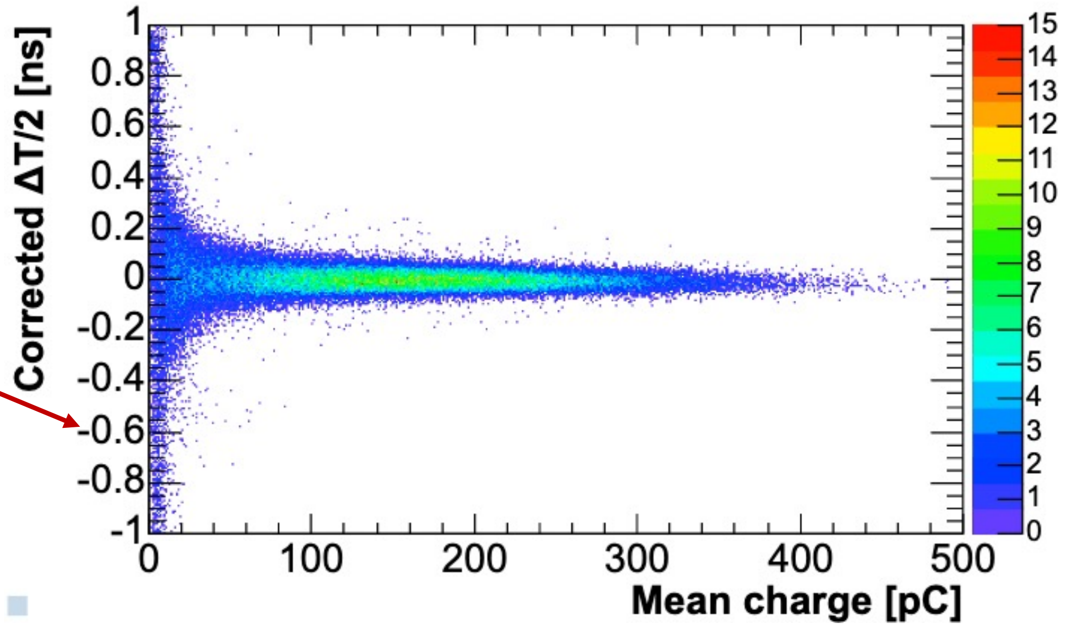
Correction process

- 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



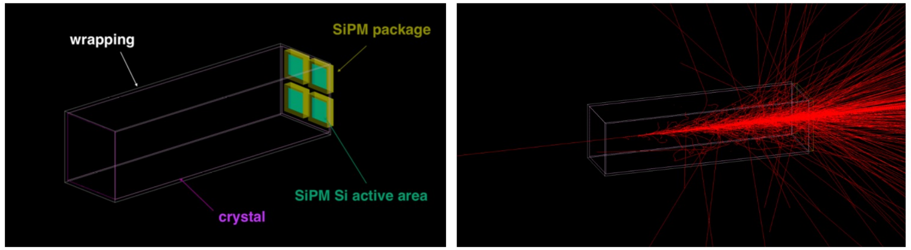


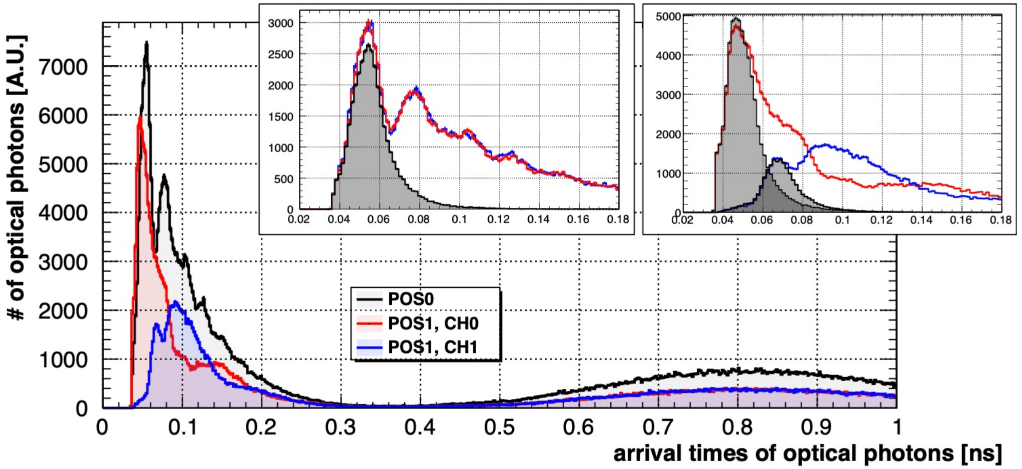


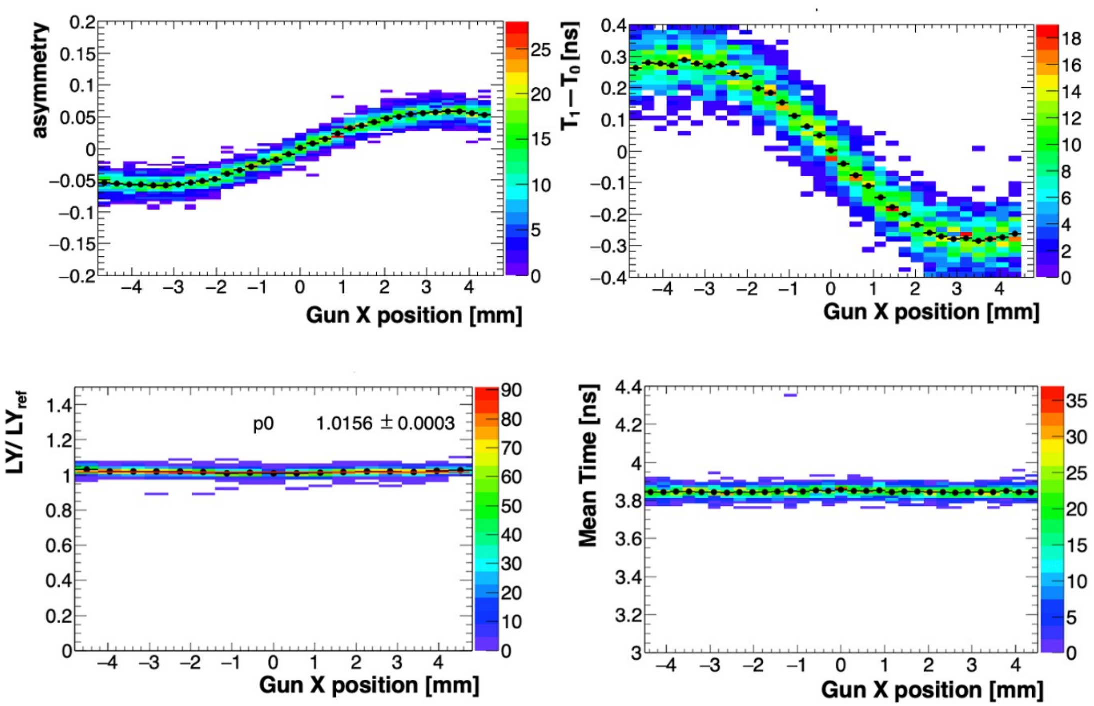


MC validation: optical simulation

- 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)





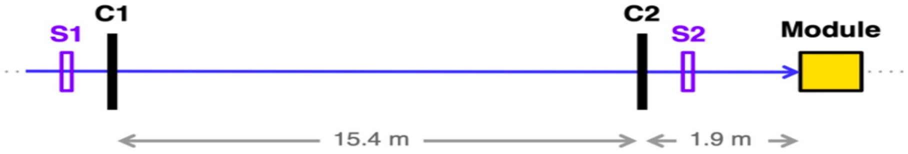


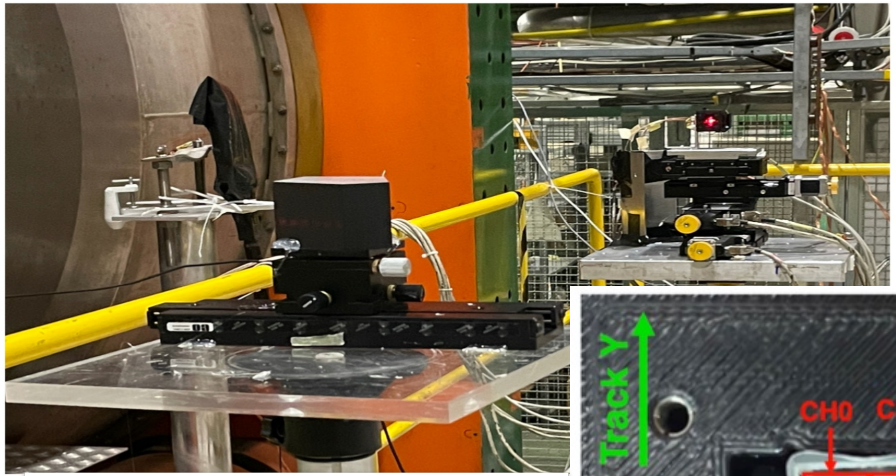
- Confirmation of the positional effects
- Charge asymmetry matched within 20 %
- Smaller timing offsets in simulation wrt data
- mean-time and mean-energy information are always well behaved

Proto-0: Single crystal beam test

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

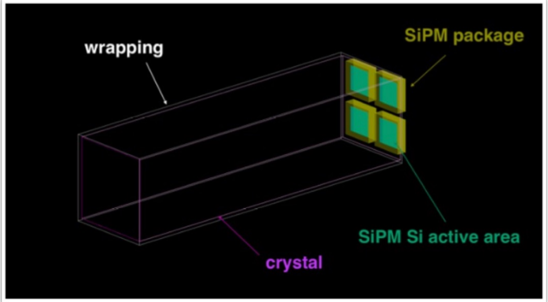
- $10 \times 10 \times 40$ mm^3 single crystal → 2 options: **PbF_2** (4.3 X_0) **$PbWO_4$-UF** (4.5 X_0).
- Four 3x3 mm^2, 10 µm pixel size SiPMs for two independent readout channels (SiPM pairs connected in series).
- Mylar wrapping - No optical grease.

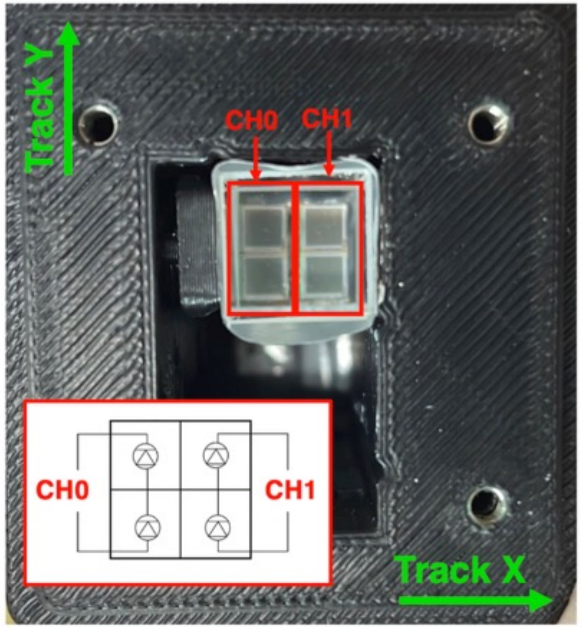




Aim:

- 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.





Results

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

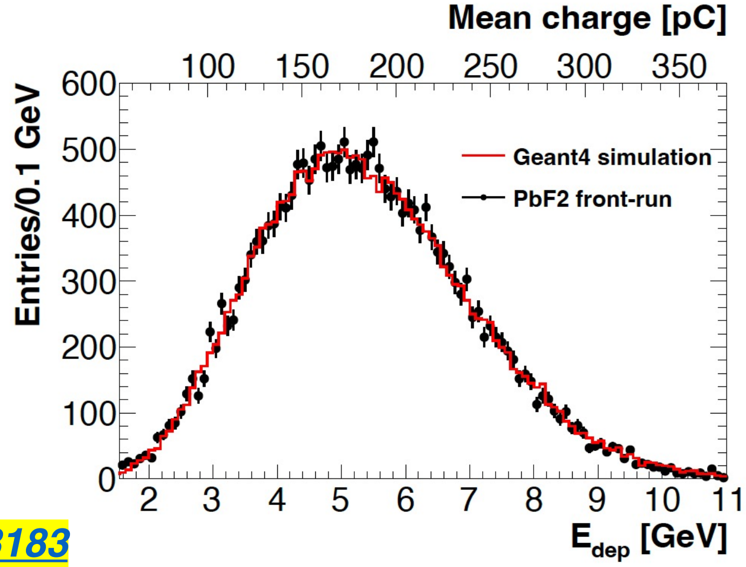
- The BACK run time resolution is better, even after correction, for both crystals.
- PbF_2 outperforms $PbWO_4$-UF despite its higher light output (purely Cherenkov)
- **PbF_2** → σ_{MT} < 25 ps worst-case for E_{dep} > 3 GeV
- **$PbWO_4$-UF** → σ_{MT} < 45 ps worst-case for E_{dep} > 3 GeV

PbF_2

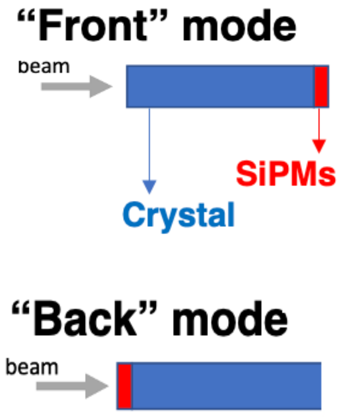
	back-run	front-run
E_{dep} MPV [GeV]	4.26 ± 0.01	4.81 ± 0.03
E_{dep} sigma [GeV]	1.35± 0.01	1.46 ± 0.02
pC/GeV	~29.3	~35.6
NPE/MeV	~0.30	~0.30

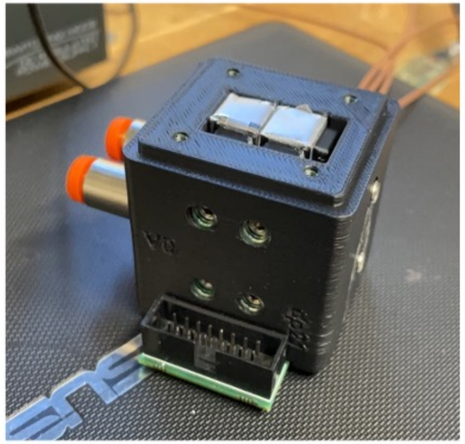
PWO-UF

	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

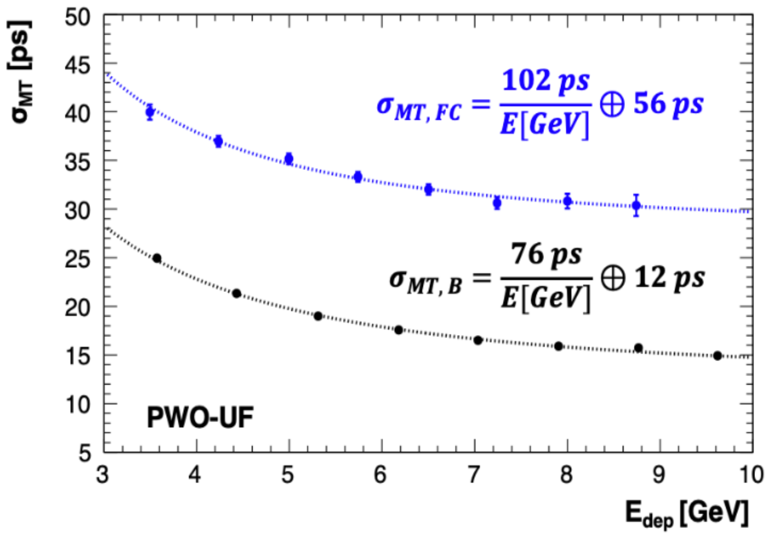


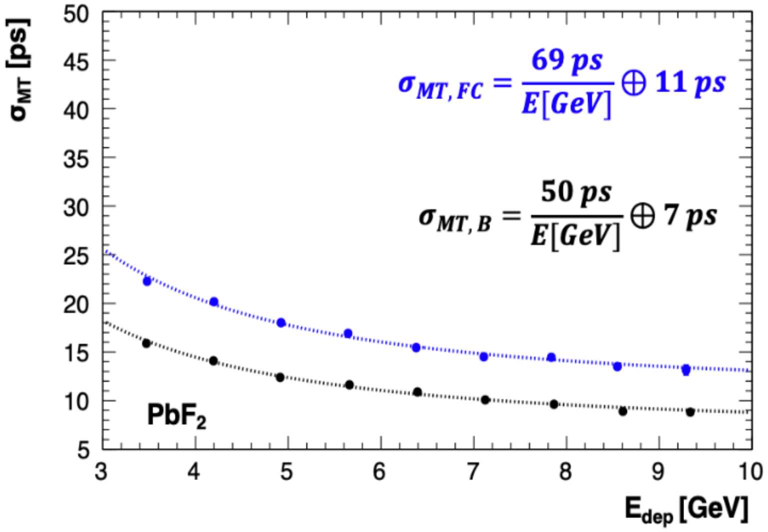
C. Cantone et al. 2023 Front. Phys. 11:1223183





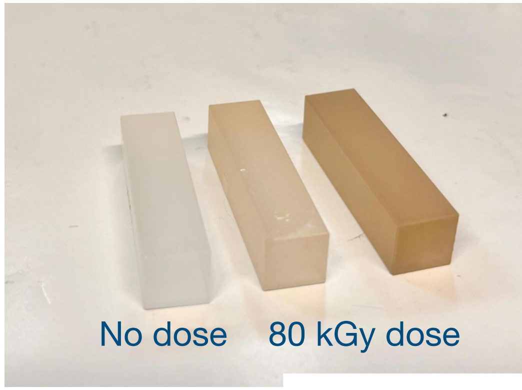
Proto-0

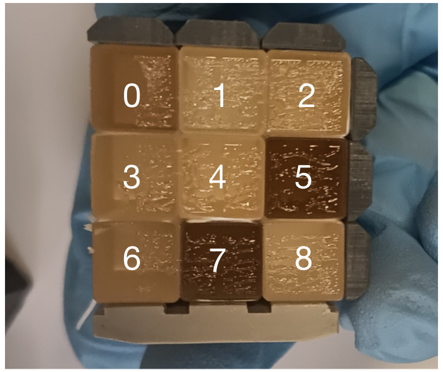


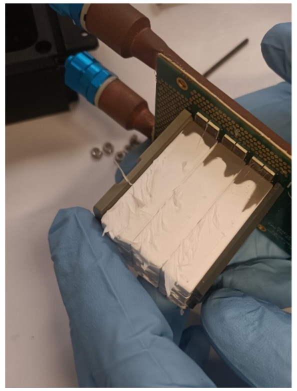


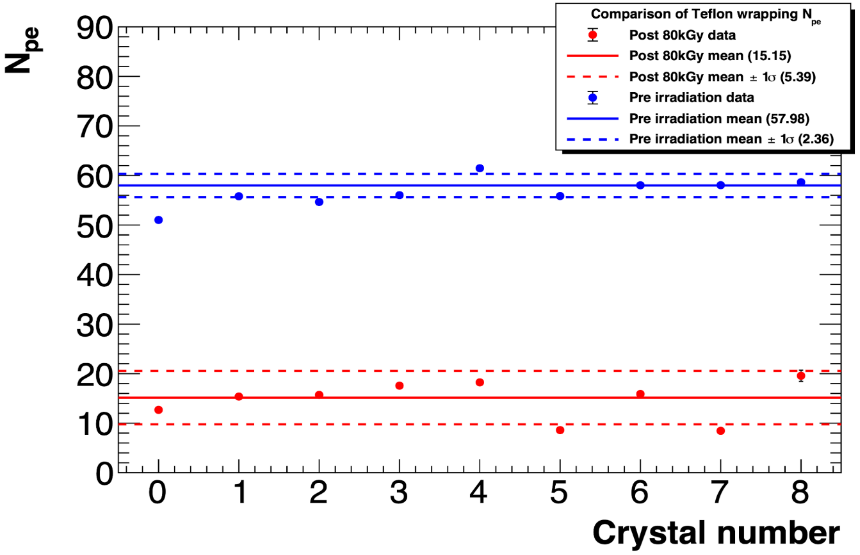
Beam test @ BTF: Teflon wrapping

After 80 kGy (8 Mrad) irradiation
- Teflon was damaged and brittle
- Crystals evident loss of transparency

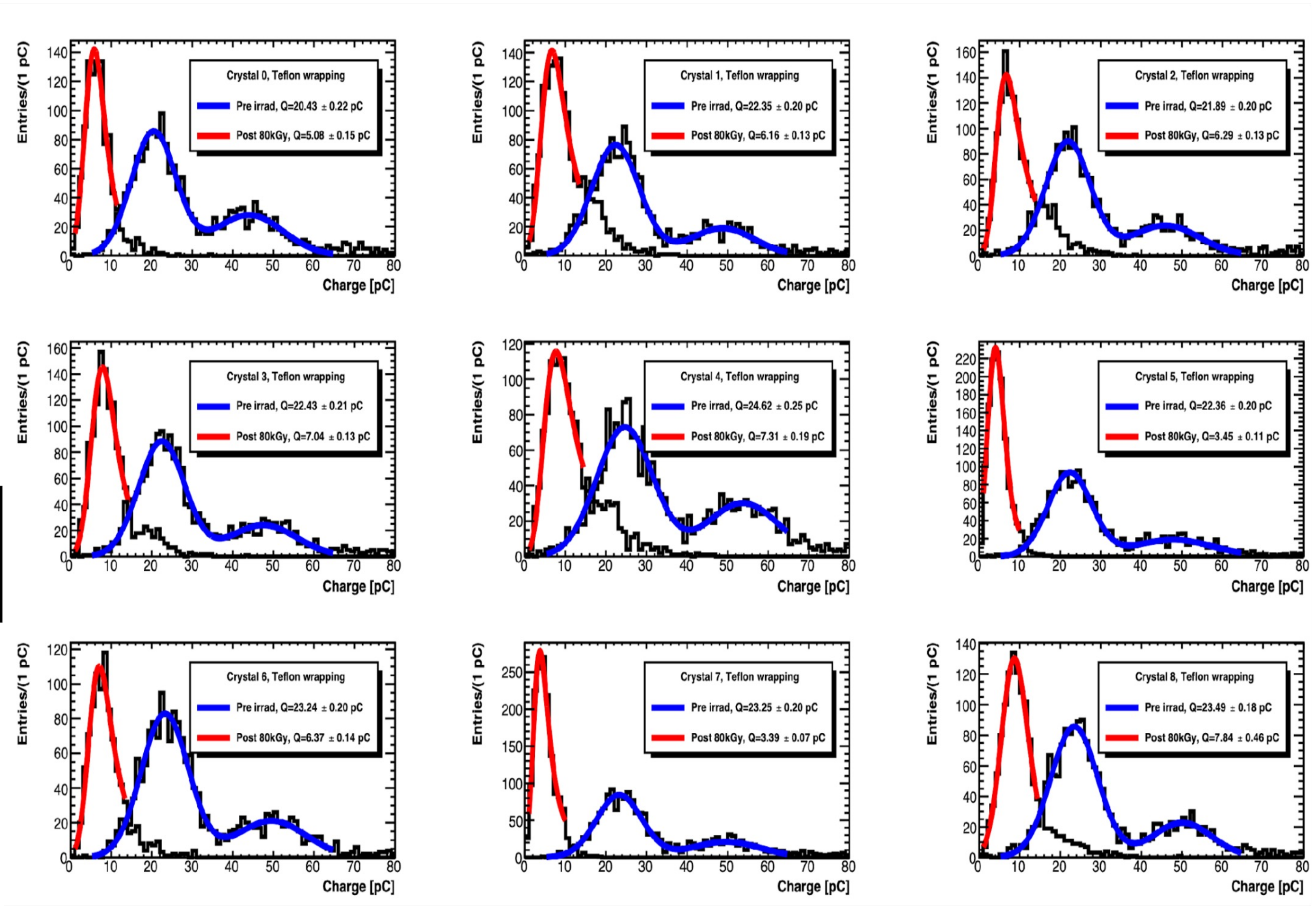






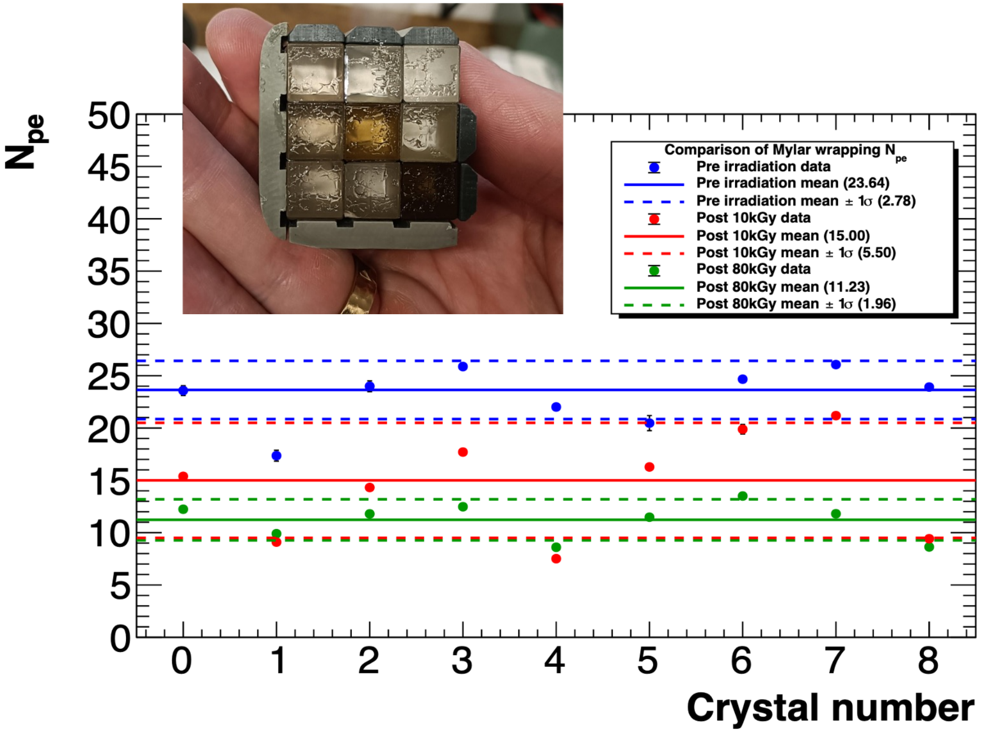


Charge distribution of PbF_2 pre and post irradiation

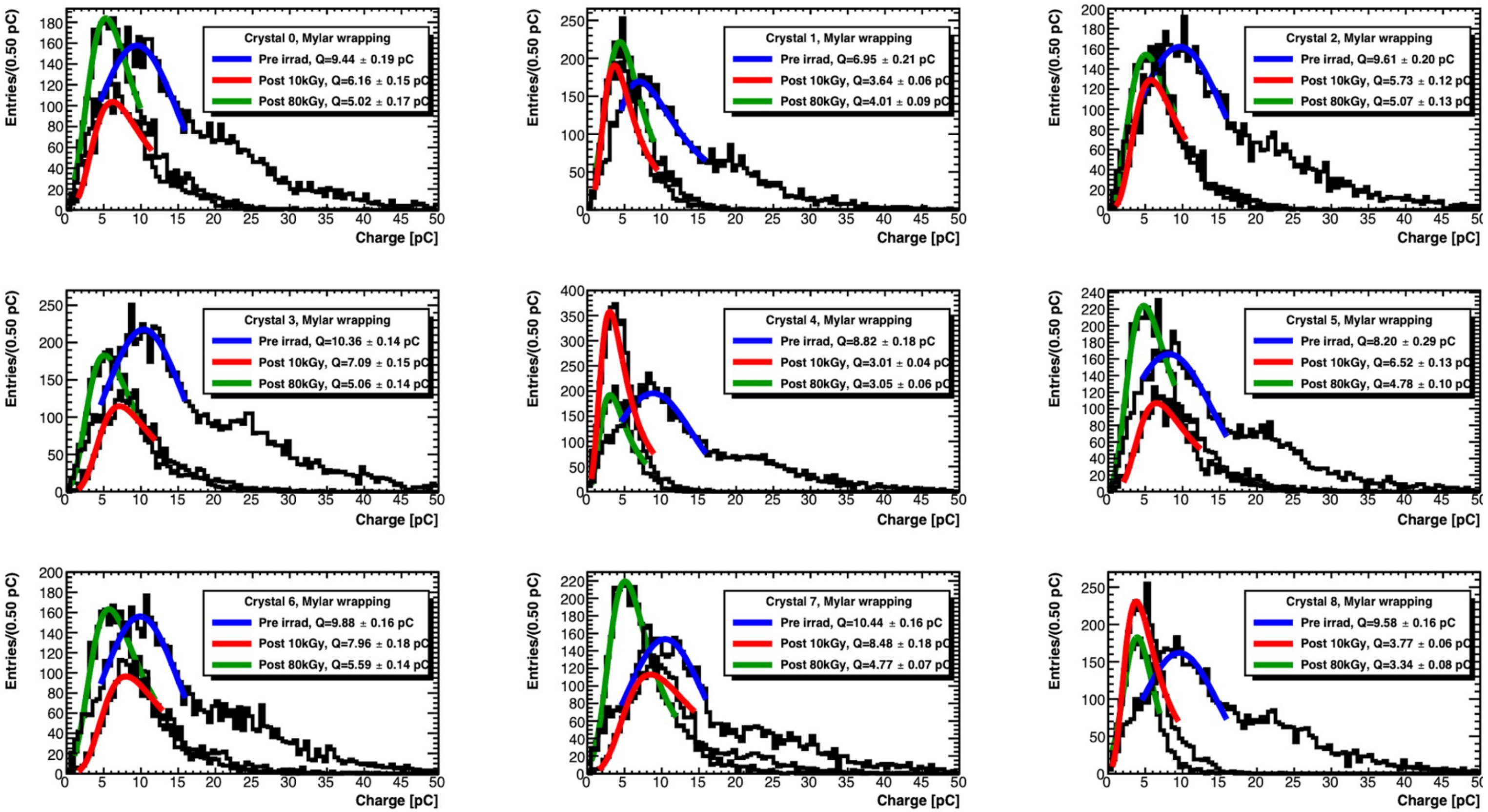


Beam test @ BTF: Mylar wrapping

- 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

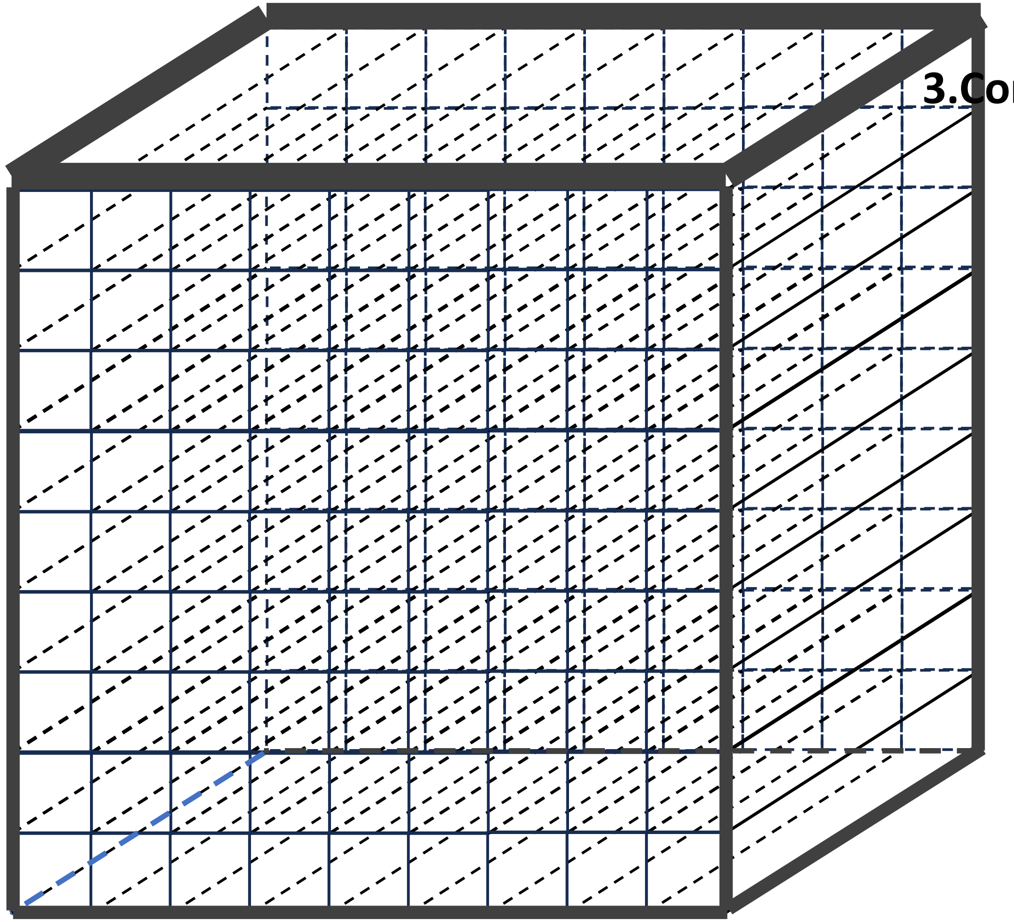


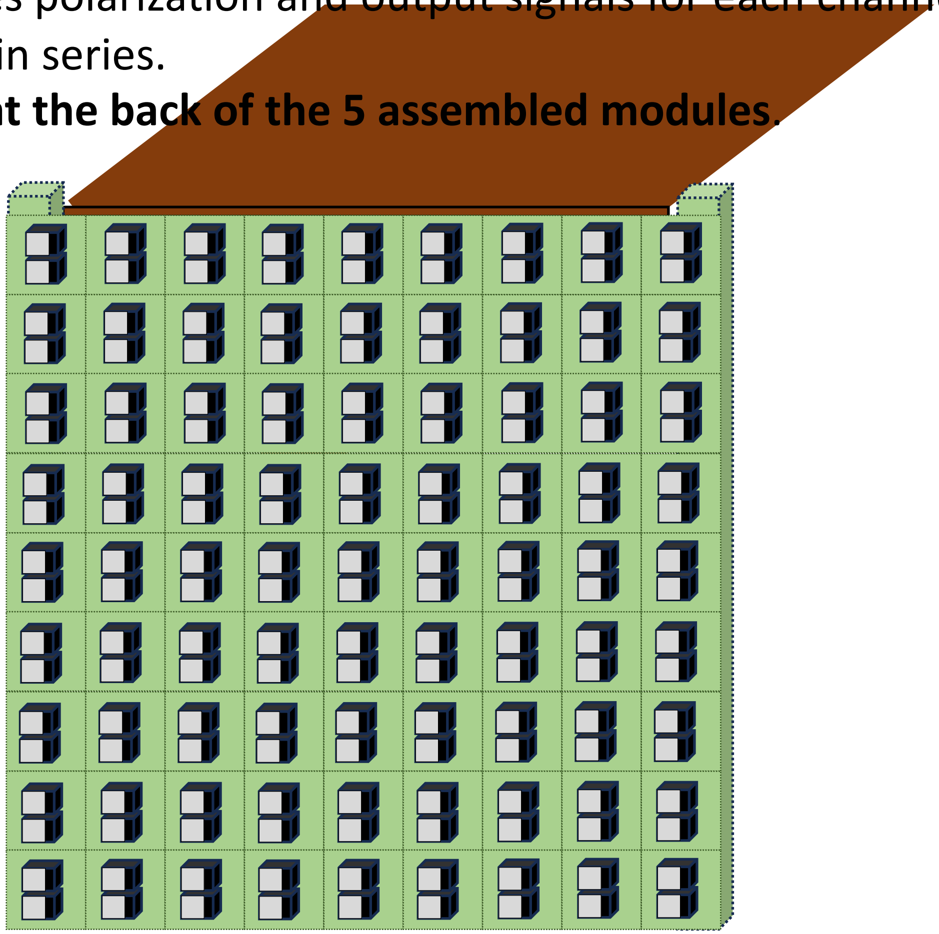
Crilin Module Prototype

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.**