Development and Test of the CRILIN Calorimeter for the Muon Collider: Status and Perspectives

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On behalf of the Crilin calorimeter group

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The Muon Collider project

- The **Muon Collider** represents a promising **future collider project**, designed to collide beams of muons (μ^-) and antimuons (μ^+) in a circular geometry at **multi-TeV center-of-mass energies**.

- Advantage of using muons is that, as **elementary particles** with **mass ~200 that of electrons**, allows to reach:
  - **- Elevate center of mass energies**
  - **- High luminosity values**
  - **- Clean collisions**

https://arxiv.org/pdf/2303.08533

✓ These characteristics allows to combine:

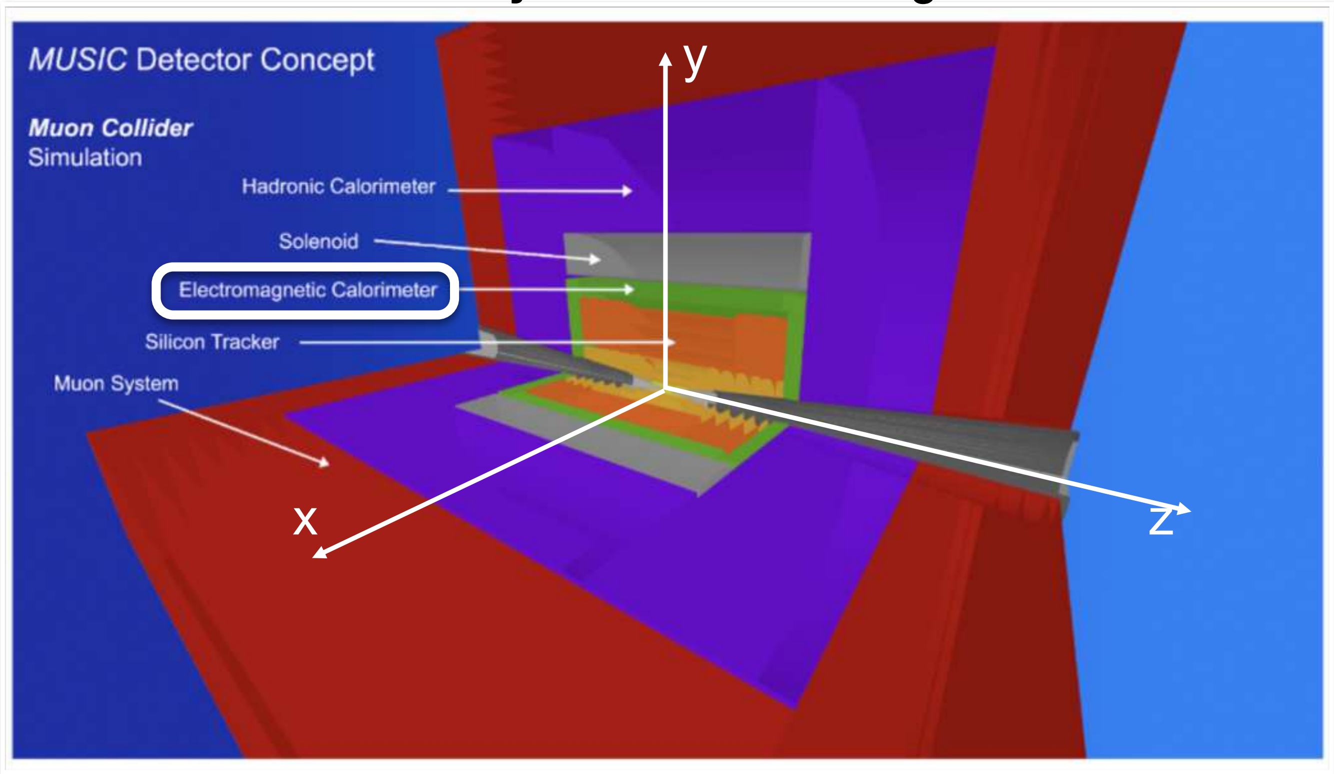
Direct search on new physics	**Precision measurements**
E.g. the dark sector	ideal tool for Higgs boson studies

The MUSIC detector layout

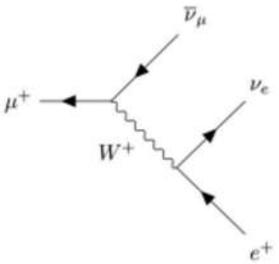
- The detector follows a classical **cylindrical shape** and **hermetic geometry** typical for a multi-purpose detectors for symmetric collisions.

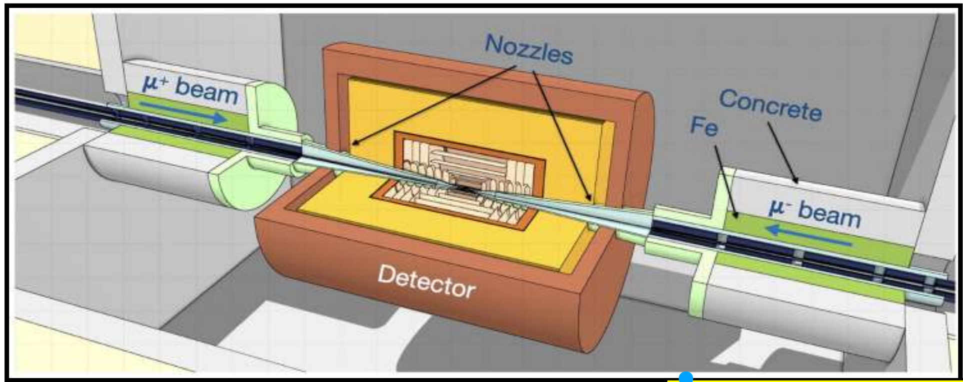
- **Electromagnetic calorimeter** placed in between the **Silicon Tracking system** and the **5 T superconductive solenoid**.

MUSIC: MUon System for Interesting Collisions

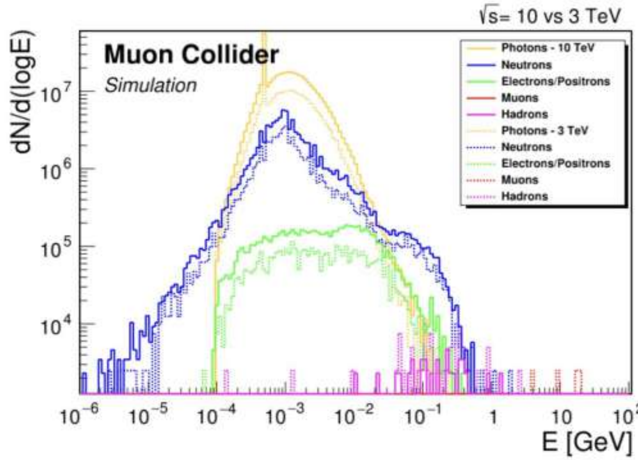


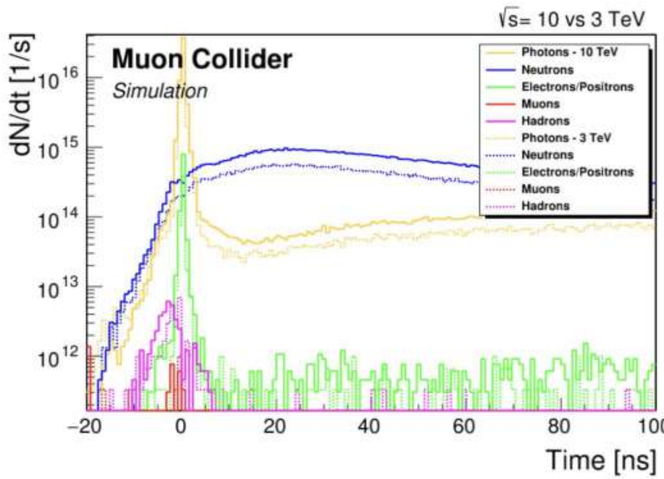
The machine background from muon decays





https://arxiv.org/abs/2311.03280





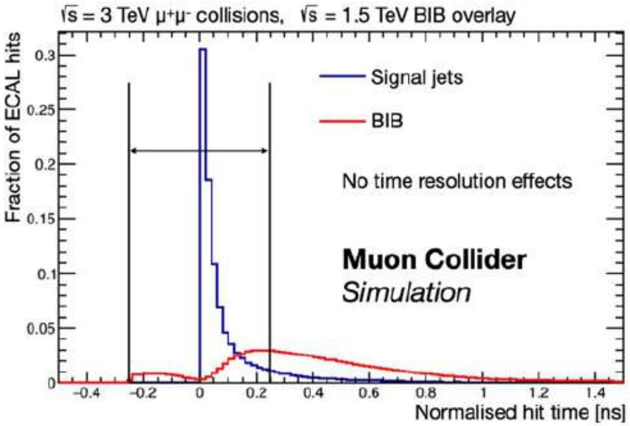
- The **decay of muons** in flight along the accelerator ring produces high-momentum secondary particles, which interact with the machine's materials, and generate an **intense flux of tertiary particles** →**Beam-Induced Background** **(BIB)**
- Pair of Tungsten conical-shape absorber (nozzles) in the forward region on the detector.
- Residual component characterized by: **low energy** and **broad arrival time distributions**.

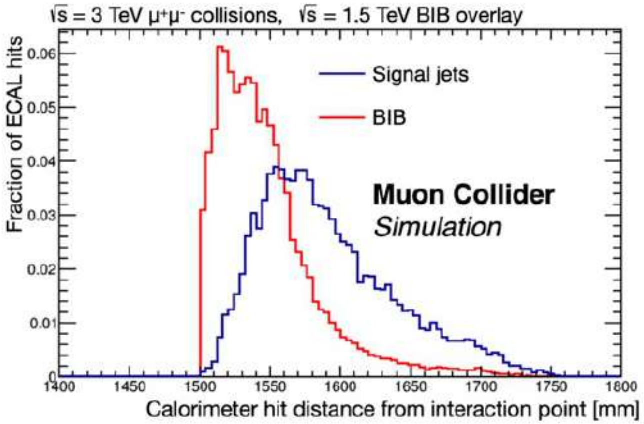
For √s=10 TeV, the **incoherent pair production process** is an important source of high-energy background particles in time with the signal.

Muon collider requirements

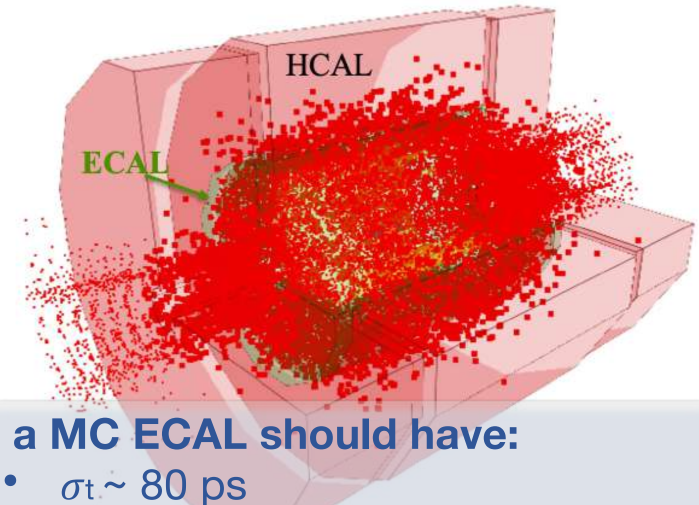
BIB in the ECAL region (after nozzles and tracking system):

- 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

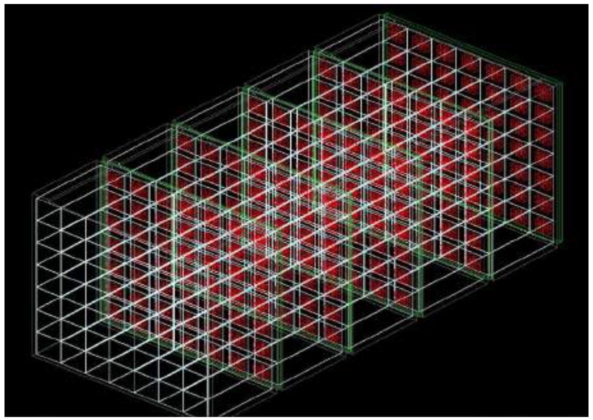
Perfectly suitable for any future collider!

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…**



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

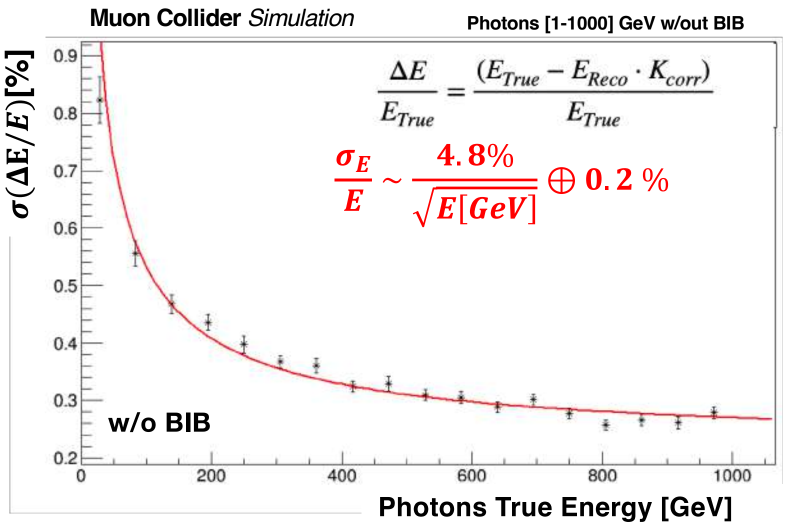
Compactness: Unlike segmented or high granularity calorimeters CRILIN can optimize energy detection while staying compact

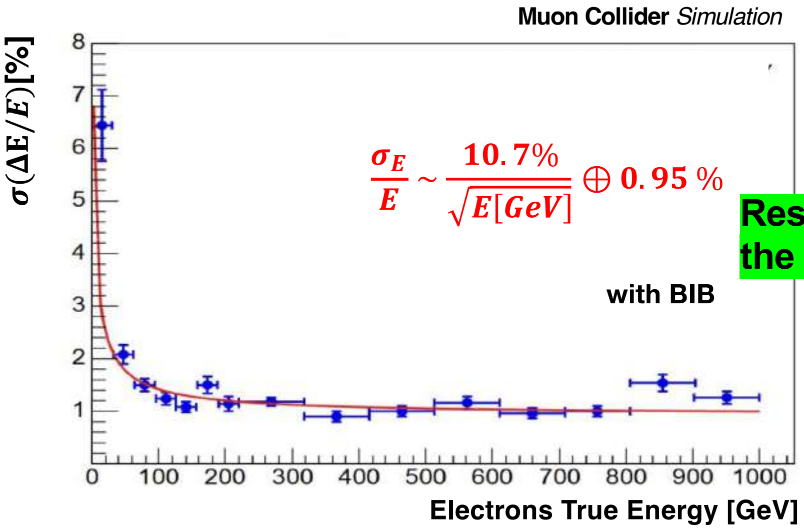
*S. Ceravolo et al 2022 JINST **17** P09033*

Simulated performances

- The ECAL barrel with Crilin technology has been implemented in the Muon Collider simulation framework
  - ➢ 6 layers of 45 mm length, 10 X 10 mm^2 cell area → **25 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
- 6 layers wrt to 40 layers of the W-Si calorimeter → **factor 10 less in cost (6 vs 64 Mchannels)**





Results in agreement with the ECAL requirements!

Towards the real detector

Towards the real detector

Prototype versions

- Proto-0 (2 crystals → 4 channels)
- Proto-1 (3x3 crystals x 2 layers → 36 channels, one layer w/ SiPM series connection the other with parallel connection)

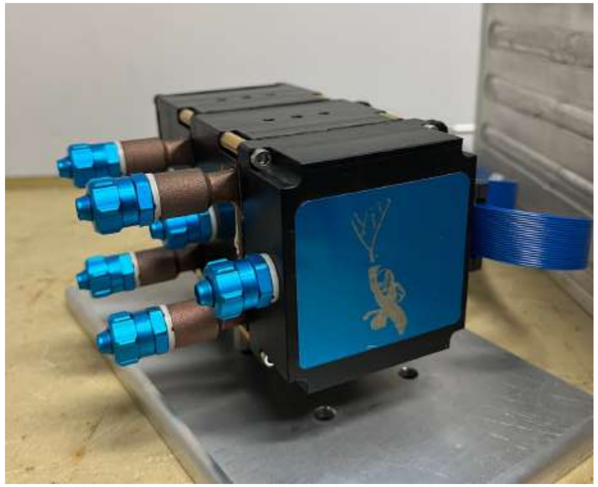
Front-end electronics

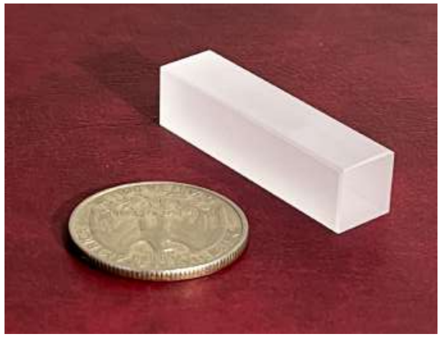
- Design completed
- Production and QC completed

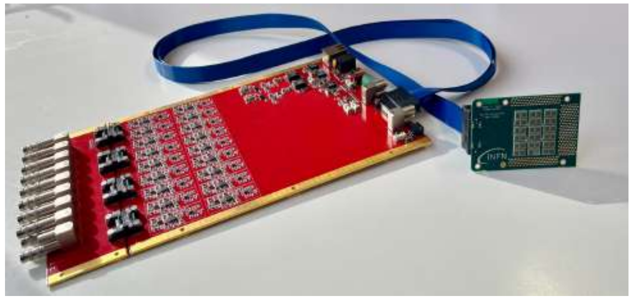
Radiation hardness campaigns

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 and CERN (August 2023)



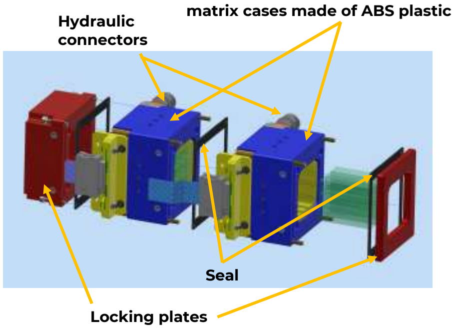


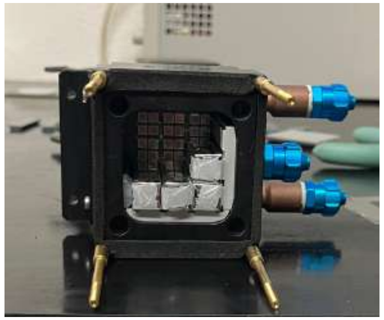


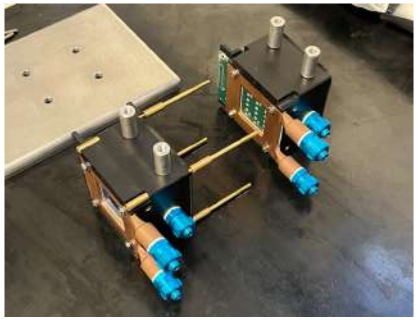
Proto-1: Mechanics and Electronics

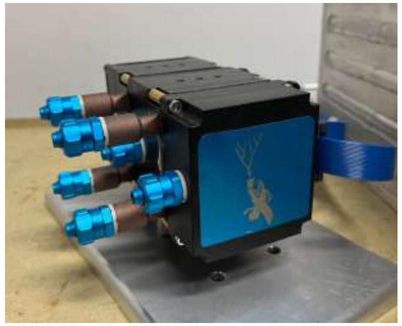
Mechanics:

- 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.



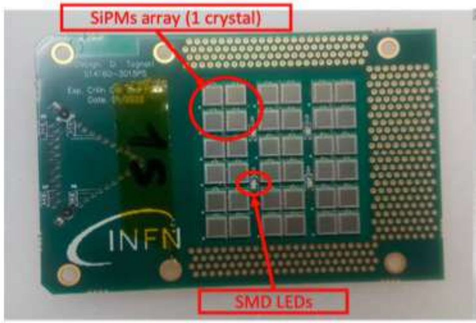


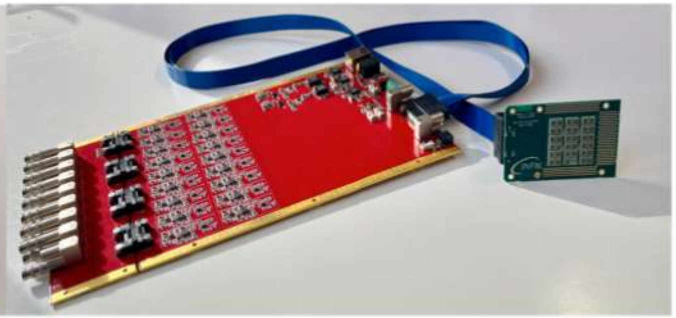




Electronics:

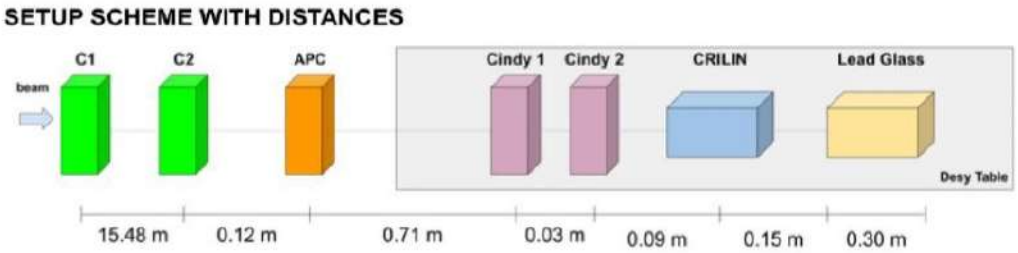
- **SiPMs board:** custom SiPM array board 36x10 µm Hamamatsu SMD SiPMs
- **Mezzanine board:** 18x readout channels → amplification, shaping and individual bias regulation, slow control routines

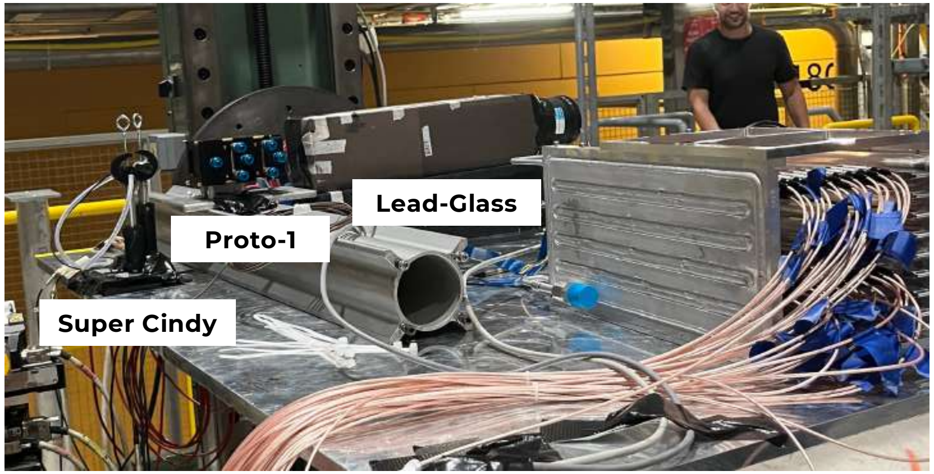




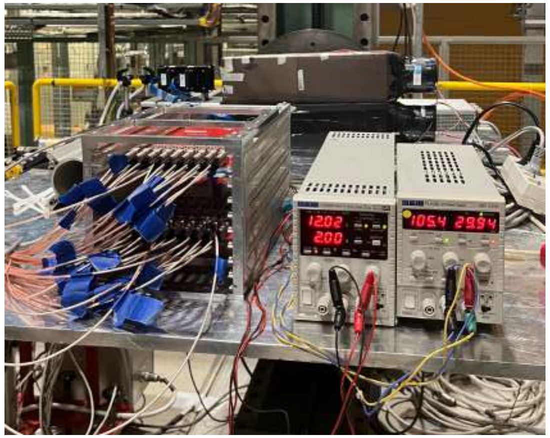
Beam test @ CERN

H2-SPS-CERN, August 2023





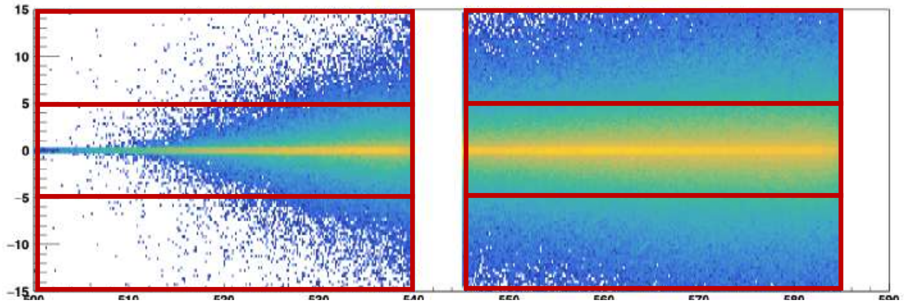
- Electron beam from 40 GeV up to 150 GeV
- Beam reconstructed with 2 silicon strip telescopes
- Data acquisition with 2 CAEN V1742 (32 ch each) modified @ 2 Vpp
- 5 Gs/s sampling rate



Beam test @ CERN: MC agreement

- **Electron beam from 40 GeV up to 150 GeV**
- **Proto-1** (2 crystal layers totalling **8.5 X_0**) is not deep enough to fully contain the electromagnetic shower, making energy resolution studies unfeasible.

MC
120 GeV e$^-$

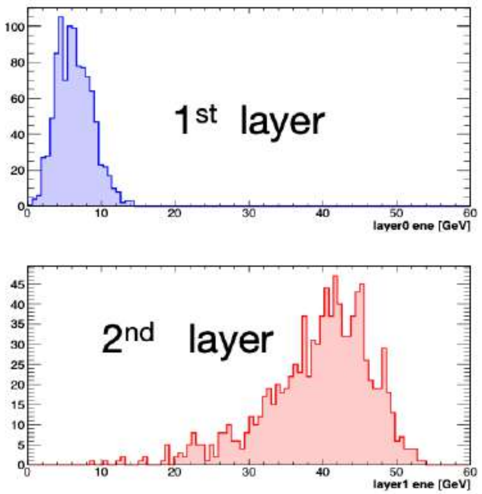


Will be possible with new larger prototype, now under construction

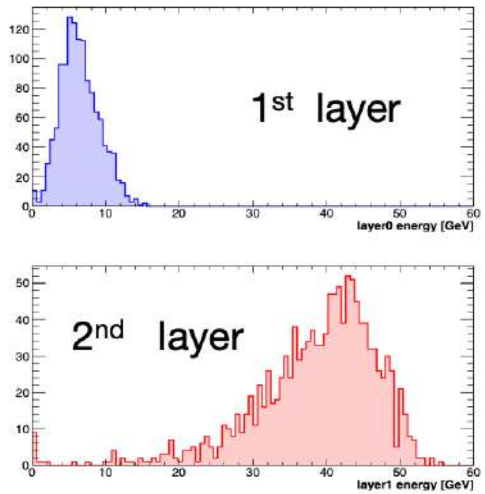
- Great agreement between **MC simulation studies** and **experimental data** from the test beam on the energy deposited in the prototype.

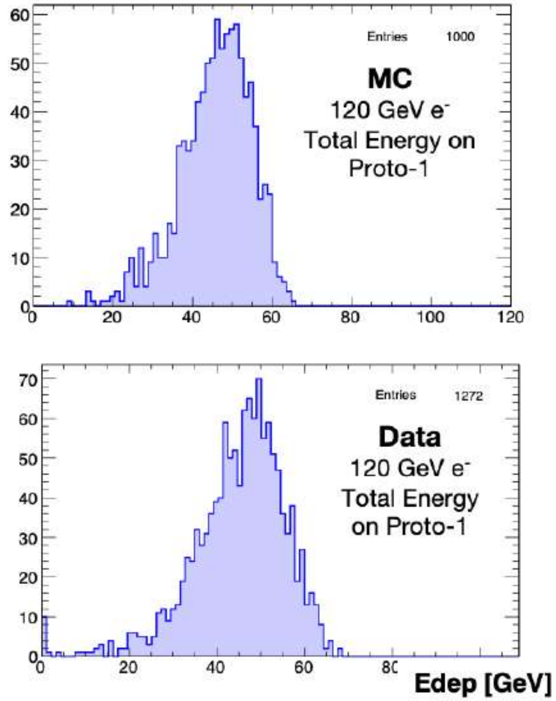
- Validation of the **simulation model**.

MC
120 GeV e$^-$



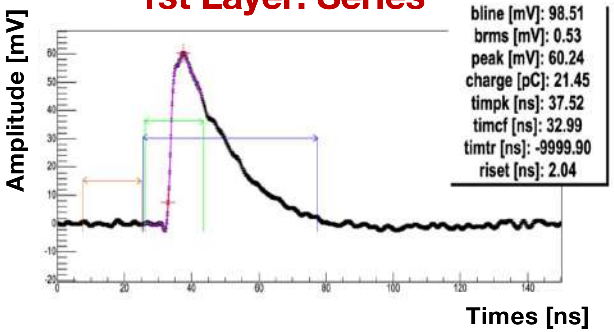
DATA
120 GeV e$^-$



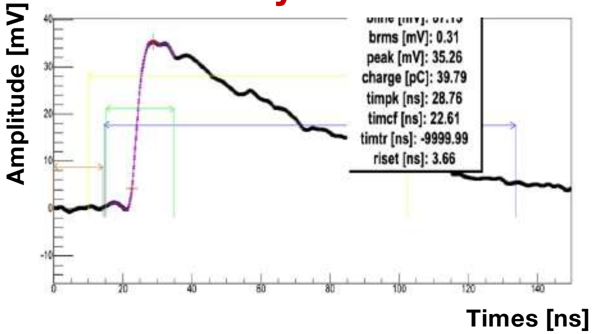


Beam test @ CERN: Configuration

1st Layer: Series



2nd Layer: Series

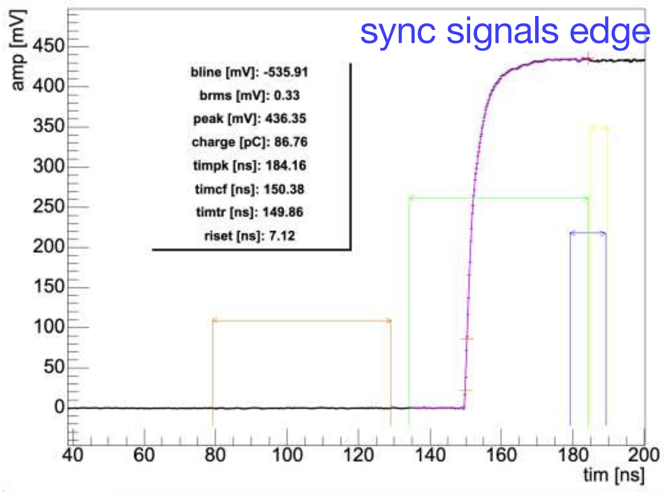


- **Two different connection in the two layers:** series and parallel
- **Low pass filtering** (Bessel 2nd order) cutoff_parallel ~ 2 * cutoff_series.
- Cut-off frequency based on two parameters: baseline RMS and risetime (10-90%)
- Wave quality flag based on baseline RMS, peak, and risetime to discard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

Sync pulses reconstruction:

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

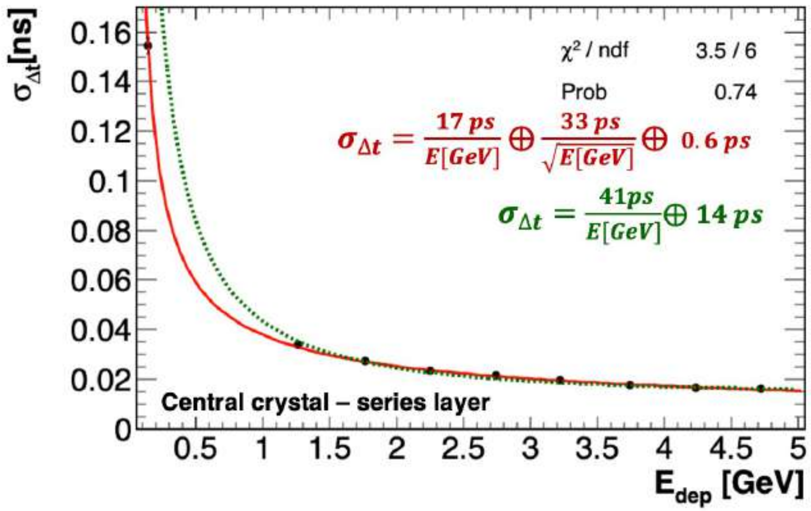
- O(30 ps) board-to-board jitter

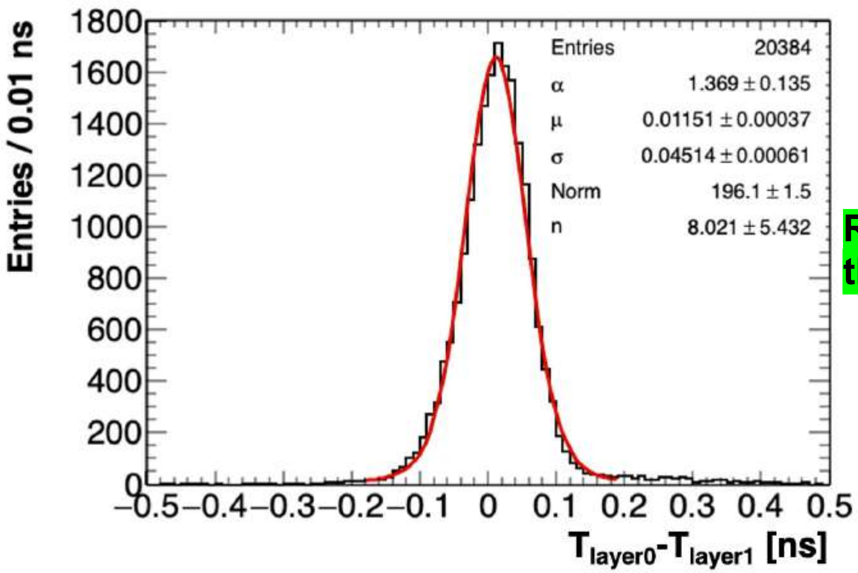


Beam test @ CERN: Timing

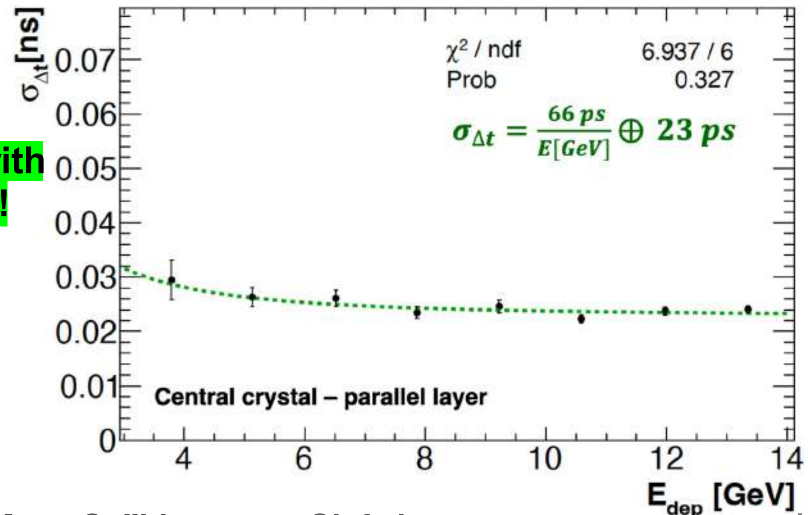
- Time Resolution of **O(20 ps)** both in the series and in the parallel layers using the SiPMs time difference of the central crystals

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





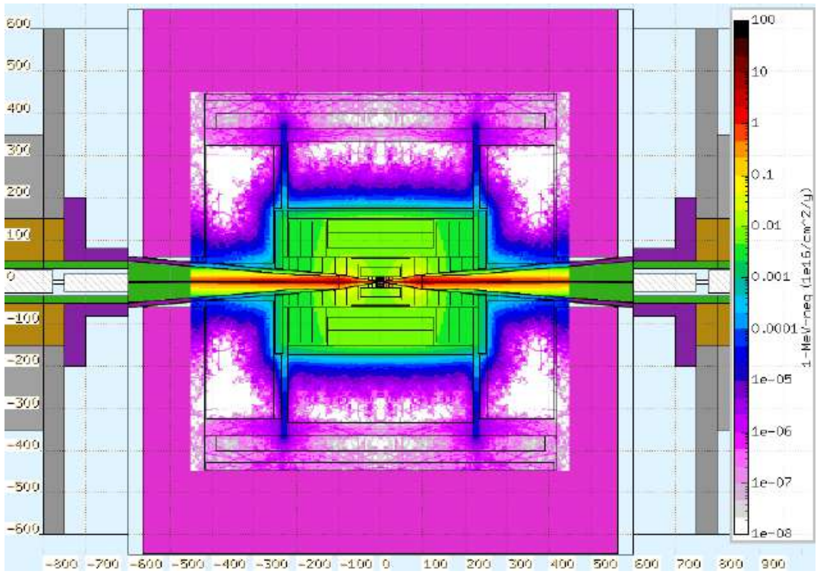
Results in agreement with the ECAL requirements!

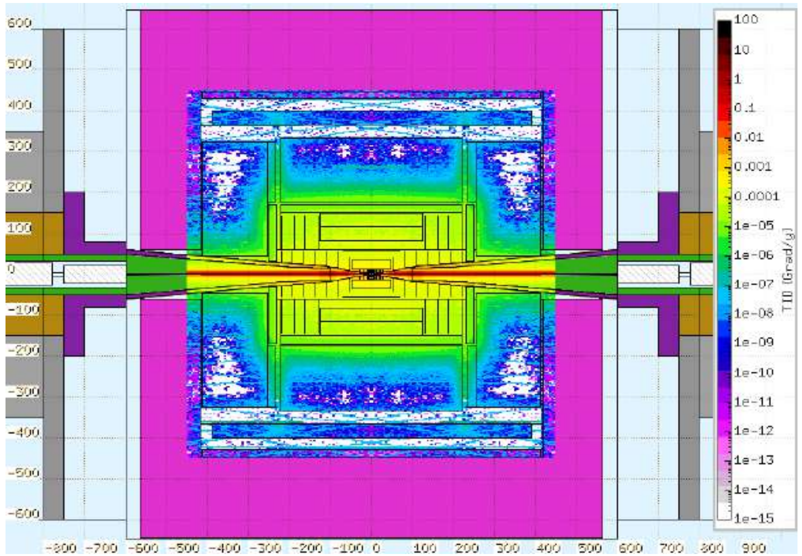


Radiation hardness studies

Radiation enviroment

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



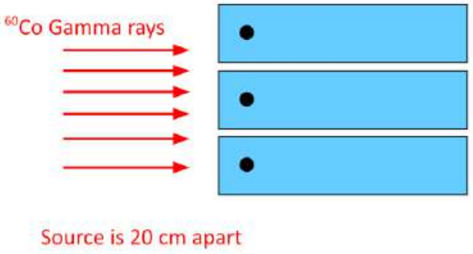


- **Neutron fluence** $\sim\mathbf{10^{14}}$ n$_{1MeVeq}/\boldsymbol{cm^2}$**year** on ECAL.
- **TID** ~ **1 kGy/year** on ECAL.

Crystal radiation hardness

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

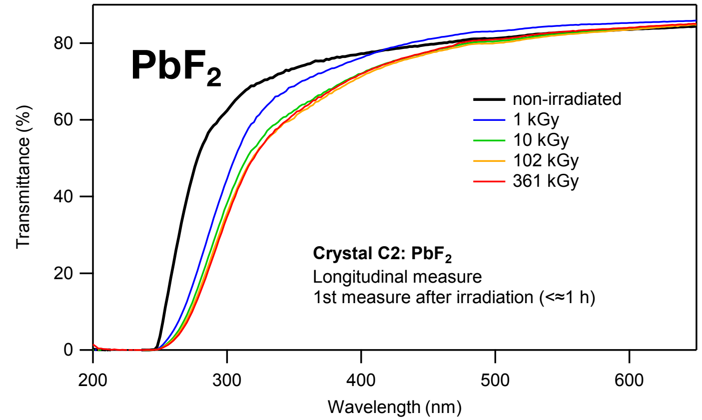
Radiation hardness of two PbF_2 and $PbWO_4$-UF crystals (10x10x40 mm^3) checked for TID (up to 100 Mrad @ Calliope, Enea Casaccia) and neutrons (14 MeV neutrons from Frascati Neutron Generator, Enea Frascati, up to 10^{13} n/cm^2)

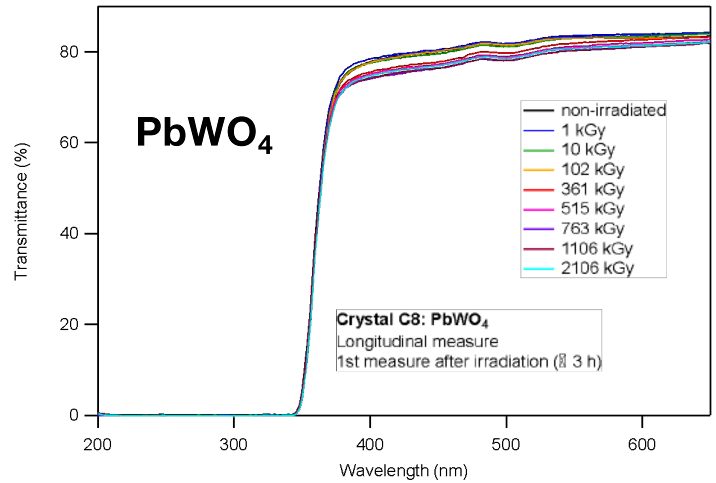


- **For PbF_2:**
  - **after a TID > 350 kGy no significant decrease** in transmittance observed.
  - Transmittance after neutron irradiation showed no deterioration
- **For $PbWO_4$-UF:**
  - **after a TID > 2 MGy no significant decrease** in transmittance observed.

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





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.

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

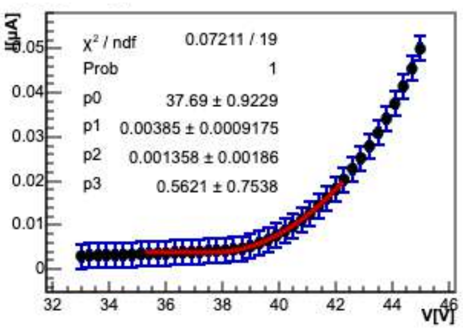
T [°C]	V_{br} [V]	$I(V_{br}+4V)$ [mA]	$I(V_{br}+6V)$ [mA]	$I(V_{br}+8V)$ [mA]
-10 ± 1	75.29 ± 0.01	12.56 ± 0.01	30.45 ± 0.01	46.76 ± 0.01
-5 ± 1	75.81 ± 0.01	14.89 ± 0.01	32.12 ± 0.01	46.77 ± 0.01
0 ± 1	76.27 ± 0.01	17.38 ± 0.01	33.93 ± 0.01	47.47 ± 0.01

10 μm pixel-size

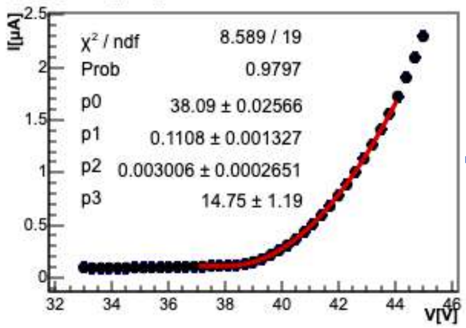
T [°C]	V_{br} [V]	$I(V_{br}+4V)$ [mA]	$I(V_{br}+6V)$ [mA]	$I(V_{br}+8V)$ [mA]
-10 ± 1	76.76 ± 0.01	1.84 ± 0.01	6.82 ± 0.01	29.91 ± 0.01
-5 ± 1	77.23 ± 0.01	2.53 ± 0.01	9.66 ± 0.01	37.51 ± 0.01
0 ± 1	77.49 ± 0.01	2.99 ± 0.01	11.59 ± 0.01	38.48 ± 0.01

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

Pre 10kGy



Post 10kGy

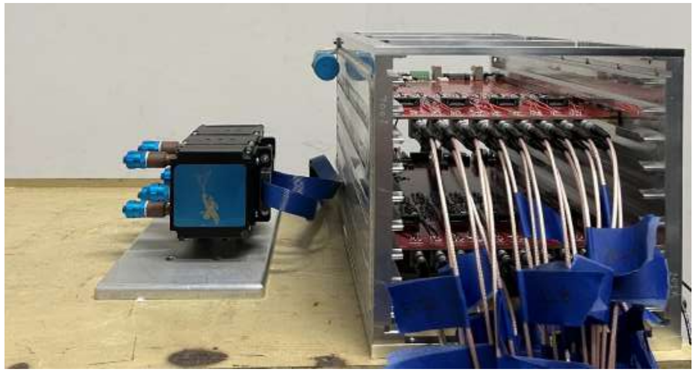


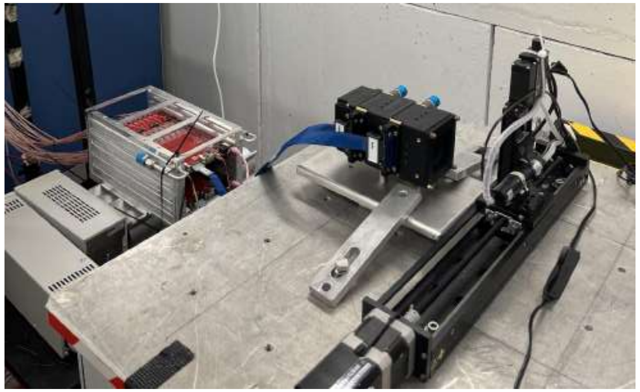
Dark current @ V_{op} goes from 12 nA to 600 nA

LY loss evaluation @ BTF

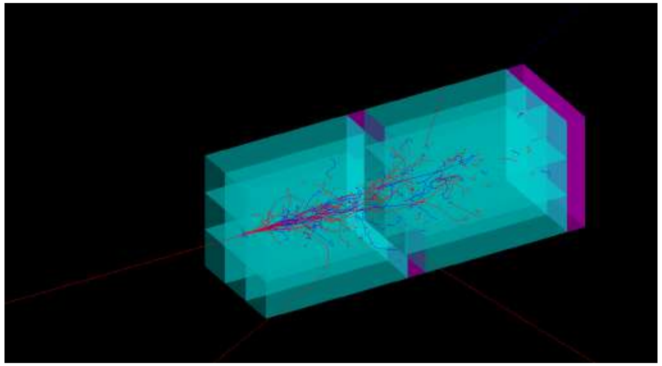
BTF, April 2024

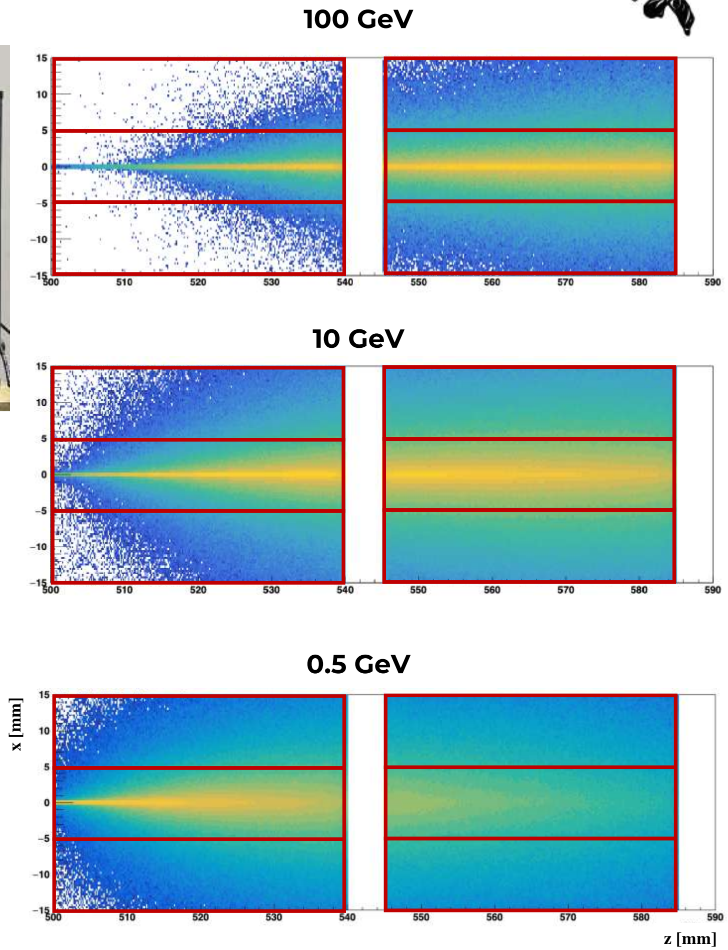
- Study of the LY loss of one layer of Proto-1 after Gamma ray irradiation
- Beam: 450 MeV electrons with multiplicity set to 1
- Beam centered on a different crystal at each run





Monte Carlo

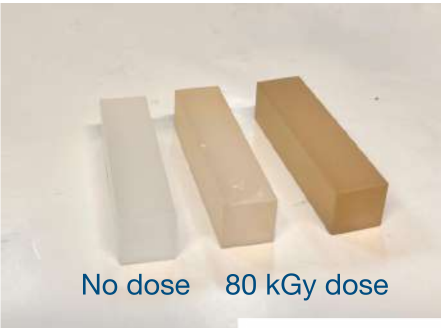


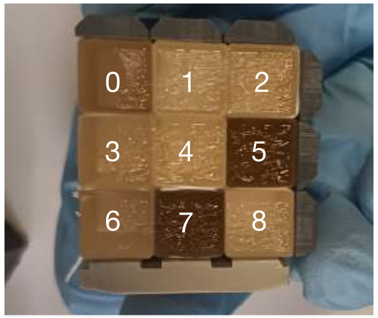


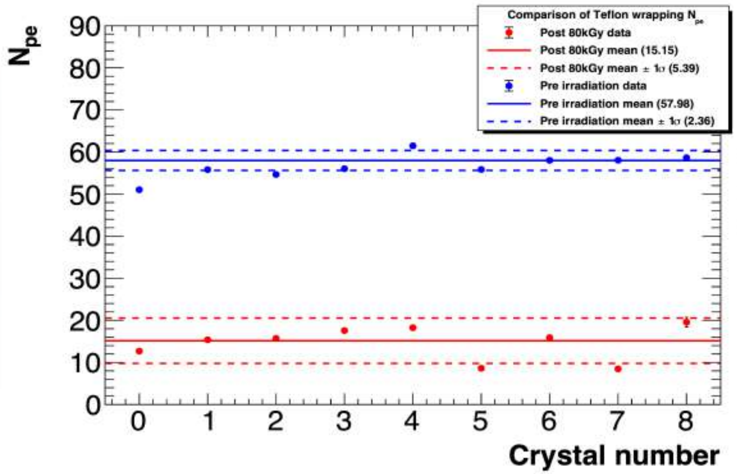
Beam test @ BTF: Teflon wrapping

After 80 kGy (8 Mrad) irradiation

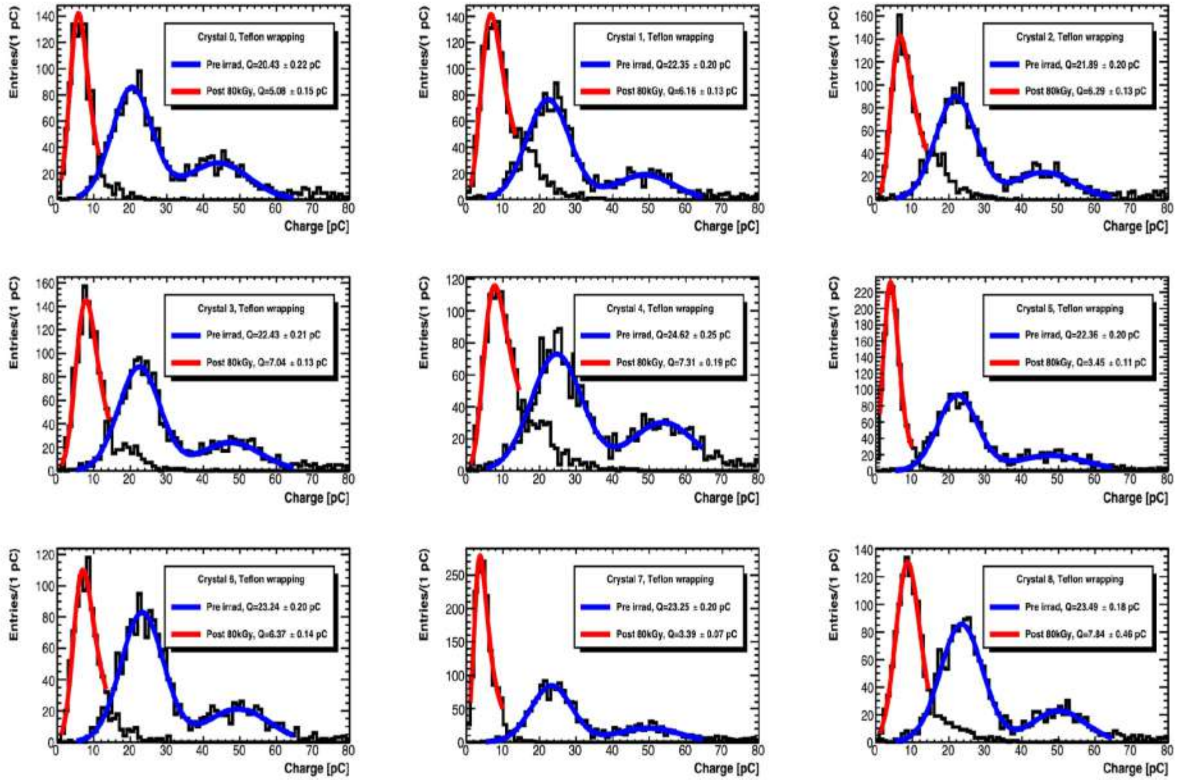
- Teflon was damaged and brittle
- Crystals evident loss of transparency





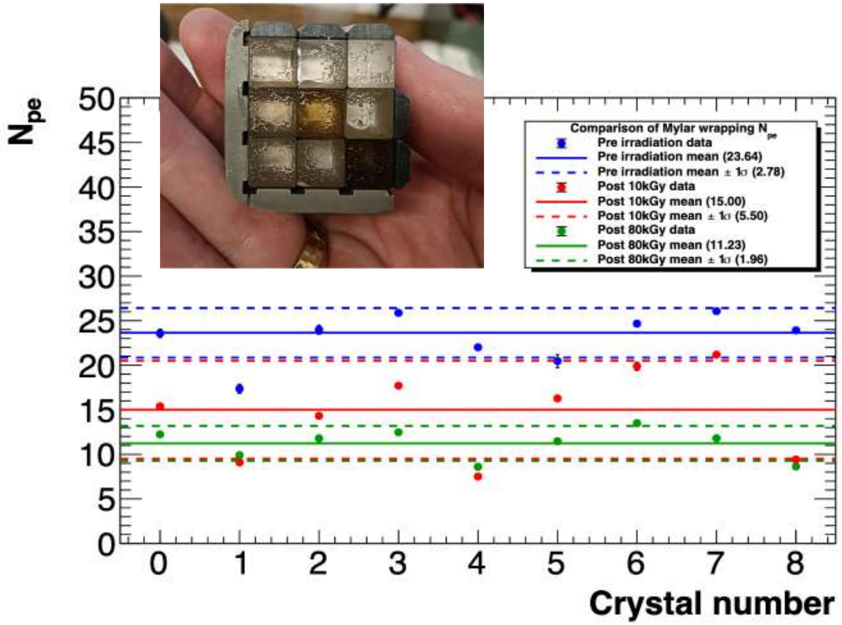


Charge distribution of PbF_2 pre and post irradiation

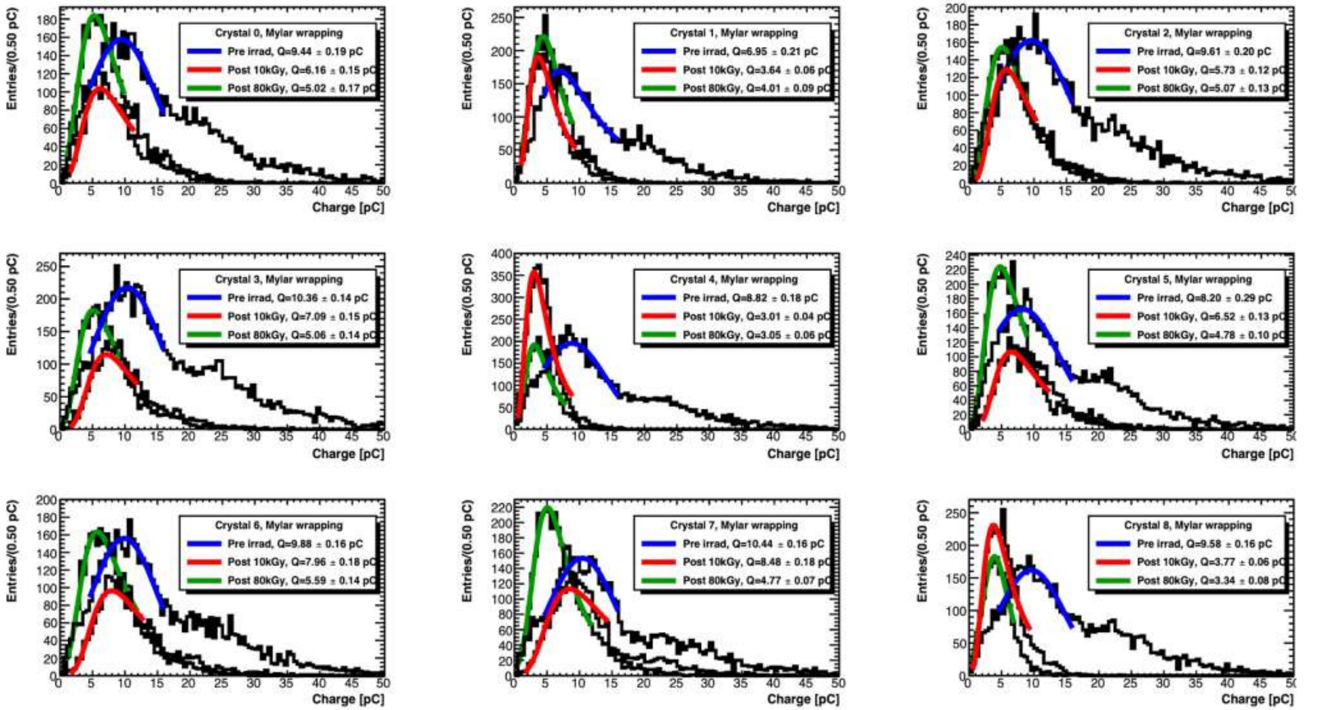


Beam test @ BTF: Mylar wrapping

- 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

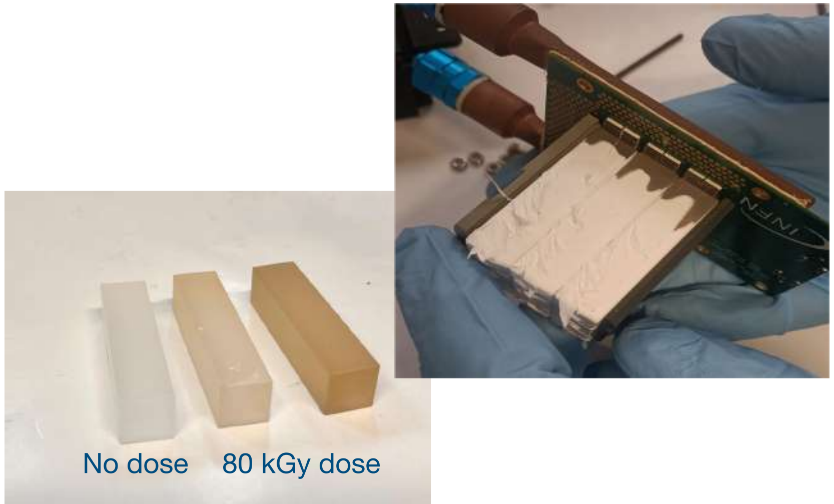


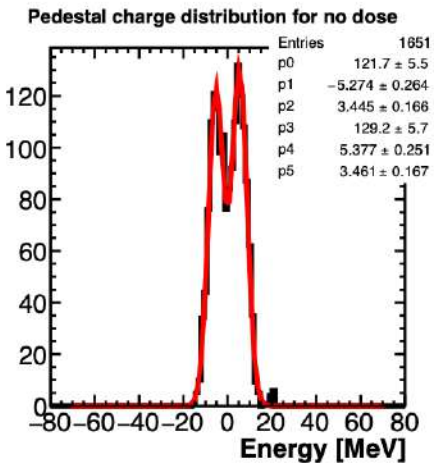
Charge distribution of PbF_2 pre, after 10 kGy and after 80 kGy irradiation

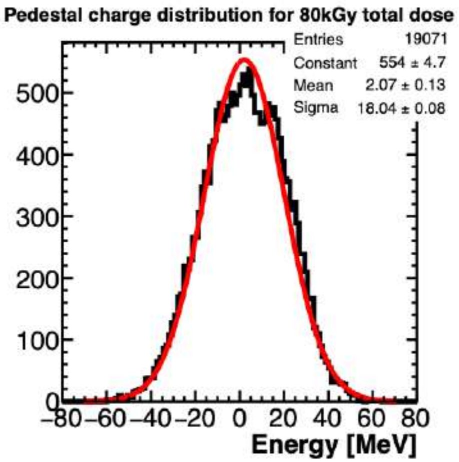


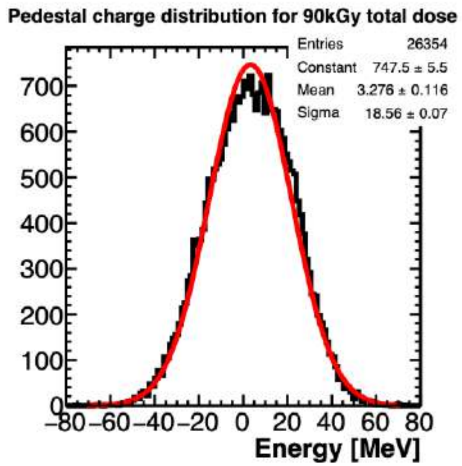
Beam test @ BTF: considerations

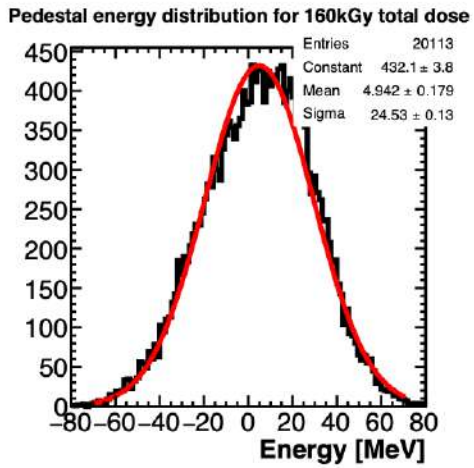
- Considerable variability in crystals' response to radiation, despite SICCAS claiming use of high-purity (>99.9%) PbF_2 powder for crystal growth
- **Crystals evident loss of transparency**, uniform along the longitudinal axis
- Teflon was damaged and brittle → **Mylar is the best choice**
- SiPM dark counts increases significantly with the absorbed dose
- New tests planned to evaluate SiPMs PDE loss











2025: Proto-2

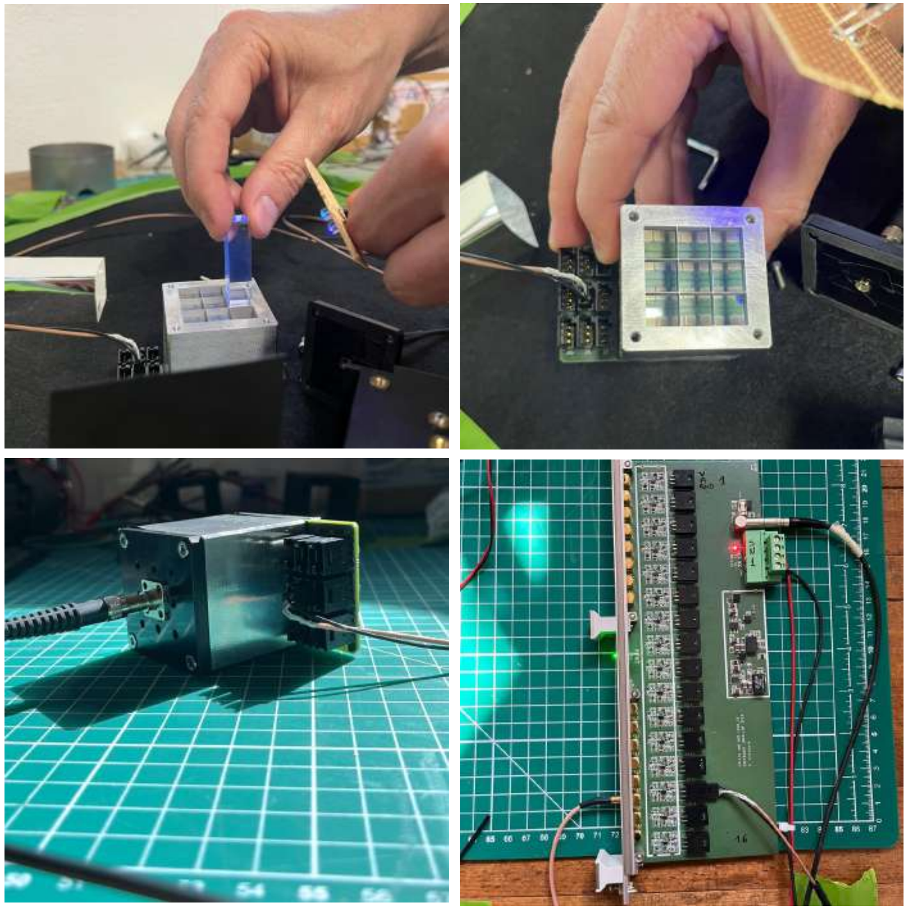
Towards the real detector

Prototype versions
- Proto-2 (3x3 crystals x 1 layers)

Mechanics
- New Aluminum 3x3 matrix with 150 um septa

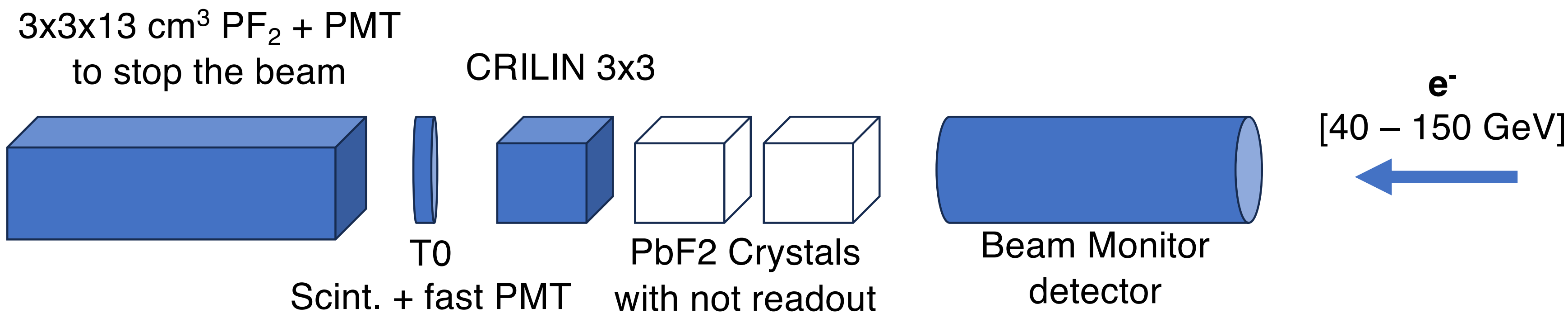
Front-end electronics
- Upgraded Low-Power Electronics Developed and Ready for Adaptation to Kapton Strip Design

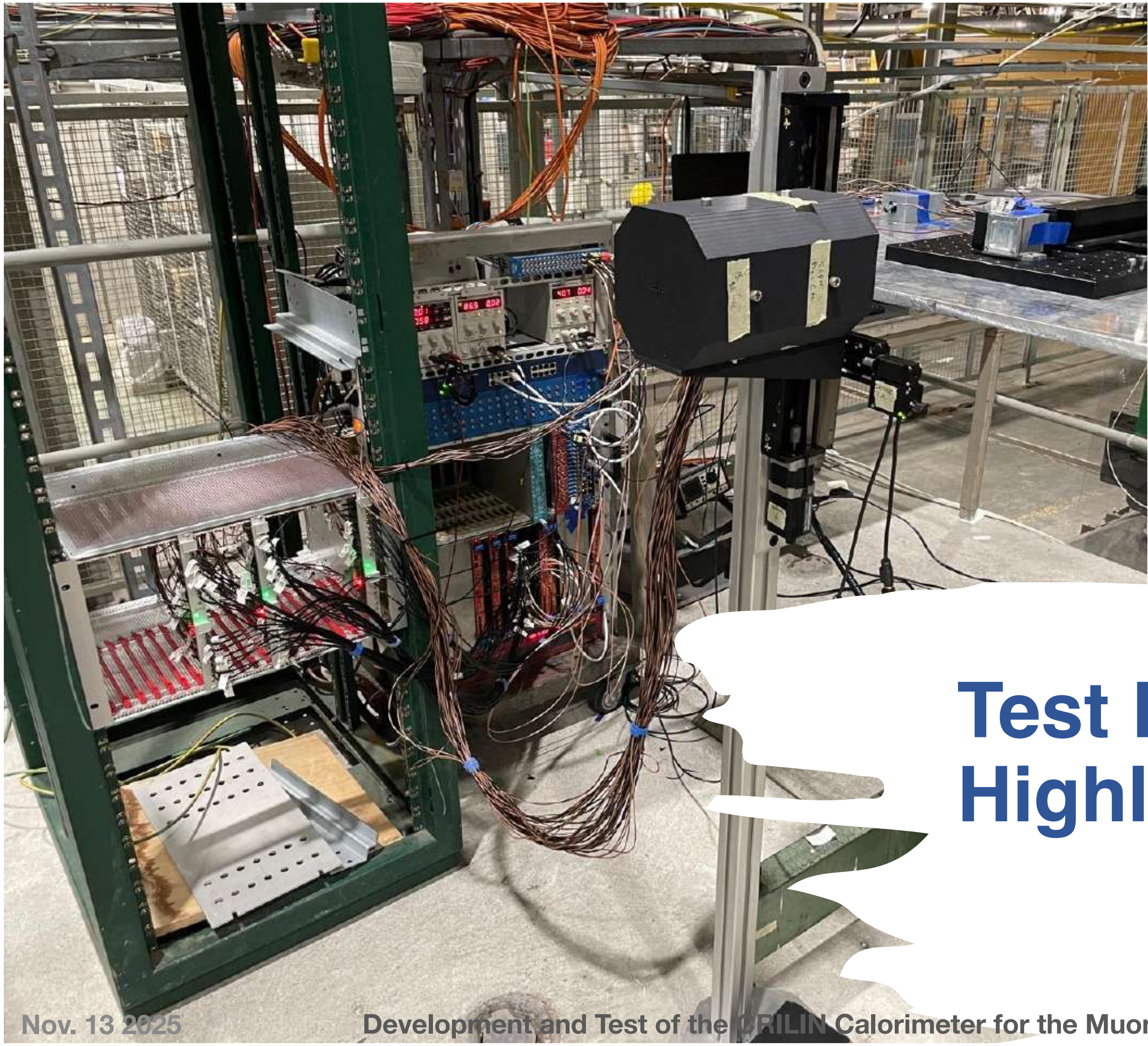
Beam test campaigns
- Proto-2 at CERN H2 (September 2025)

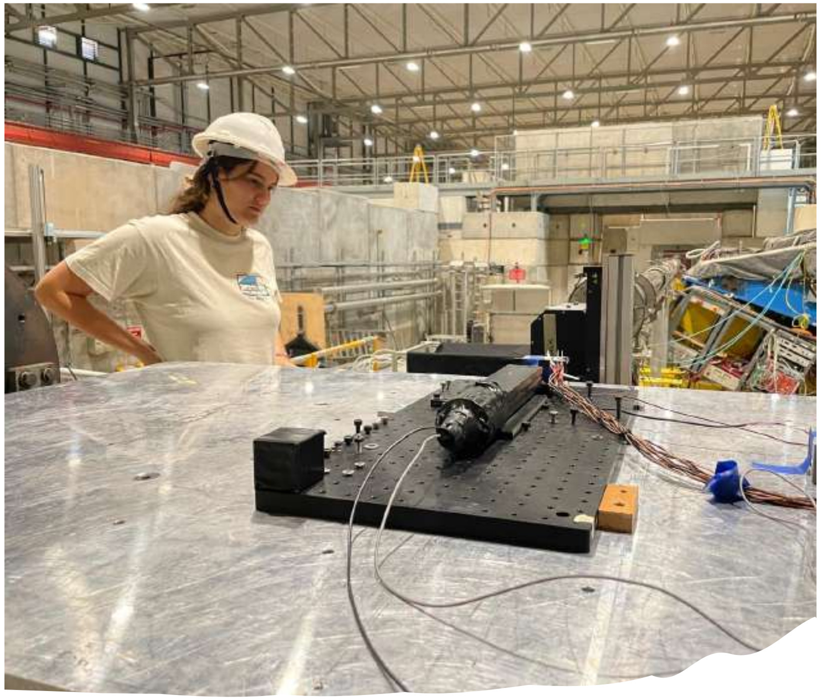


Test Beam @ CERN SPS 2025

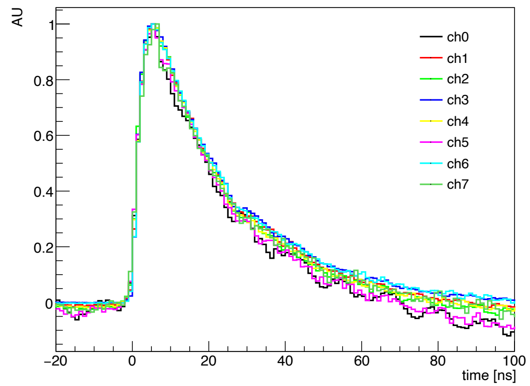
- Measured the response of layers 1, 2, and 3 by adding crystal layers at different beam energies (20, 60, 100, and 140 GeV)
- Tested the beam monitoring system → achieved a spatial resolution of about 300 μm in x and y
- Collected runs where the 9 channels of the crystal matrix were read out simultaneously with both the V1742 and the picoTDC





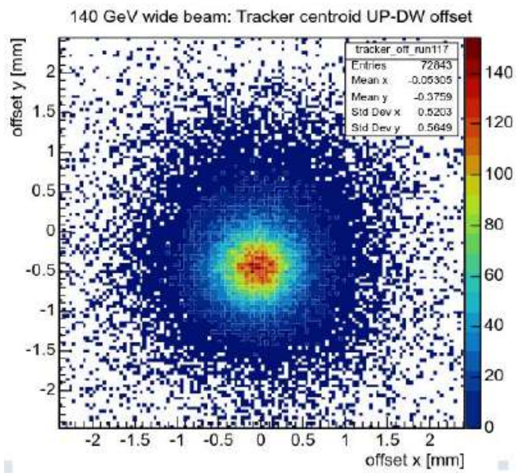


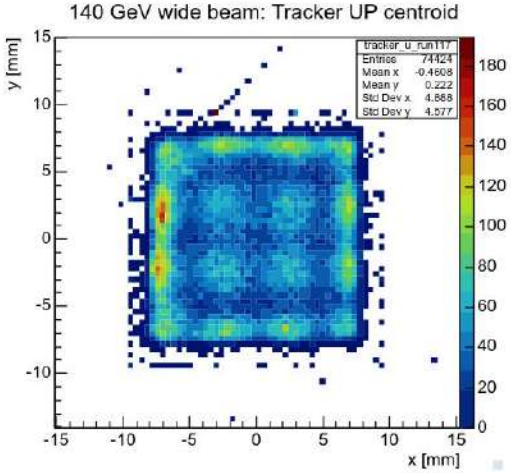
Test Beam Highlights

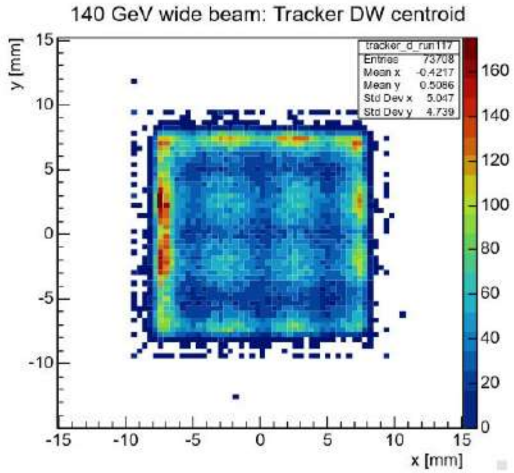


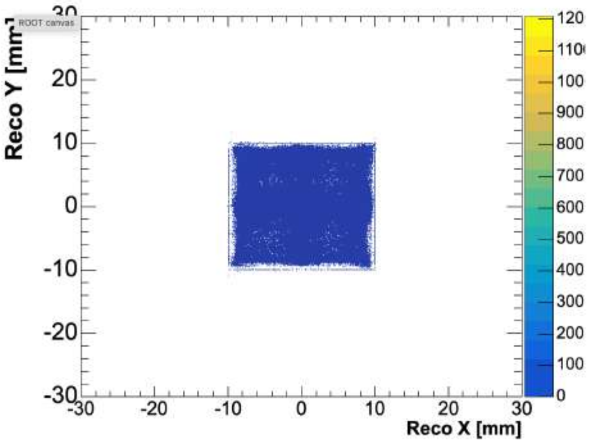
Test Beam Highlights

Beam profile observed with the "astronave" detector and resolution of the two layers

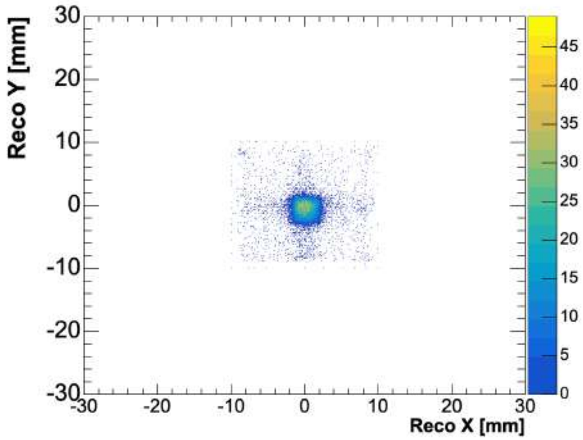






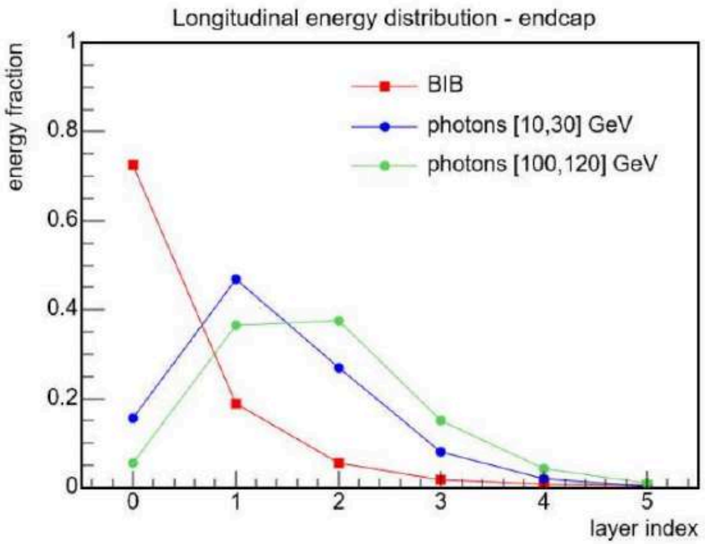


Centroid of the 9 crystals before and after the fiducial cut on the "astronave", within ± 2.5 mm in x and y

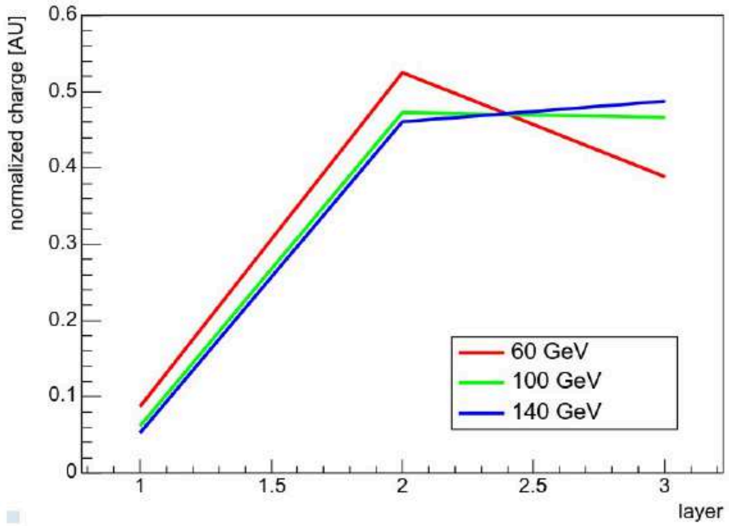


Edep vs Layer

Muon Collider Simulation

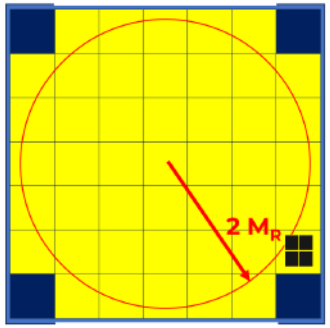


Test Beam Data



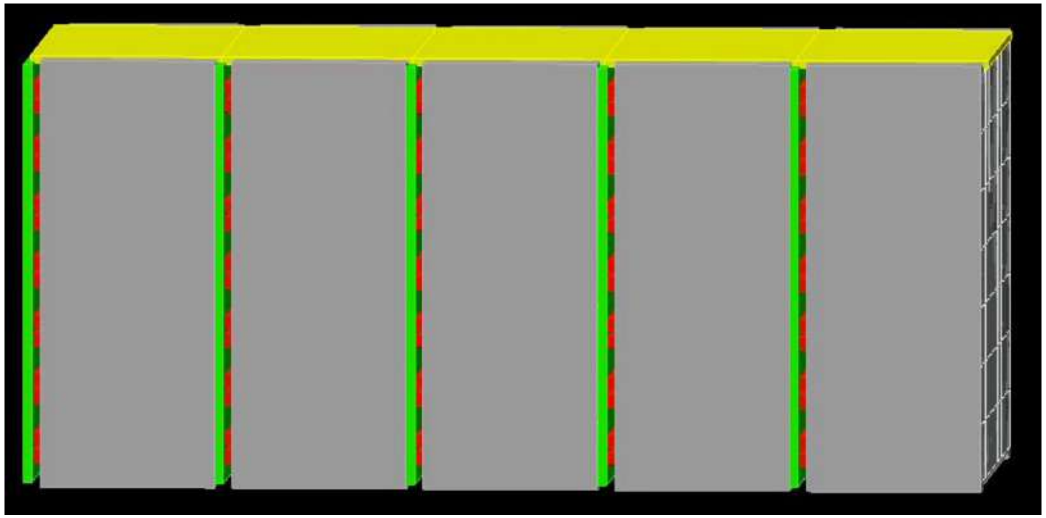
New prototype

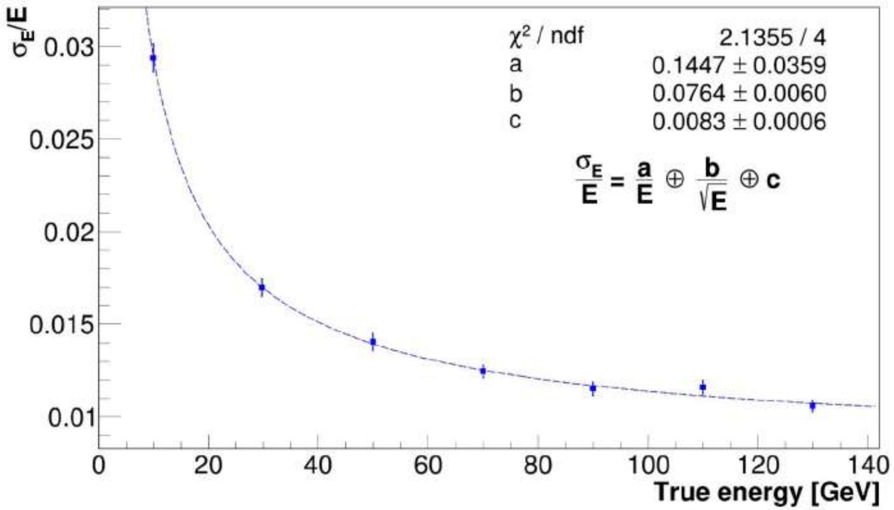
New 7x7 module



FINAL PROTOTYPE: **5 layers, 7x7 crystals, ~ 250 channels**

- slightly wider crystals (PbF2 1.3x1.3 cm^2 with 0.1mm tolerance)
- 100μm printing per side
- Aluminum matrix support
  - → max 200μm inter-crystal thickness
  - → max 2mm external envelope thickness
  - → max 5mm between layers



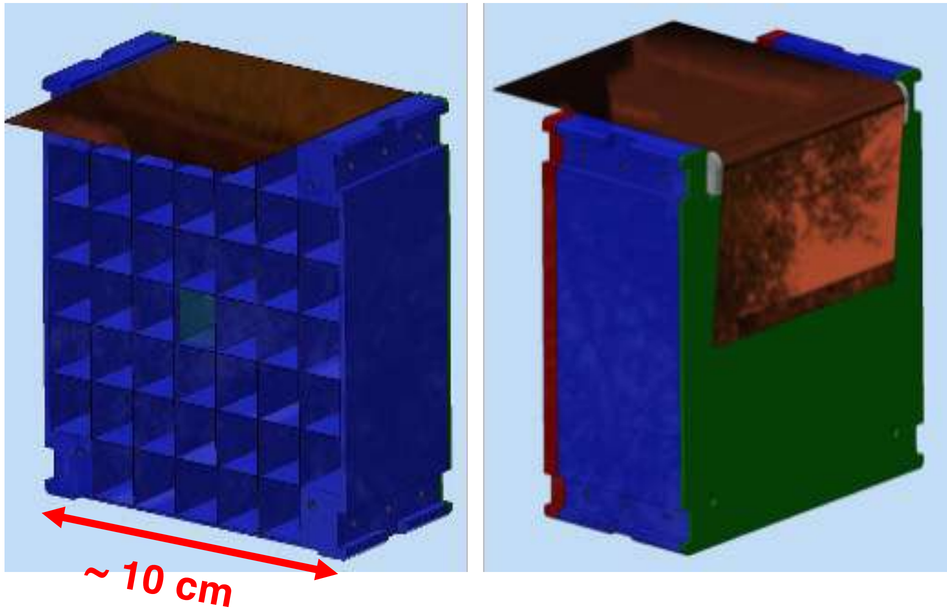


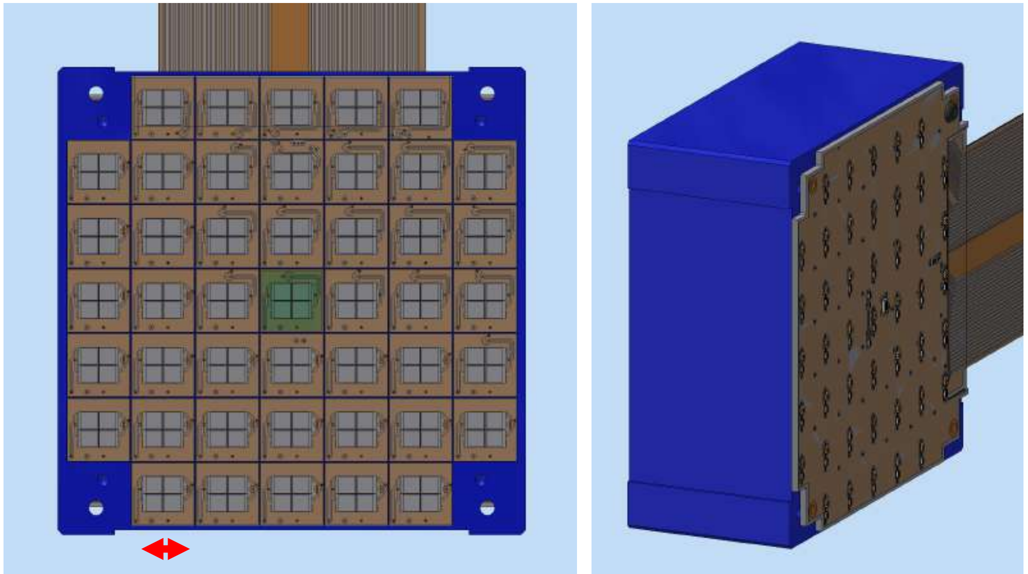
Simulation: Energy Resolution ~ 7.5%/√E

- 0.2 P.E./MeV per crystal
- gaussian noise σ = 10 MeV
- 30 MeV energy threshold per crystal

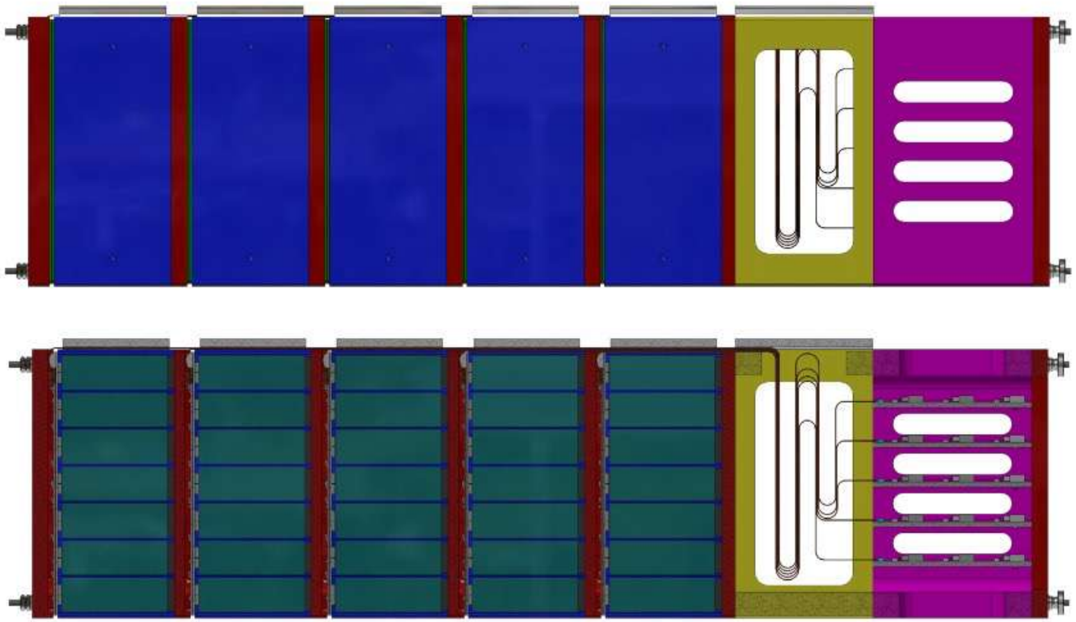
Improved readout:

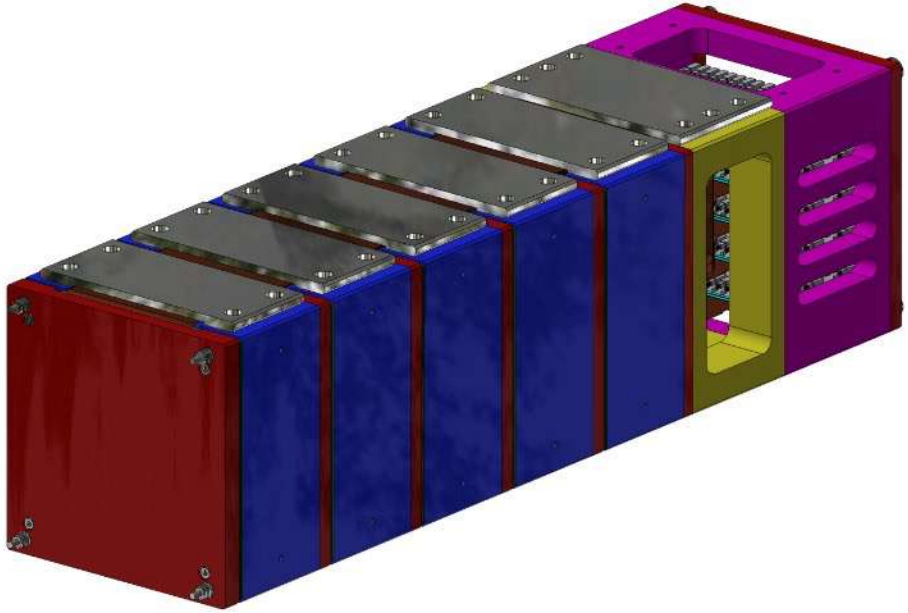
- Kapton strip for SiPM connection
- New custom FEE
- CAEN V1742 digitizer





4 SiPM 3x3 mm^2 per crystal





Test Beam @ BTF (e$^-$ @ 500 MeV crystals calibration)
March/April 2026

Test Beam @ CERN SPS (Energy Resolution)
May/June 2026!

Summary

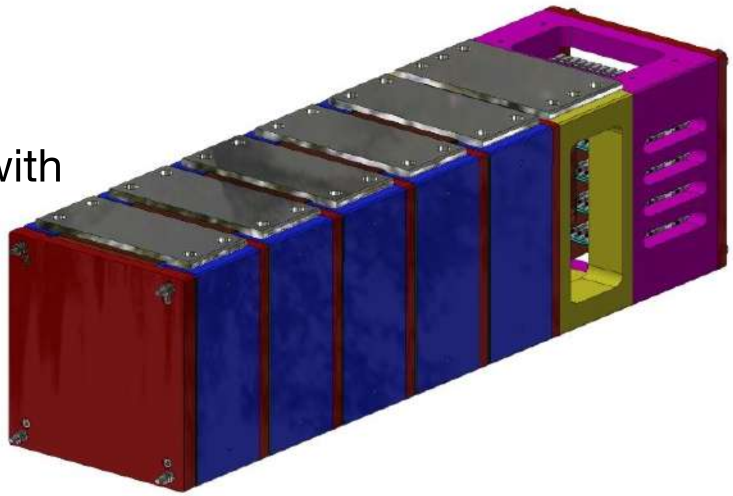
- **Simulated energy resolution** perfectly in line with the Muon Collider requirements
- **Time resolution**: < 40 ps for single crystals, for E_{dep} > 1 GeV
- **Radiation resistance:** transmittance PbF_2($PbWO_4$-UF) robust to > 35(200) Mrad and SiPMs validated up to 10^{14} n_{1MeV}/cm^2 displacement-damage eq. fluence → LY loss test beam showed a strong non uniformity in response between different crystals

- *End 2025:*
  - *Conduct new irradiation tests and monitor Cherenkov light variations with a blue laser.*
  - *Simultaneously test crystals with SiPM and SiPM alone*

DRD6-WP3 2026

➢ Expanding prototype to a 7x7x5(layers) configuration, with a target of 2 M_R – 22 X_0.

- Mechanical structure and electronics expected to be ready by the end of 2025

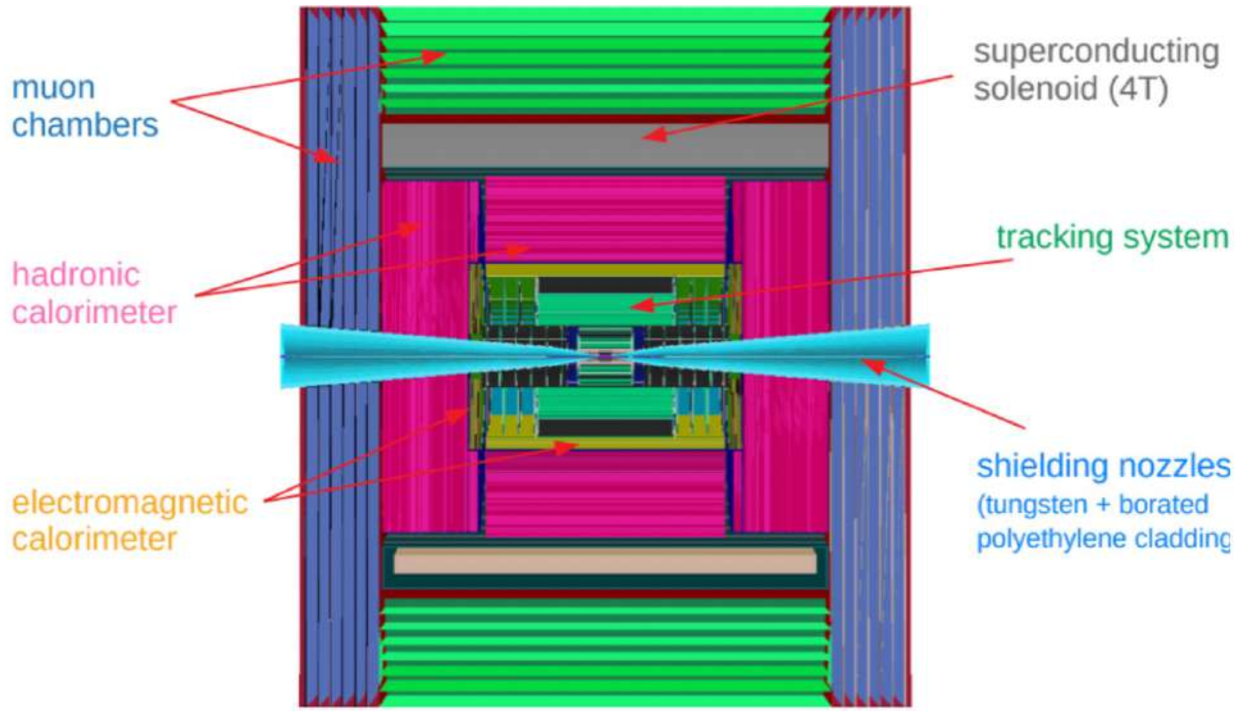


- **The calorimeter is planned to be fully assembled by March 2026**

- **Final test beam @ CERN SPS requested for May 2026**

Backup slides

Muon Collider



Main issues: BIB and radiation damage

Optimized detector interface:

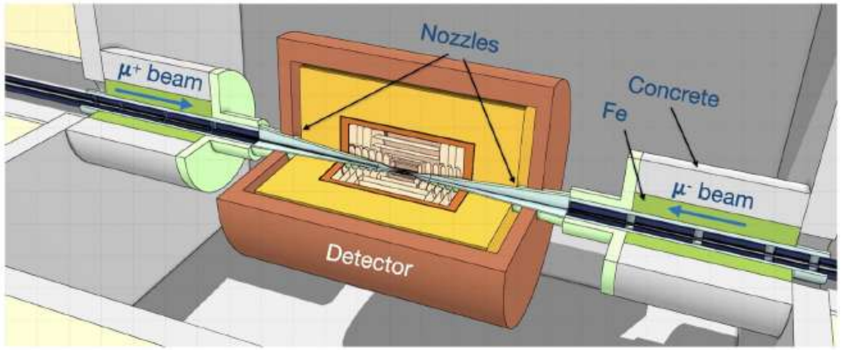
- Based on CLIC detector, with modification for BIB suppression.

- Dedicated shielding (nozzle) to protect magnets/detector near interaction region.

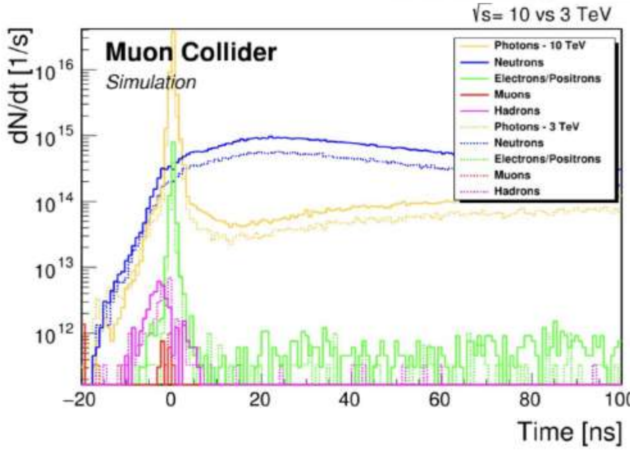
Beam Induced Background

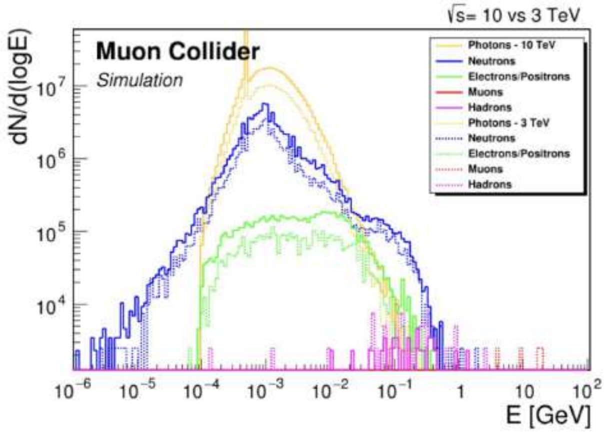
The decay of muons in flight along the accelerator ring produces high-momentum secondary particles, which interact with the machine's materials, and generate an **intense flux of tertiary particles** entering the detector region→ Beam-Induced Background (BIB)

- MDI optimized to reduce this contribution throughout a pair of Tungsten conical-shape absorber (**nozzles**) in the forward region on the detector.
- **Residual component** characterized by **low energy and broad arrival time distributions.**



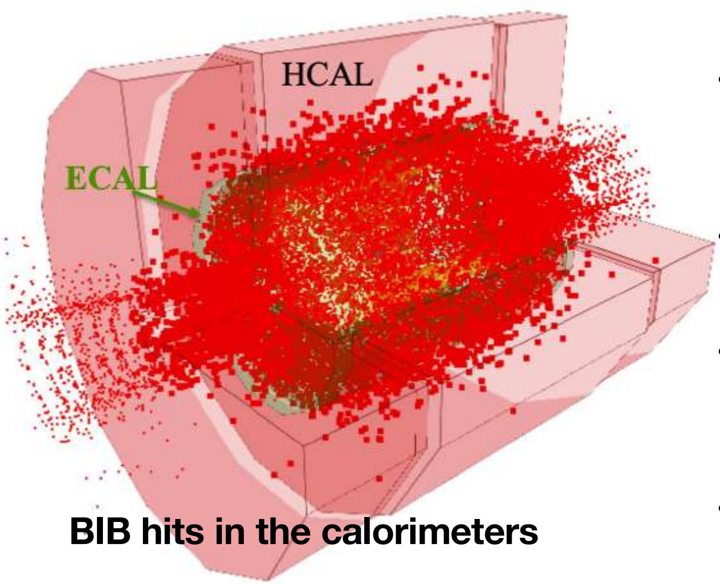
- For $\sqrt{s}$=10 TeV, also the **incoherent pair production** process is an important source of high-energy background particles in time with the signal.





Beam Induced Background

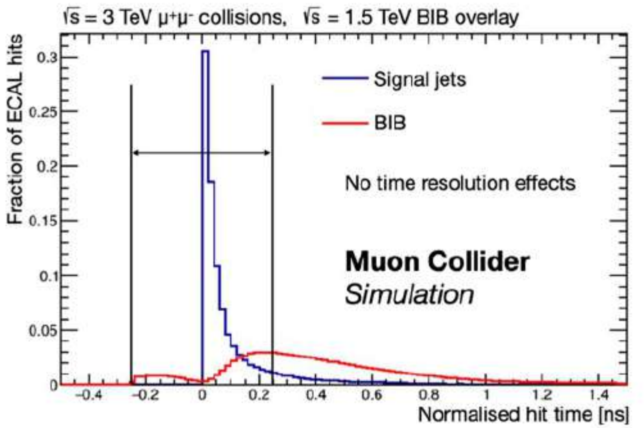
- **The beam-induced background (BIB)** poses the main challenge for the detector development at the Muon Collider
- Produced by muons decay in the beams, and subsequent interactions with the machine
- The BIB produces a flux of 300 particles per cm^2 through the ECAL surface
- 96% photons and 4% neutrons,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

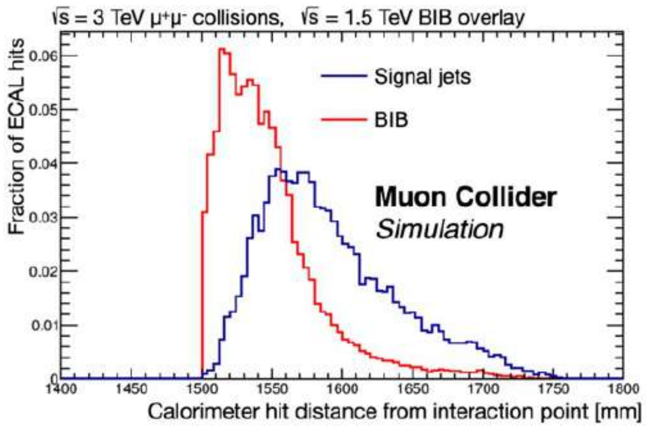


BIB hits in the calorimeters

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

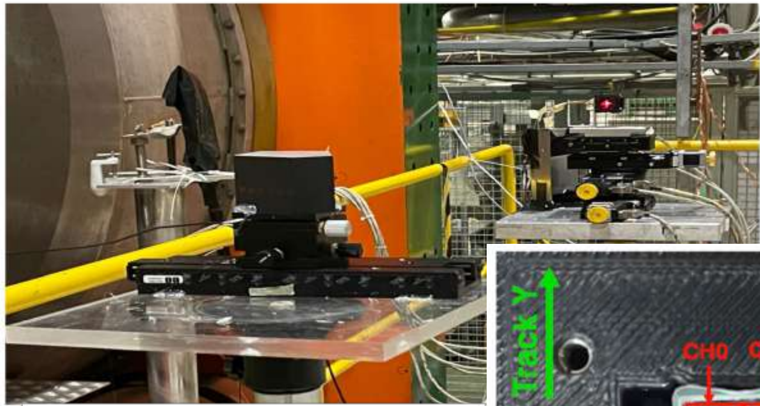




Proto-0: Single crystal beam test

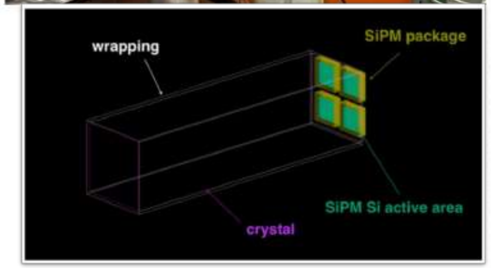
Beam test on Proto-0 in a single crystal configuration in fall 2022:

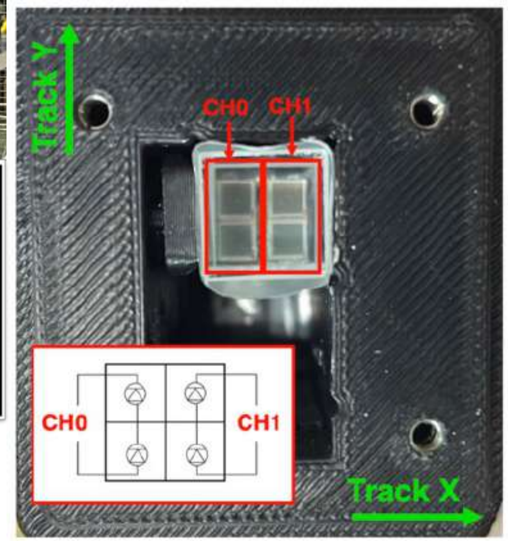
- 10 × 10 × 40 mm^3 single crystal → 2 options: **PbF_2** (4.3 X_0) **$PbWO_4$-UF** (4.5 X_0).
- Four 3x3 mm^2, 10 μm pixel size SiPMs for two independent readout channels (SiPM pairs connected in series).
- Mylar wrapping - No optical grease.



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.

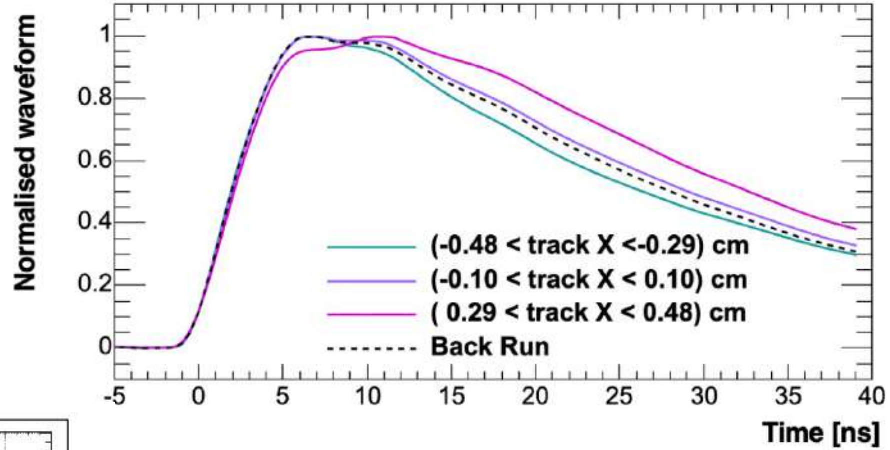


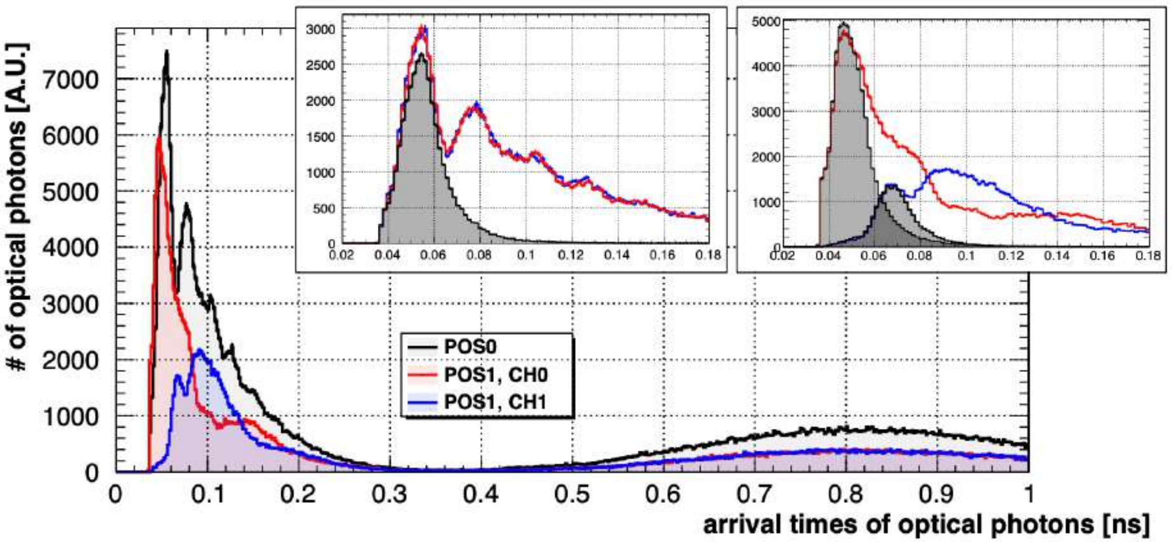


Positional effects: waveshapes

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



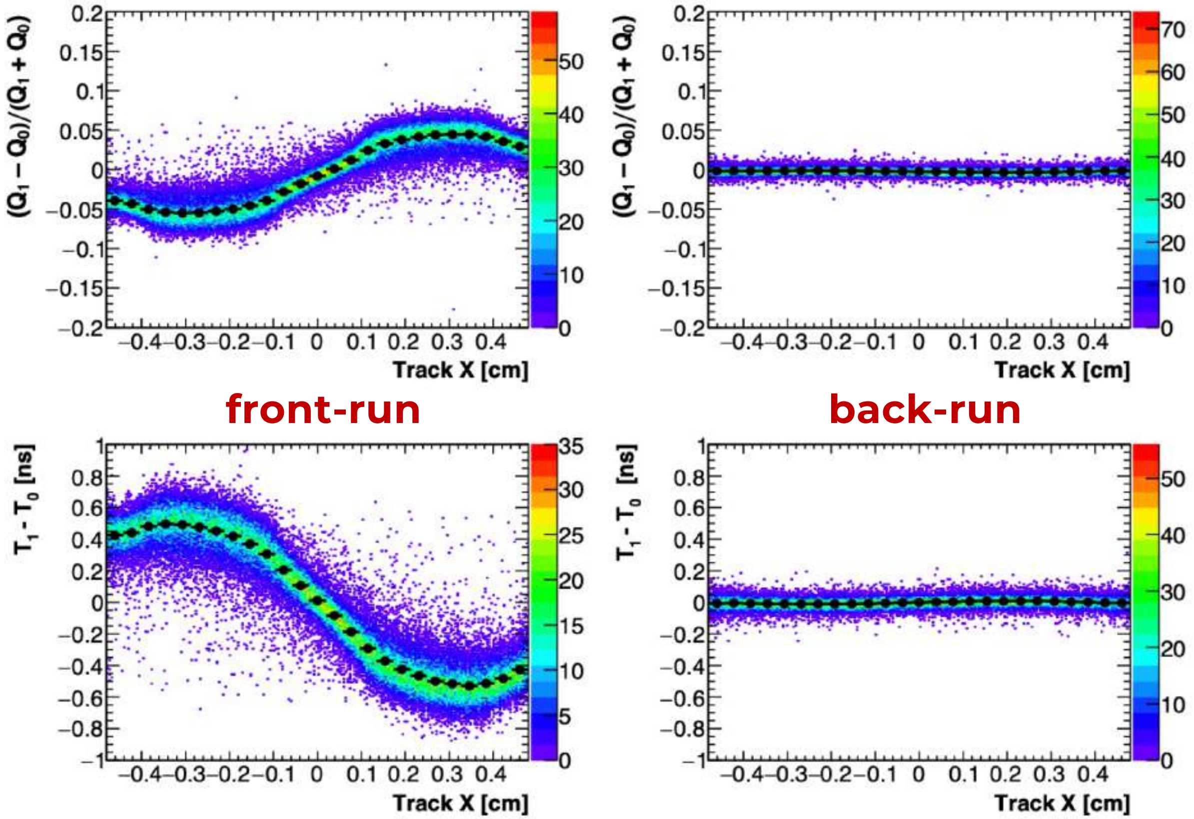


Optical simulation

- 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



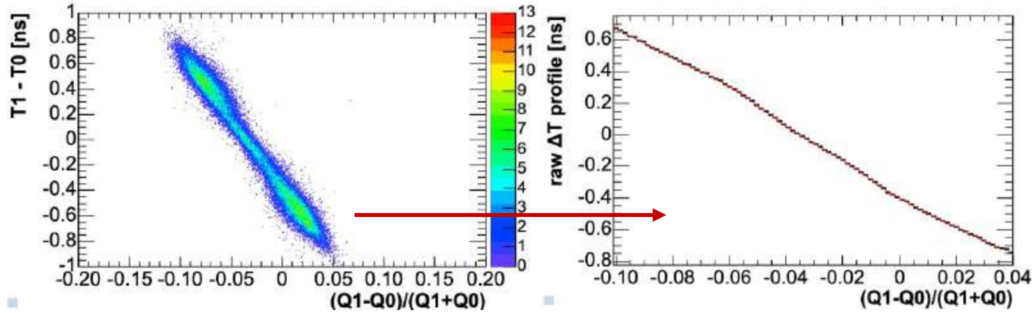
- +/- 10 % maximum imbalance in light collection
- anticorrelated effect on timing (T1-T0)

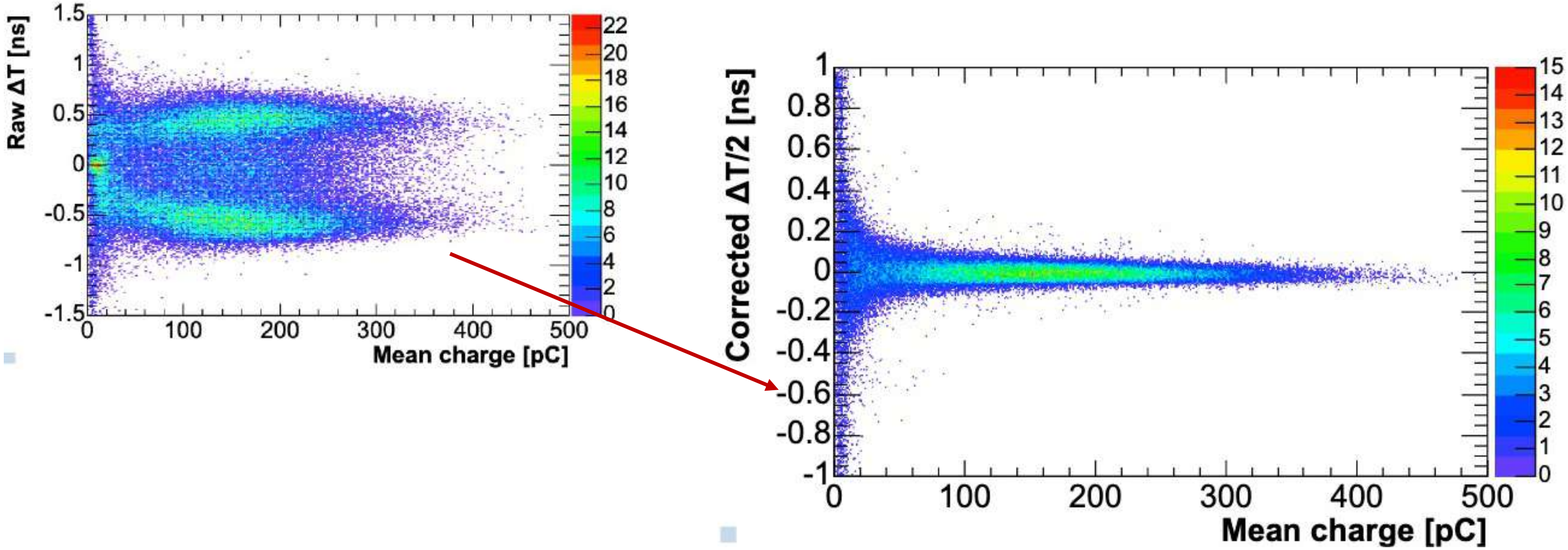
- No significant effects for back-runs
- Similar effects for PbWO4-UF

- 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

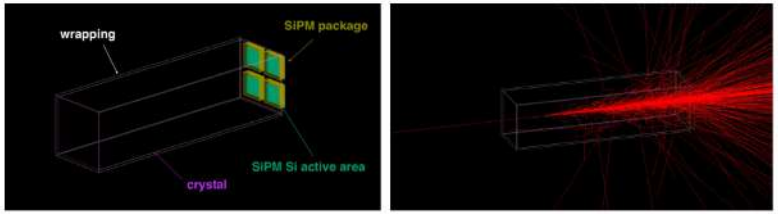
- The front mode shows a peculiar distribution both in time time difference and charge sharing:
  - ➢ the relationship between this two quantities can be used as correction function
  - ➢ Negligible effect in back runs

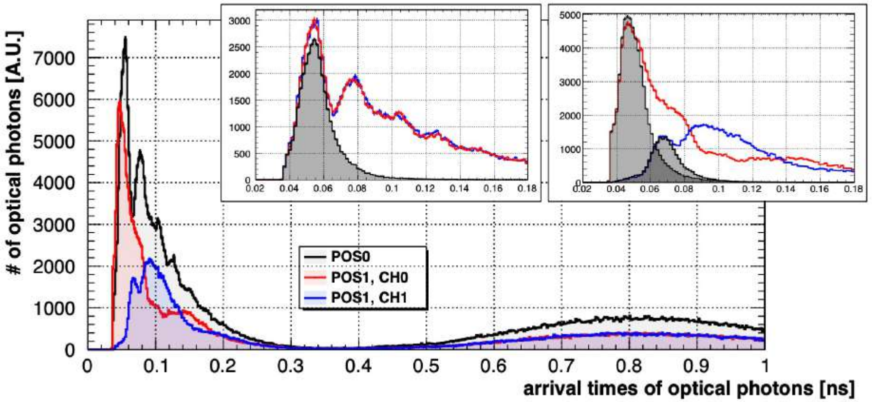


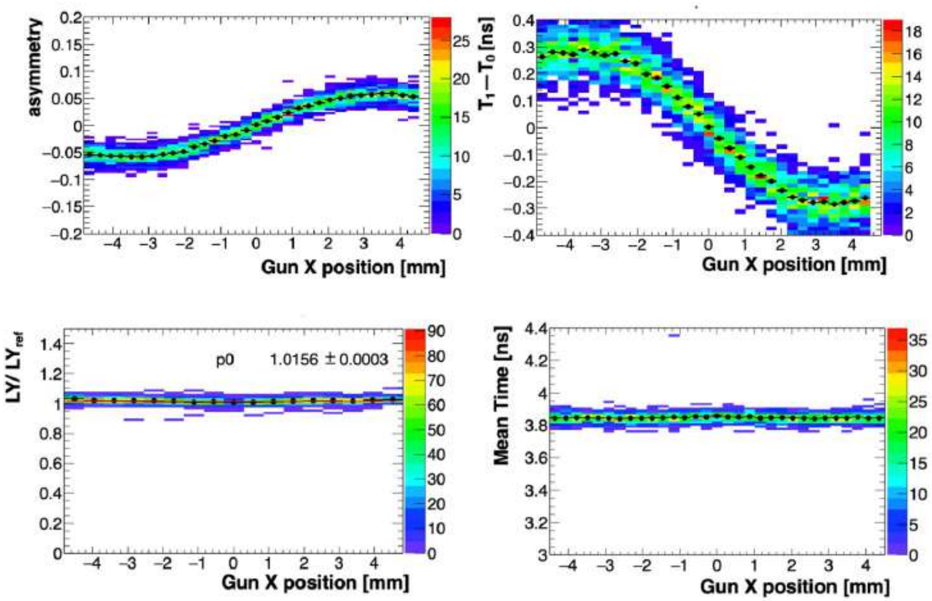


MC validation: optical simulation

- 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

Results

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

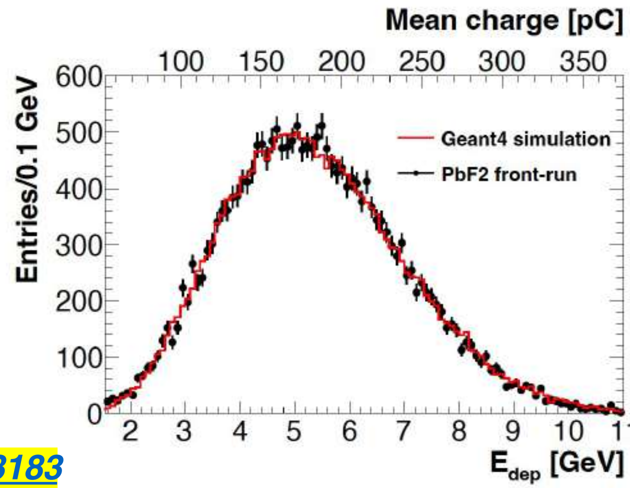
- The BACK run time resolution is better, even after correction, for both crystals.
- PbF_2 outperforms $PbWO_4$-UF despite its higher light output (purely Cherenkov)
- **PbF_2** → σ_{MT} < 25 ps worst-case for E_{dep} > 3 GeV
- **$PbWO_4$-UF** → σ_{MT} < 45 ps worst-case for E_{dep} > 3 GeV

PbF_2

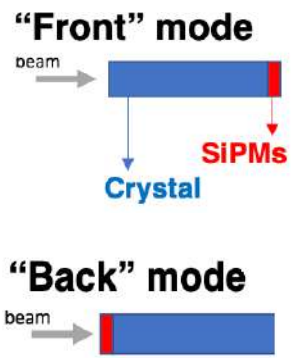
	back-run	front-run
E_{dep} MPV [GeV]	4.26 ± 0.01	4.81 ± 0.03
E_{dep} sigma [GeV]	1.35 ± 0.01	1.46 ± 0.02
pC/GeV	~29.3	~35.6
NPE/MeV	~0.30	~0.30

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