INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

International MUON Collider Collaboration

Crilin - 2022 status report

MUON Collider Collaboration Meeting

Pavia, 19-21 December

D. Paesani on behalf of the Crilin group

Beam Induced Background

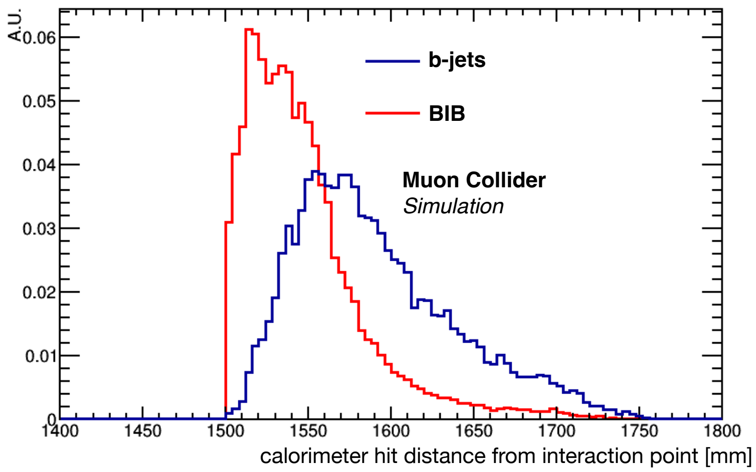
BIB flux on ECAL barrel

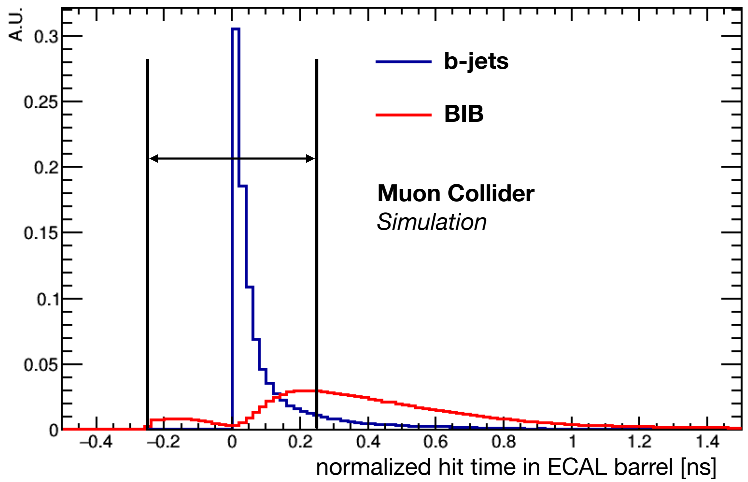
- O(300) hits/cm²/BX
- mostly photons with <E>=1.7 MeV
- Hits w/ asynchronous timing and displaced origin

BIB rejection

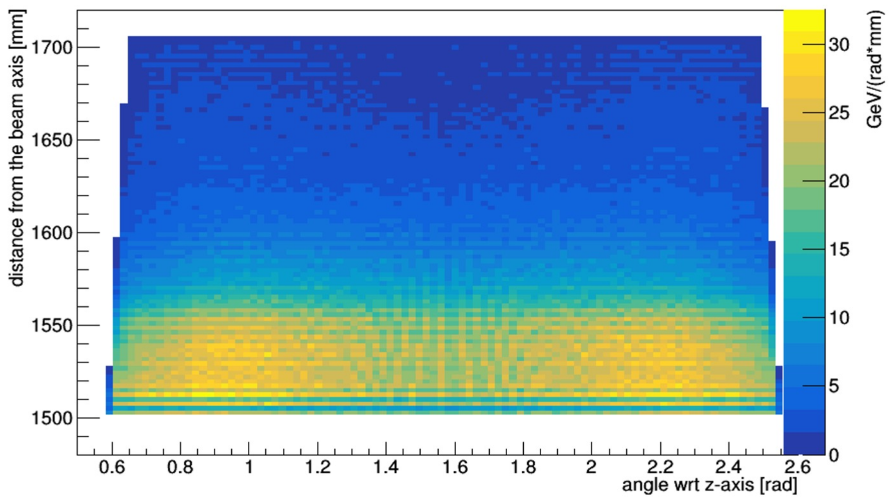
- BIB hist mostly affect the first centimeters of the calorimeter
- Fast response, good timing and longitudinal segmentation are essential for BIB rejection
- Possibility to subtract the BIB from longitudinal measurements cell-by-cell, depending on $<E_{BIB}>$ and $sigma_{BIB}$
- sigmaT < 100 ps → [-250, +250] ps selection window across BX

BIB/b-jet separation





BIB Edep profile (1 BX) @ BIB at √s = 1.5 TeV



Crilin - concept

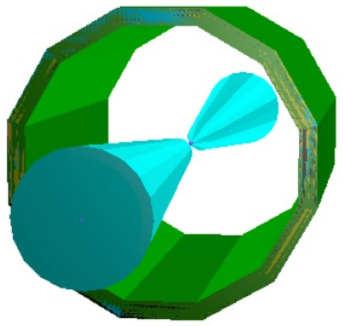
Baseline ECAL barrel solution

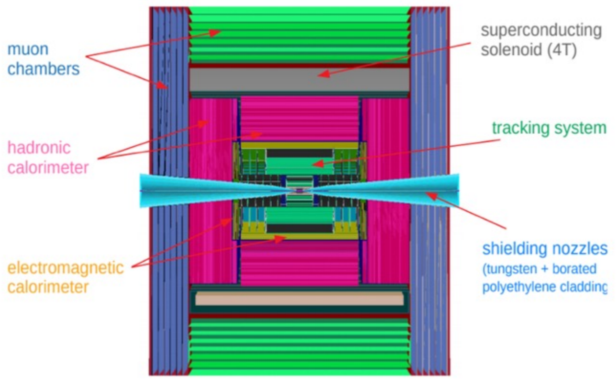
- 40 layers → 1.9 mm W absorber + silicon pad sensors
- ~64M channels w/ 5x5 mm^2 cell granularity
- 22 X0, 1 λi

Cristal Calorimeter with Longitudinal Information

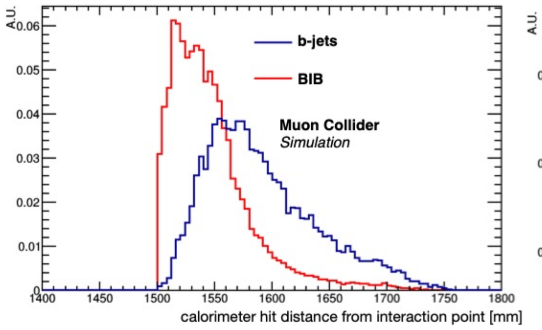
- Alternative solution for Muon Collider ECAL barrel
- High granularity, longitudinal segmentation, excellent timing
- Improved radiation resistance
- Modular and flexible architecture with stackable sub-modules allows for design optimization in many Phyiscs scenarios

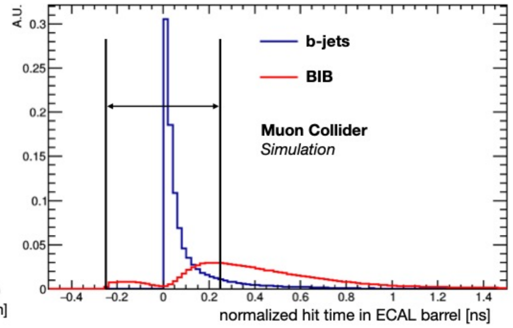
- 1x1x4 cm^3 PbF2 Cherenkov crystals + dual, UV-extended 10µm SiPM readout
- optimal rejection of beam-induced background
- Supports particle flow algorithms



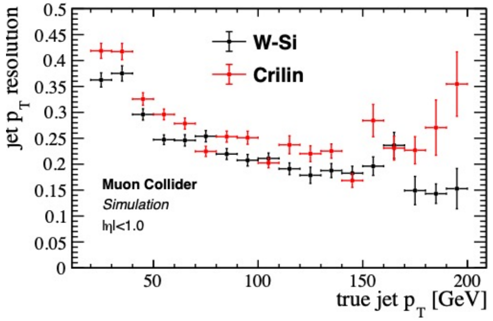


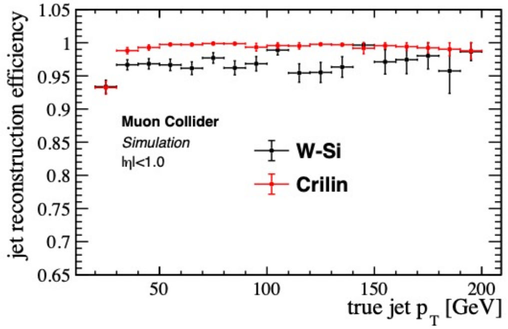
BIB/b-jet separation

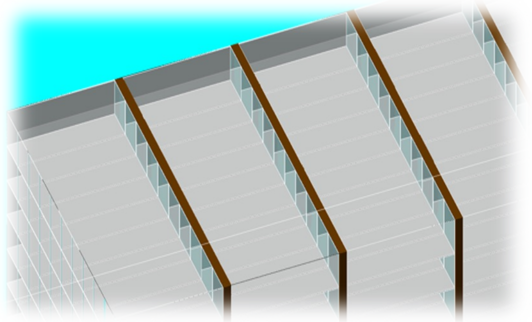


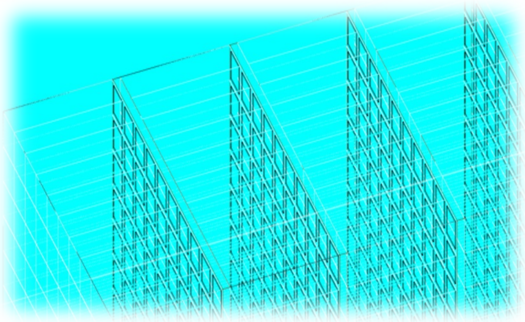


Crilin vs W-Si









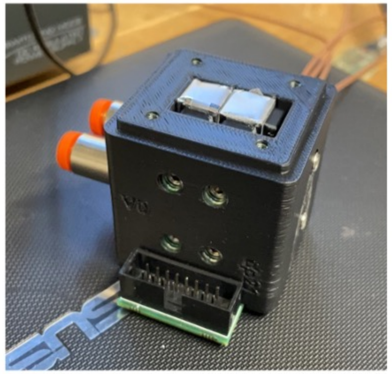
R&D status

Prototype versions
- Proto-0 (2 crystals + 4 SiPMs)
- Proto-1 (3x3 crystals + 36 SiPMs) x2 layers

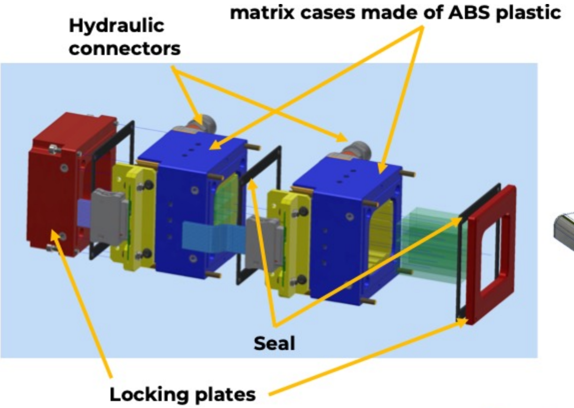
Front-end electronics
- Design completed
- Boards production complete → **see next slides**
- QC will start soon

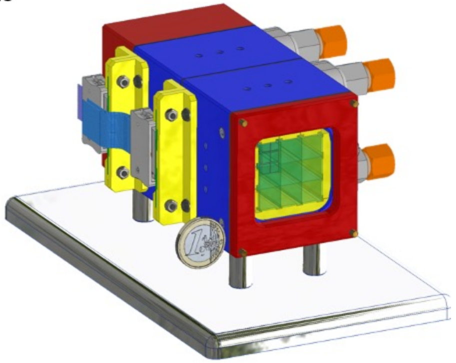
Radiation hardness campaign
- 10 and 15 um px-size SiPM tests up to 10^{14} n-1MeV-eq/cm^2 (ENEA-FNG)
- TID tests on PbF2 crystals w/ various wrapping configuration up to 4 Mrad w/ Co-60 photons (ENEA-Calliope) and 10^{13} n-1MeV-eq/cm^2 (ENEA-FNG)

Test beam campaigns
- Proto-0 H2 2020 (e- and photons up to 120 GeV)
- Proto-0 at CERN H2 2022 → **this talk**
- LNF-BTF (April) and CERN (August) → **upcoming**

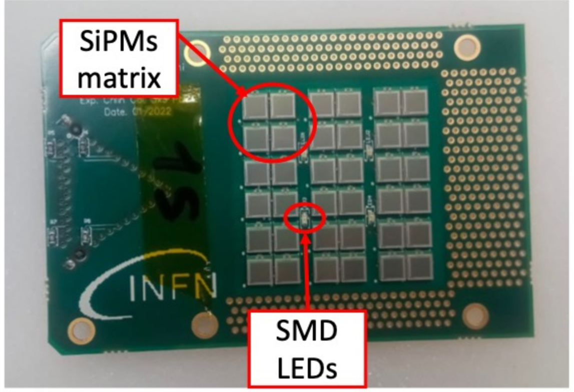


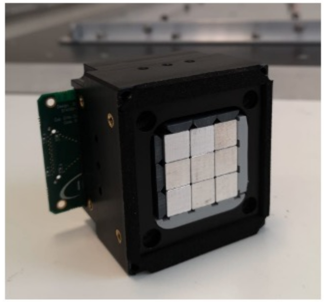
Proto-0

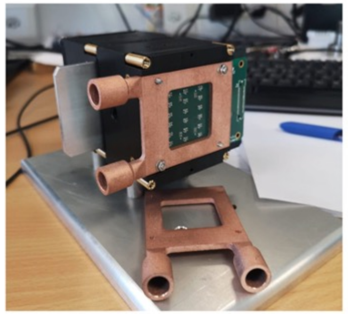




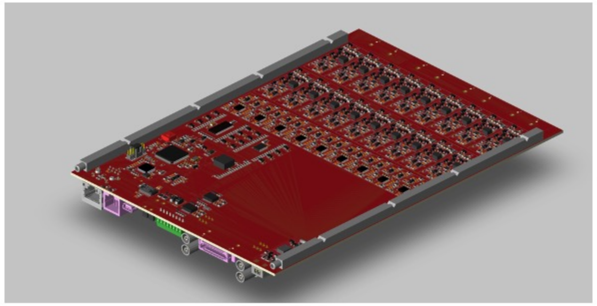
Proto-1



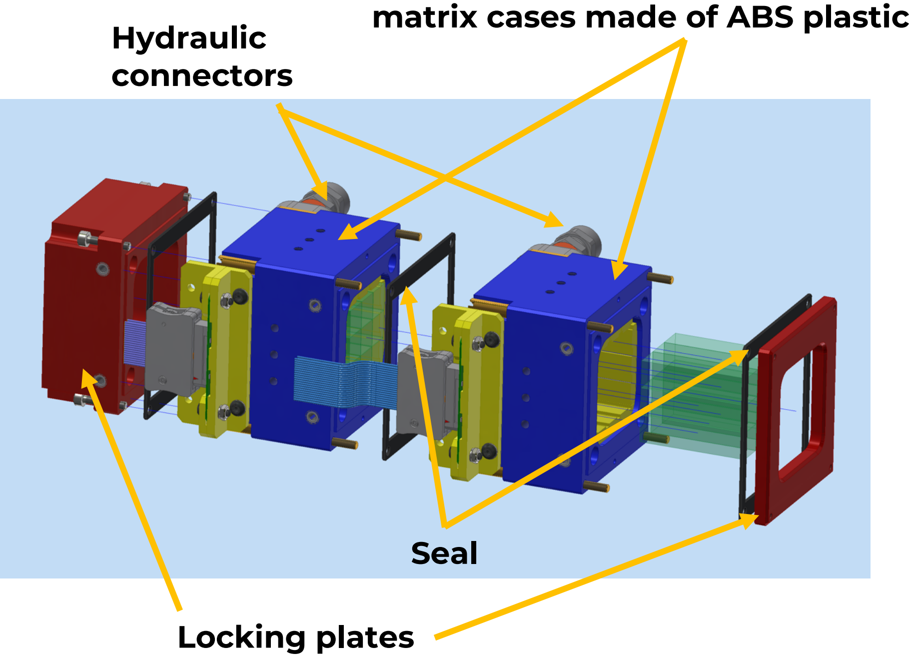




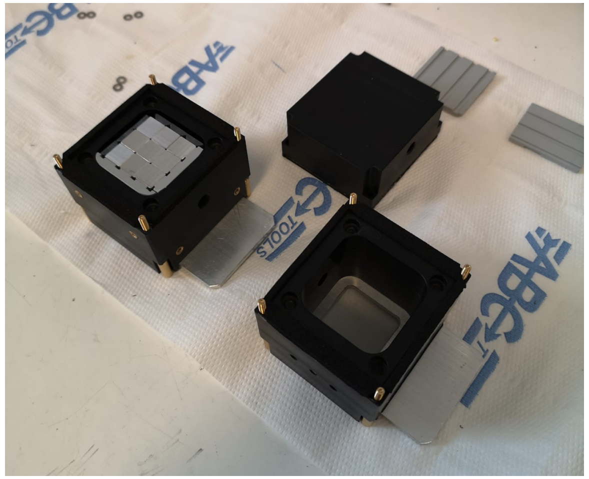
Copper exchanger

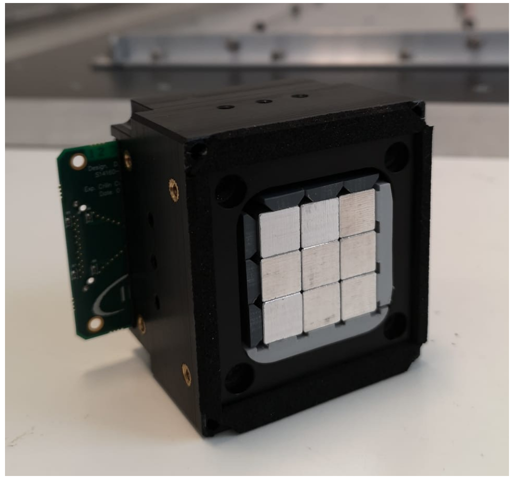


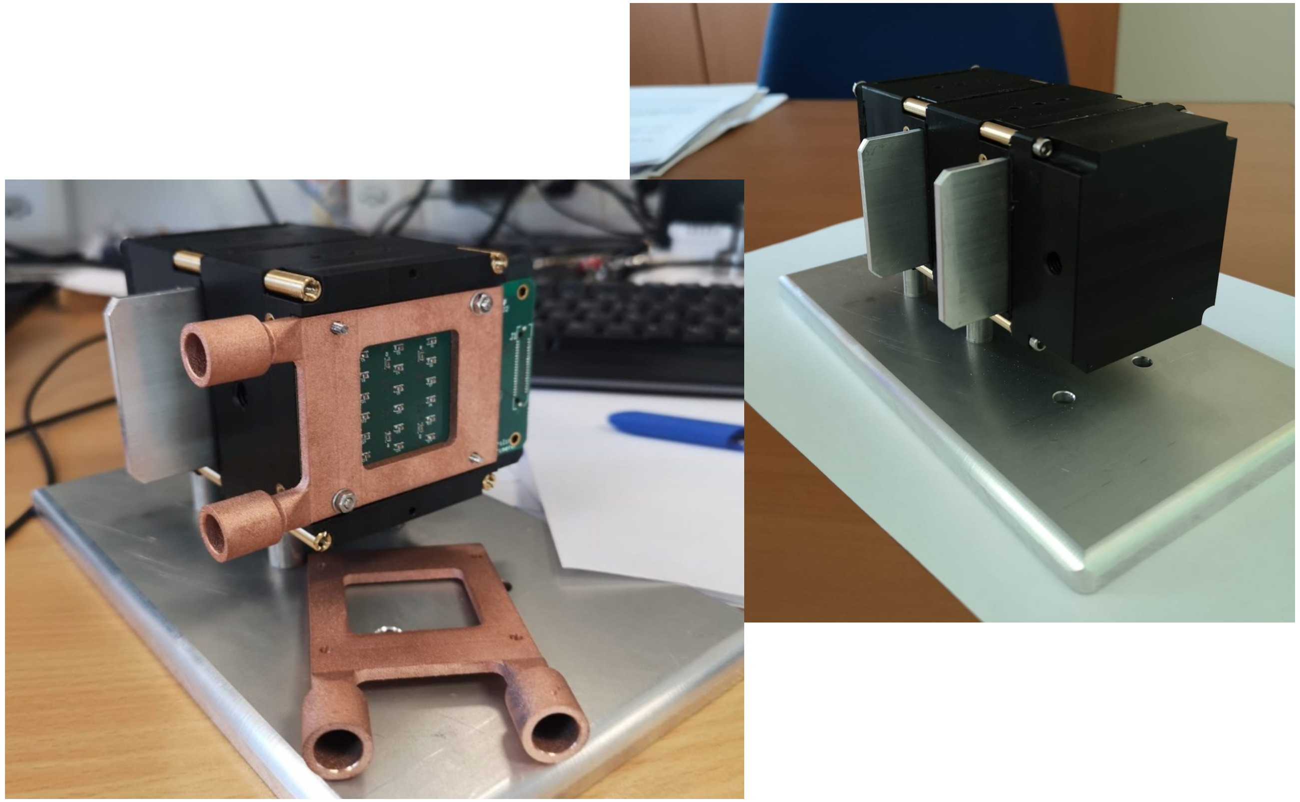
Proto-1 → Mechanics



- **350 mW / crystal** thermal load
- Additively manufactured micro-channel heat exchanger for liquid coolant circulation



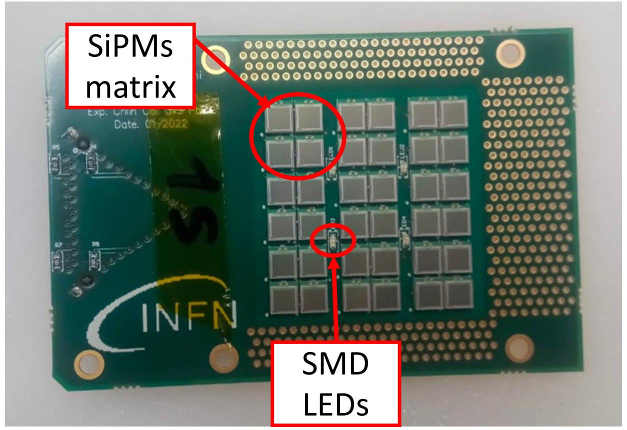


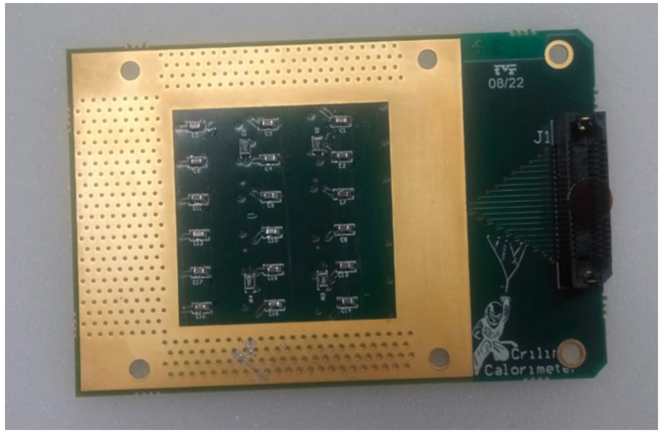


Proto-1 → Electronics

SiPM board

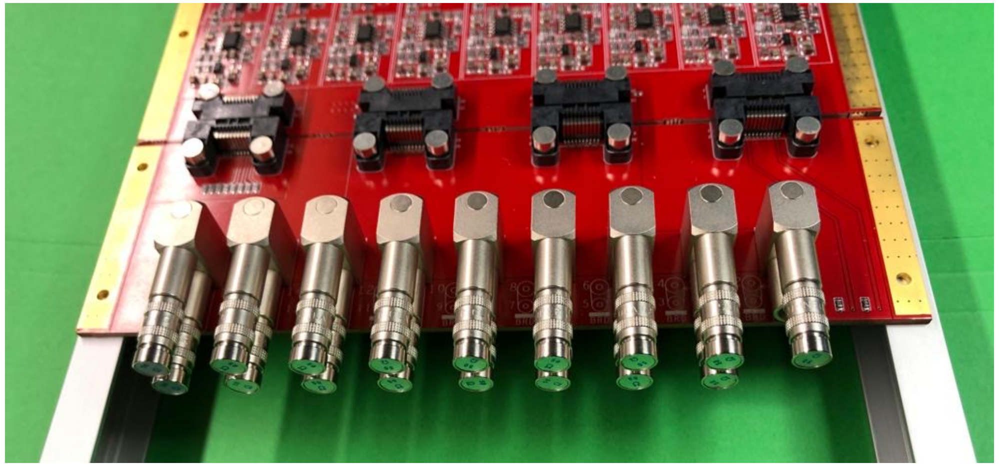
- Custom SiPM array board
- 36x 10 μm Hamamatsu SMD SiPMs
- 4 SiPM/crystal (2x 2-series connection)
- 2 independent readout channels / cell
- Integrated SiPM matrix cooling system
- 4x SMD blue LEDs nested between the photosensor packages for SiPM diagnostics

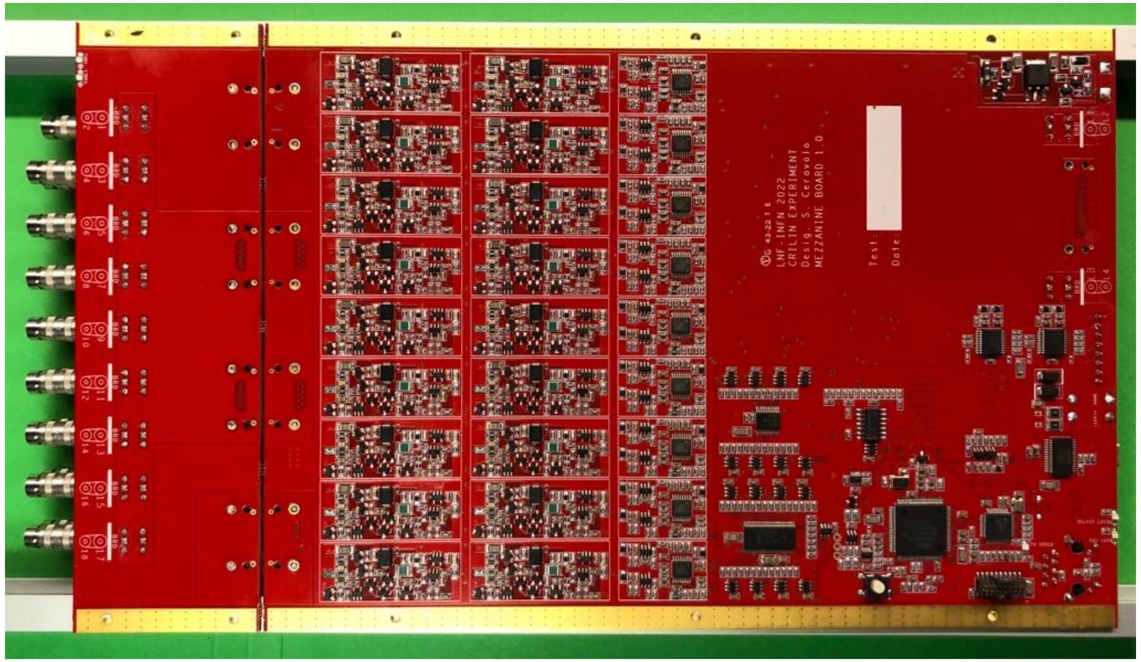




FEE/controller board

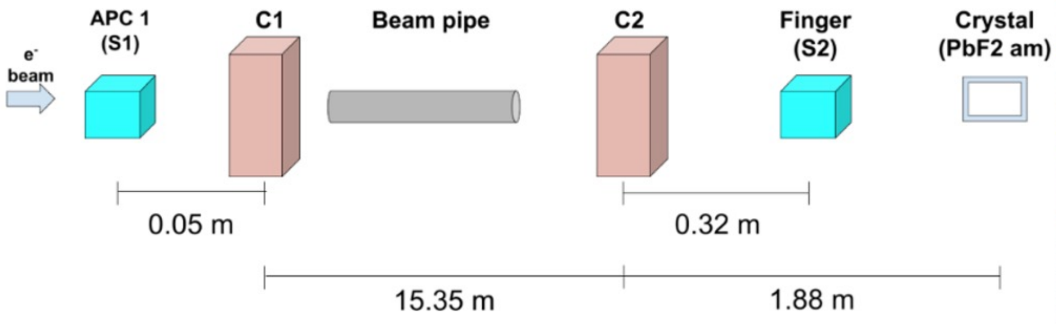
- 18x readout channels
- Amplification, shaping and individual bias regulation
- Slow control (temperature, bias and current monitors)

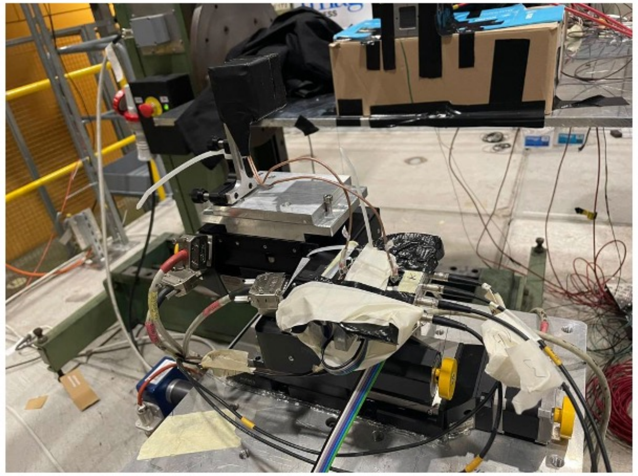




2022 Beam Test report

Setup and beams



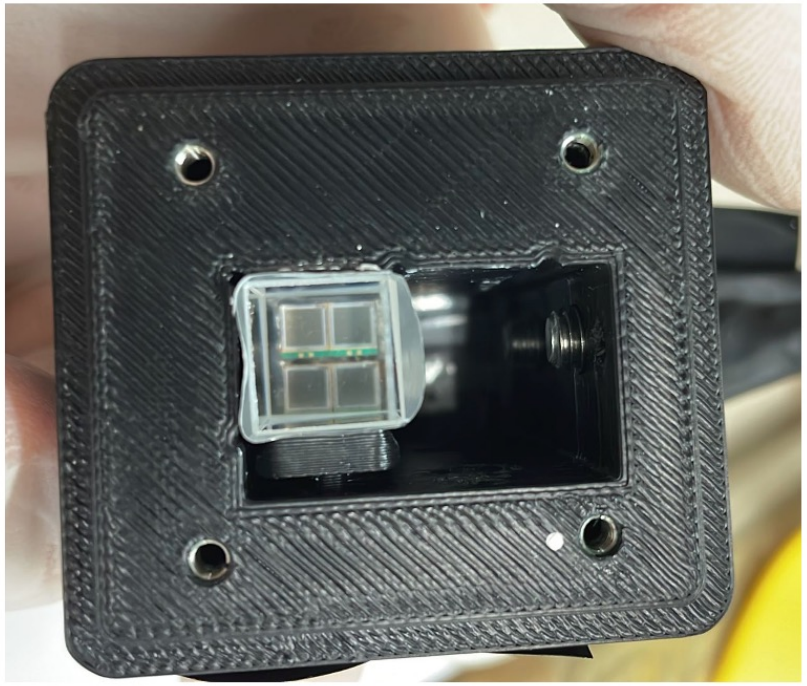


Beam + DAQ Setup

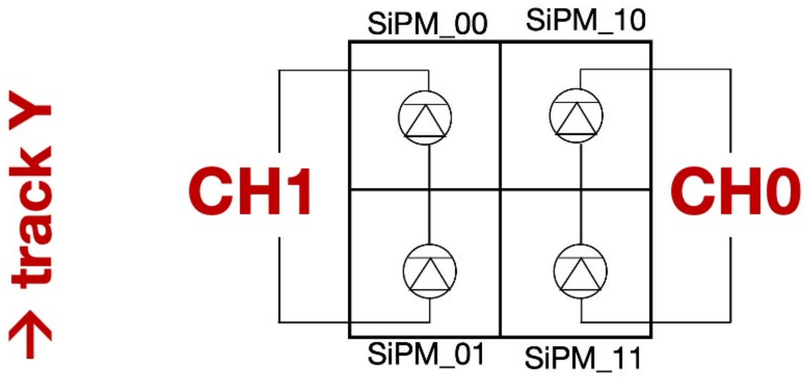
- Beam: e- 120 GeV
- C1, C2 → Si strip telescope
- 2x MCPs behind DUT
- S1, S2 scintillator fingers
- Trigger: APC1 x C1_single_clu x C2_single_clu
- 5 Gsps DRS4 digitiser

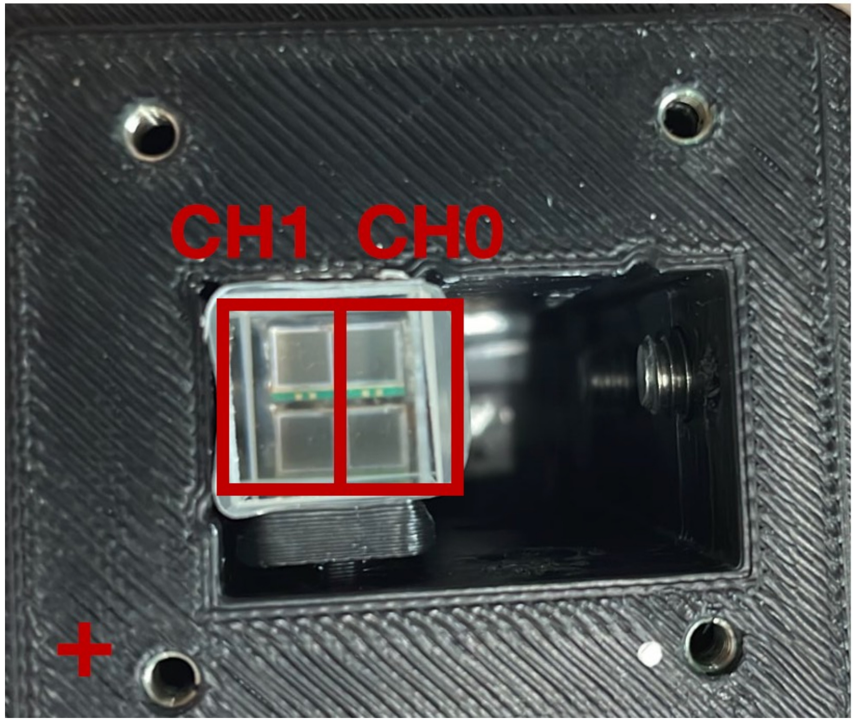
Crilin Proto-0 setup

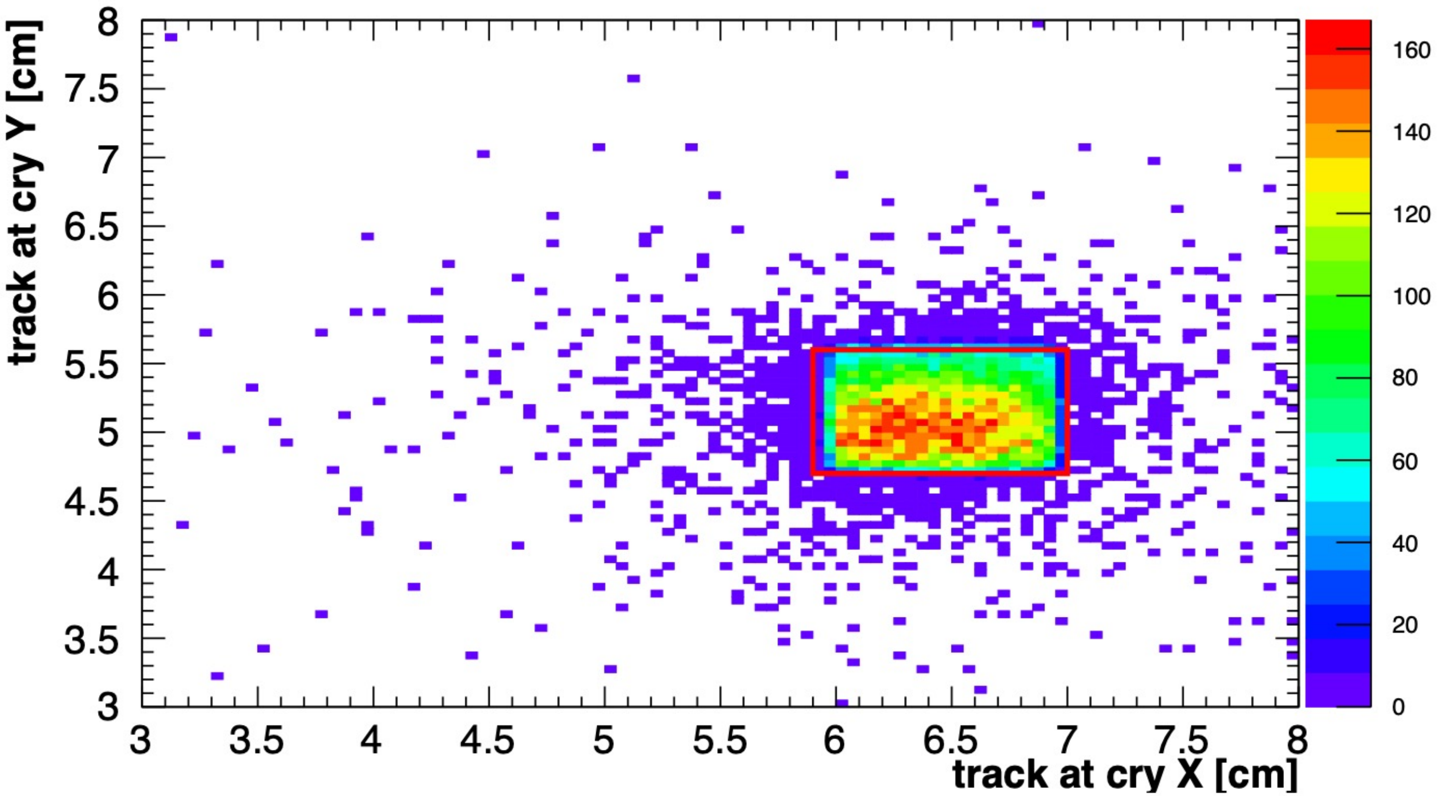
- Single crystal
- 15 um px SiPMs
- Electronics gain = 4
- Cristal option 0: PbF2
- Cristal option 1: PWO-UF
- Orientation: front or back side wrt beam direction



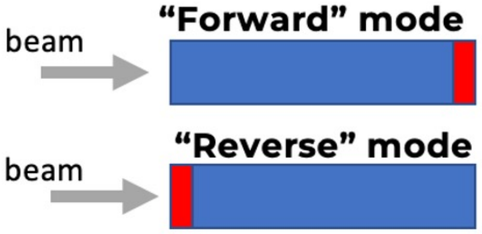
Tracking and coordinates







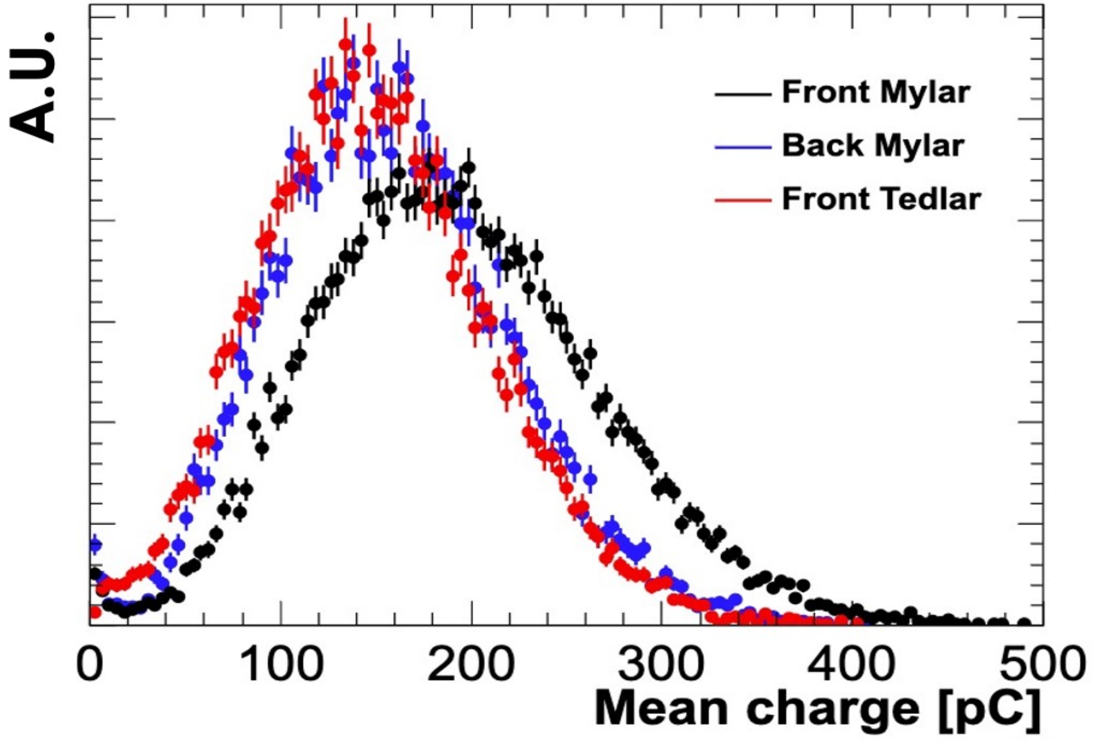
→ track X

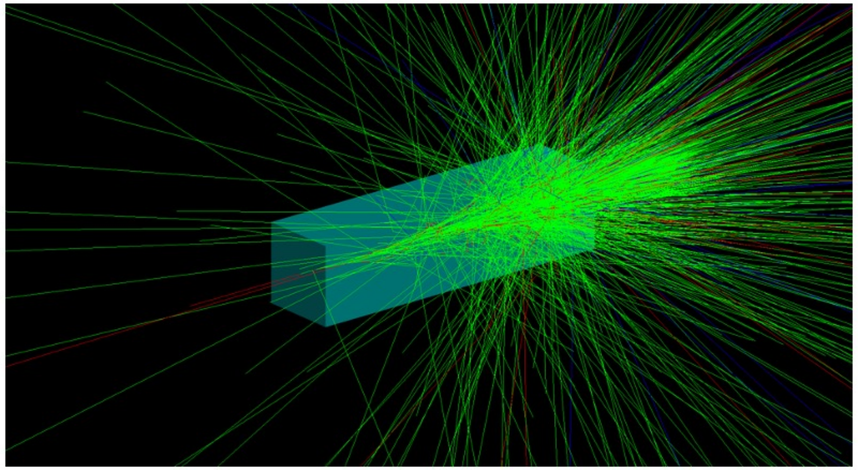


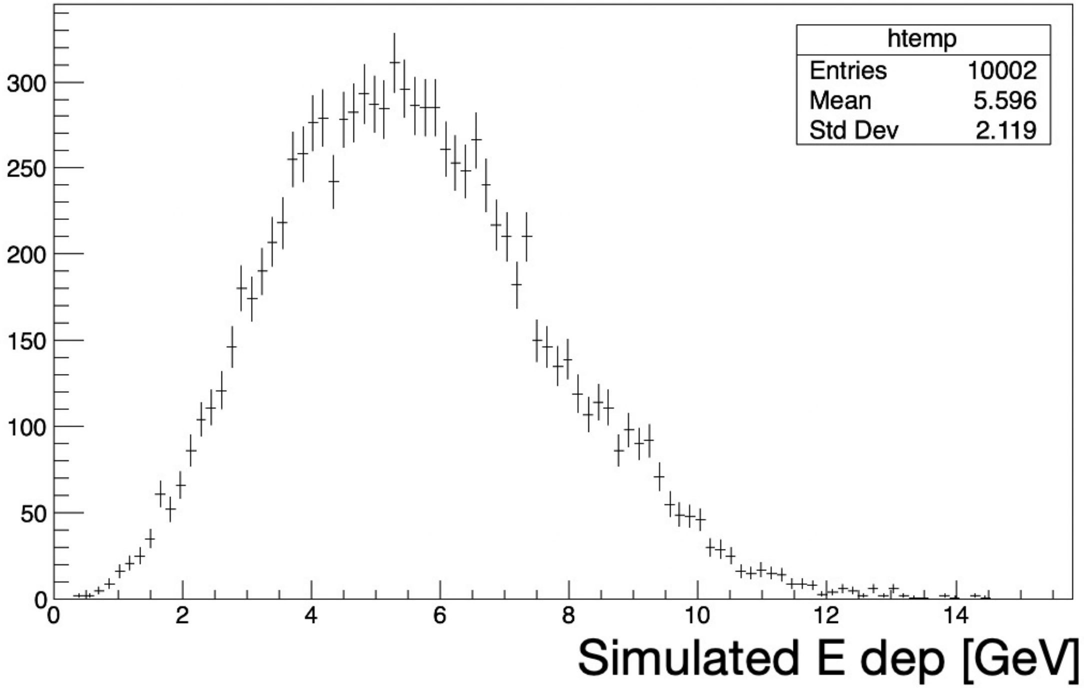
First idea of E scale

Energy scale

- Simulated e- 120 GeV
- Cut on inner fiducial region
- O(5 GeV) most probable deposit
- A first idea of our energy scale

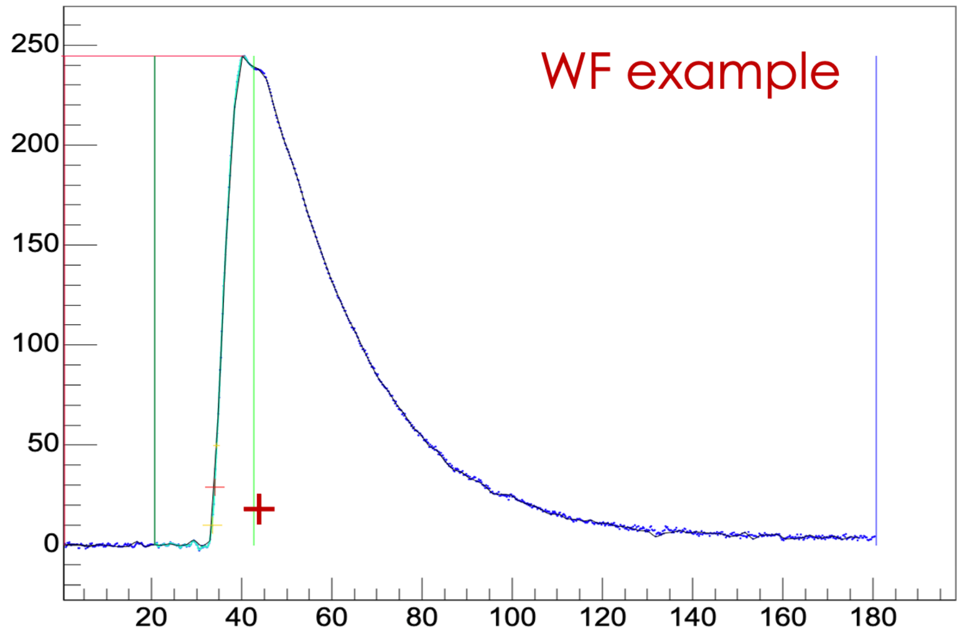


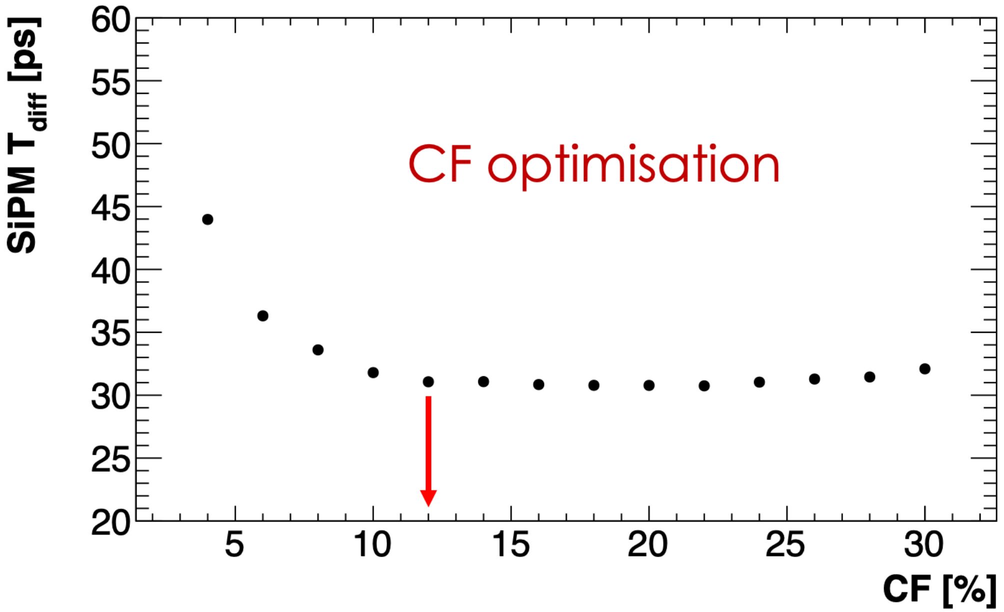


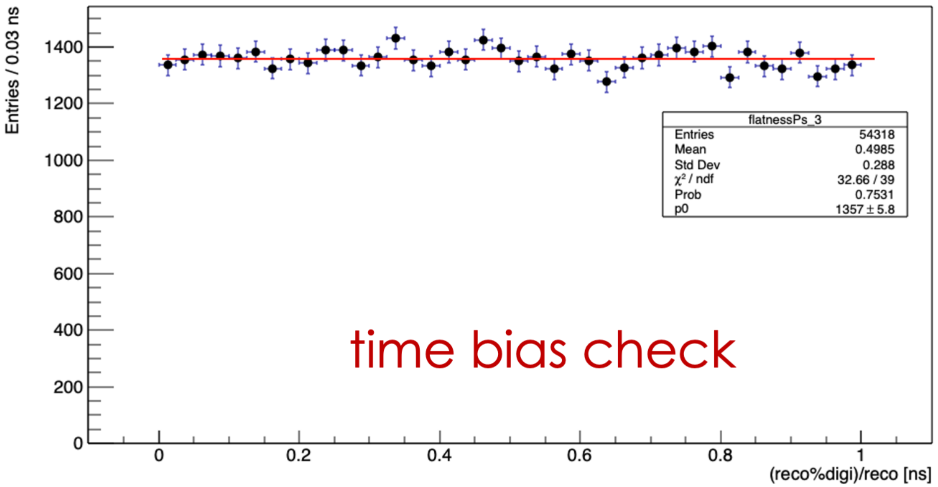


Waveform reconstruction

- Timing reconstruction via TSpline interpolation + CF
- CF=12% for both CHs, after optimisation

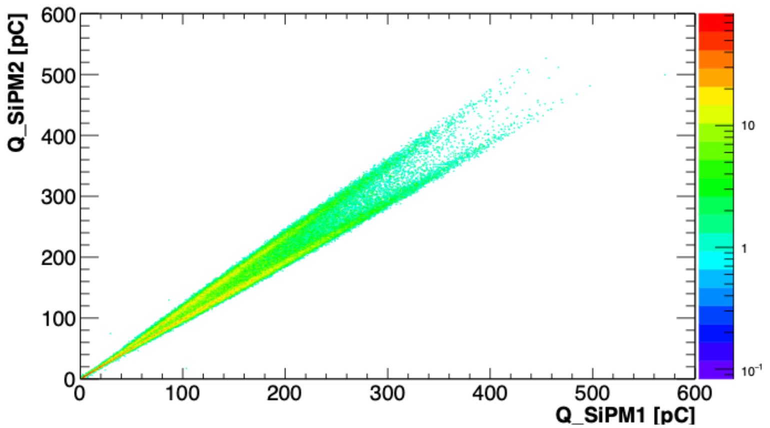


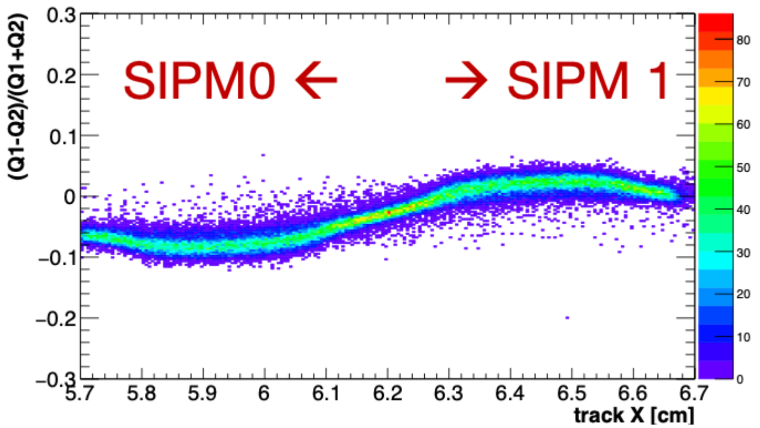


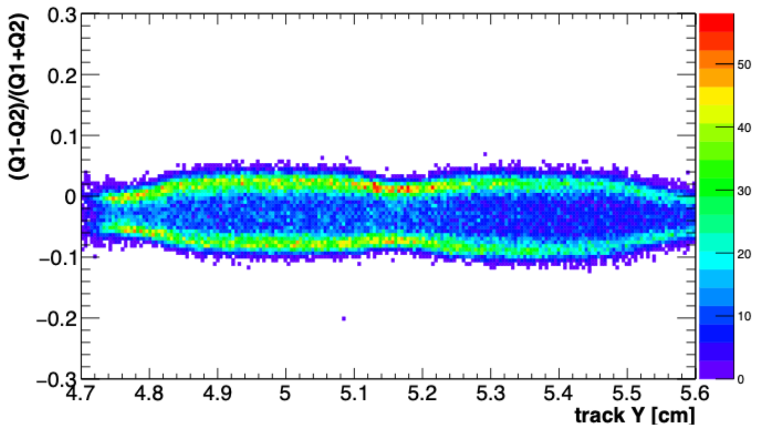


PbF2 → charge

FRONT



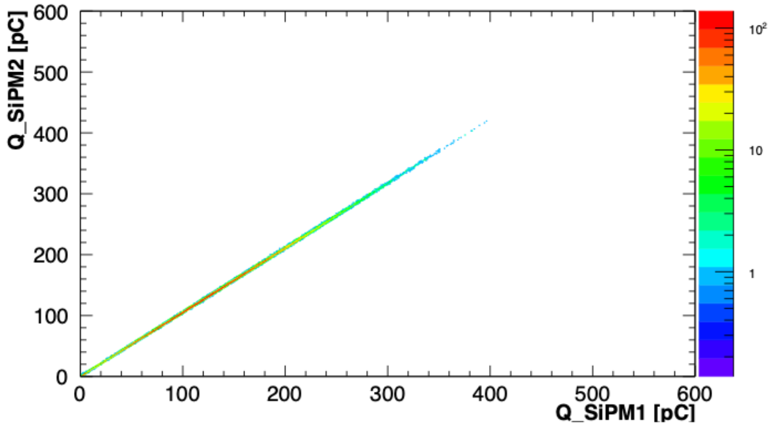


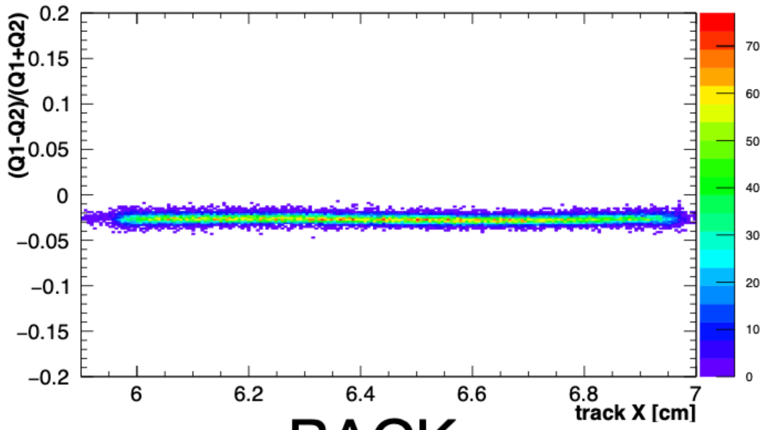


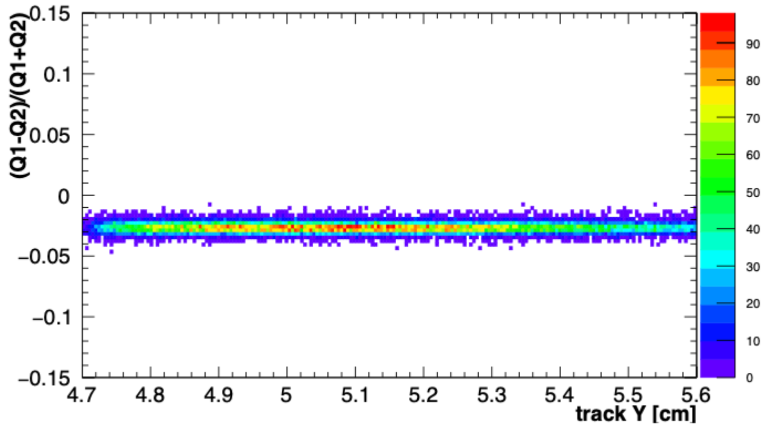
Q0 vs Q1

Q sharing vs X

Q sharing vs Y

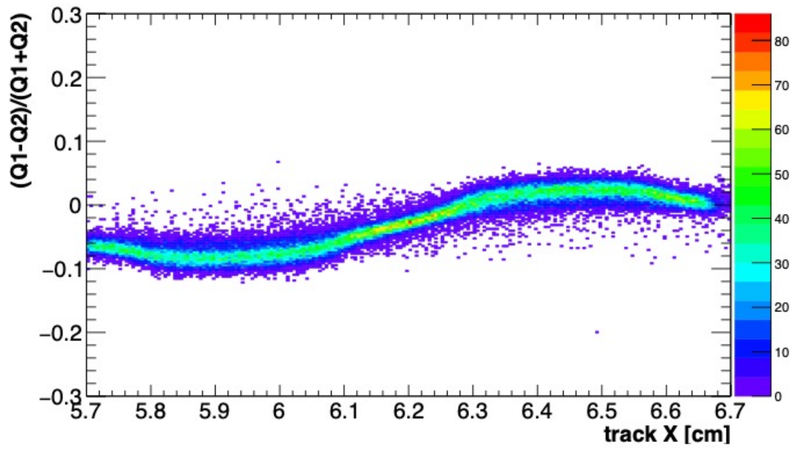




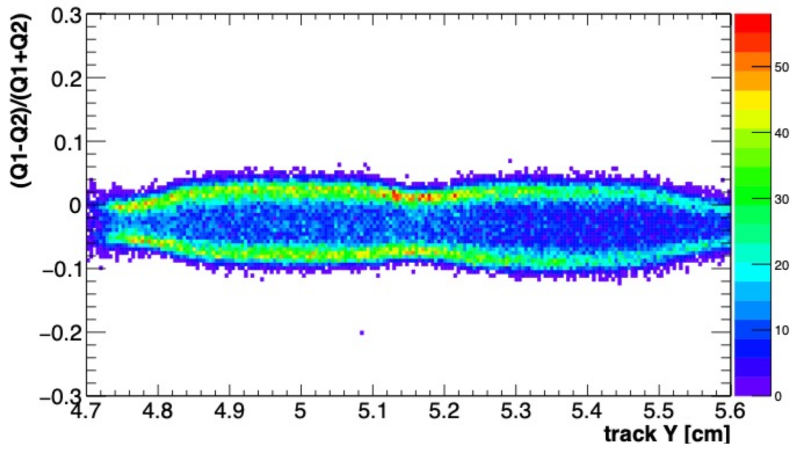


BACK

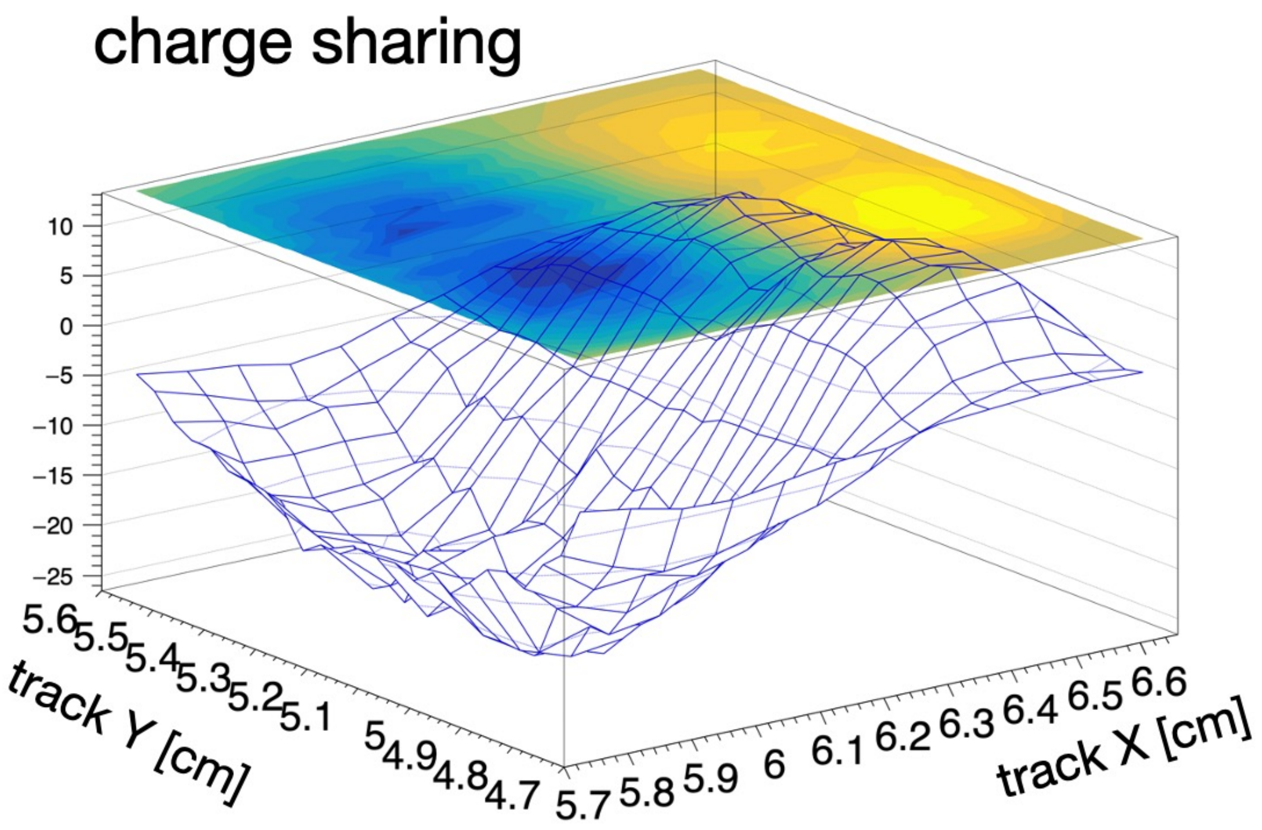
PbF2 → charge



(Q1-Q2)/(Q1+Q2)
track X [cm]



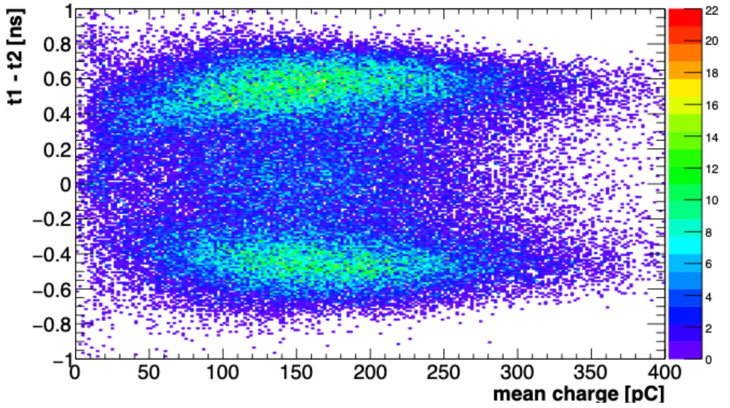
(Q1-Q2)/(Q1+Q2)
track Y [cm]



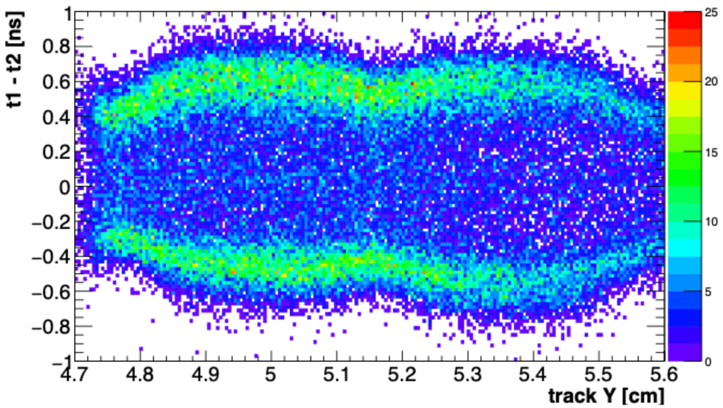
charge sharing
track Y [cm]
track X [cm]

PbF2 → time

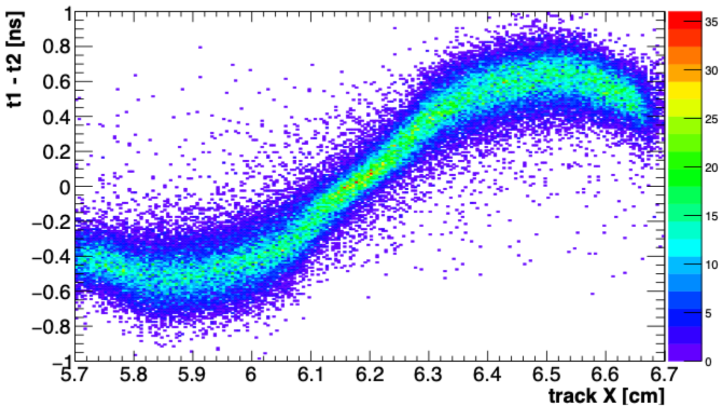
FRONT



deltaT : meanQ

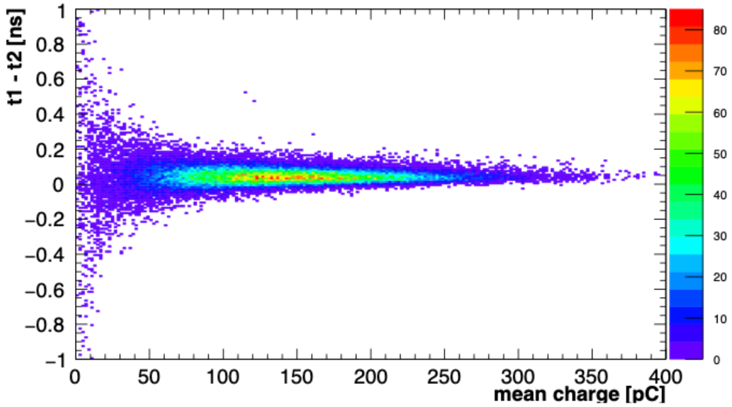


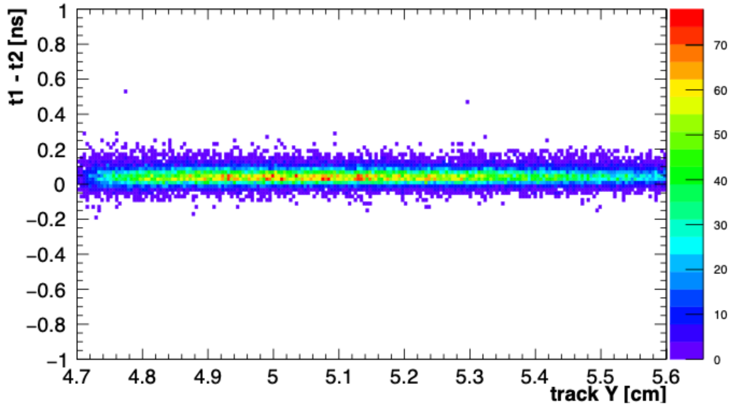
deltaT : Y

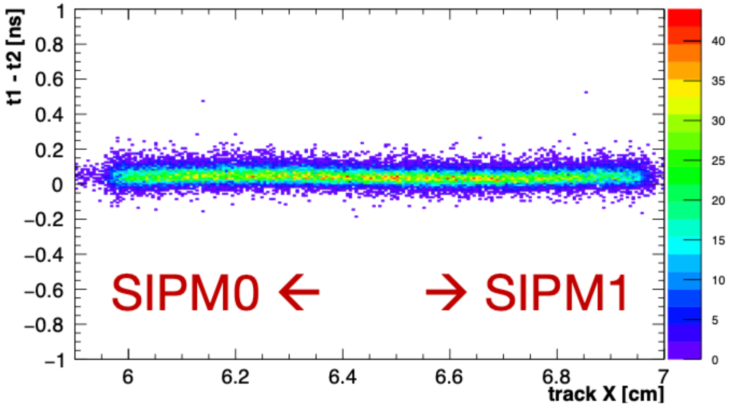


deltaT : X

BACK

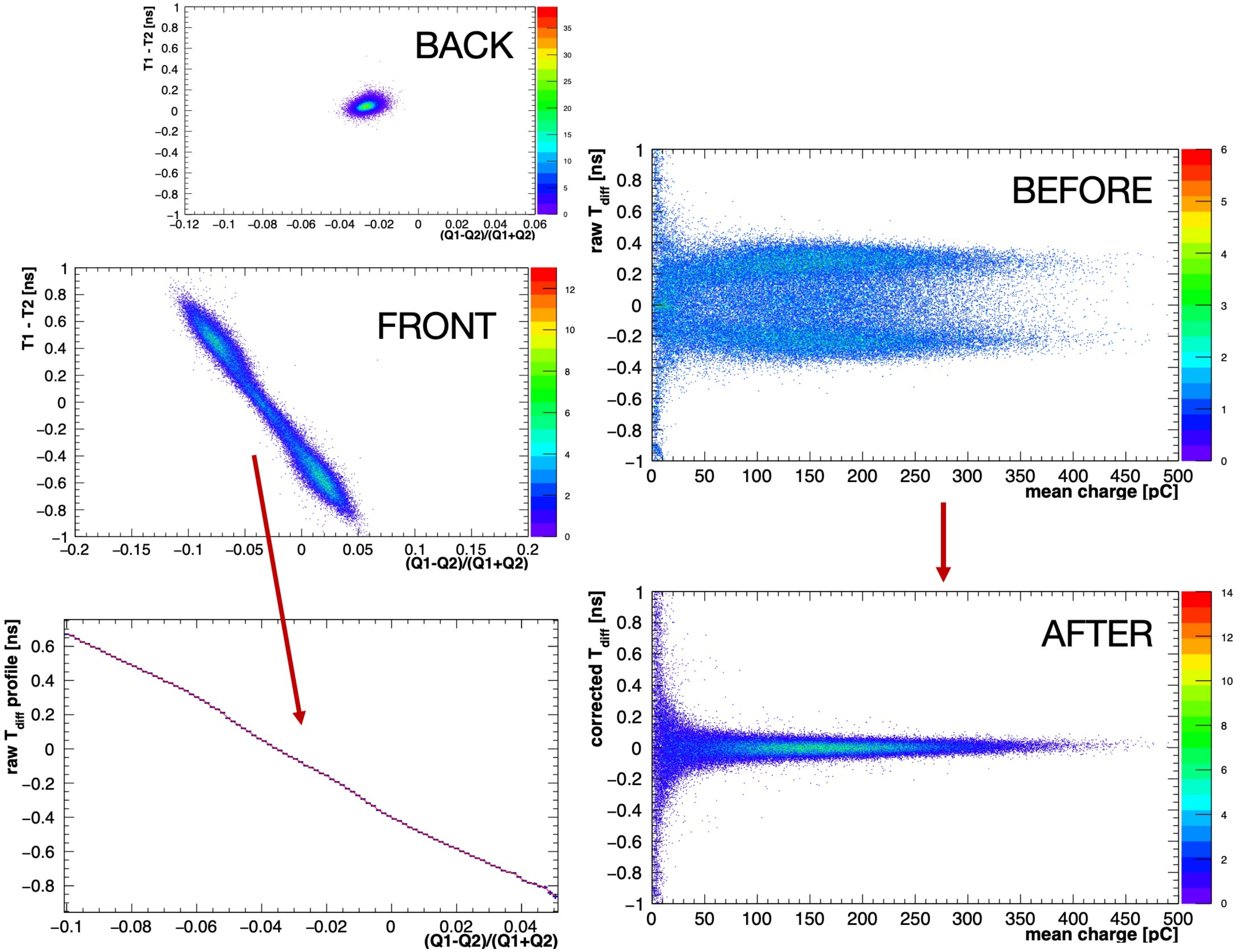






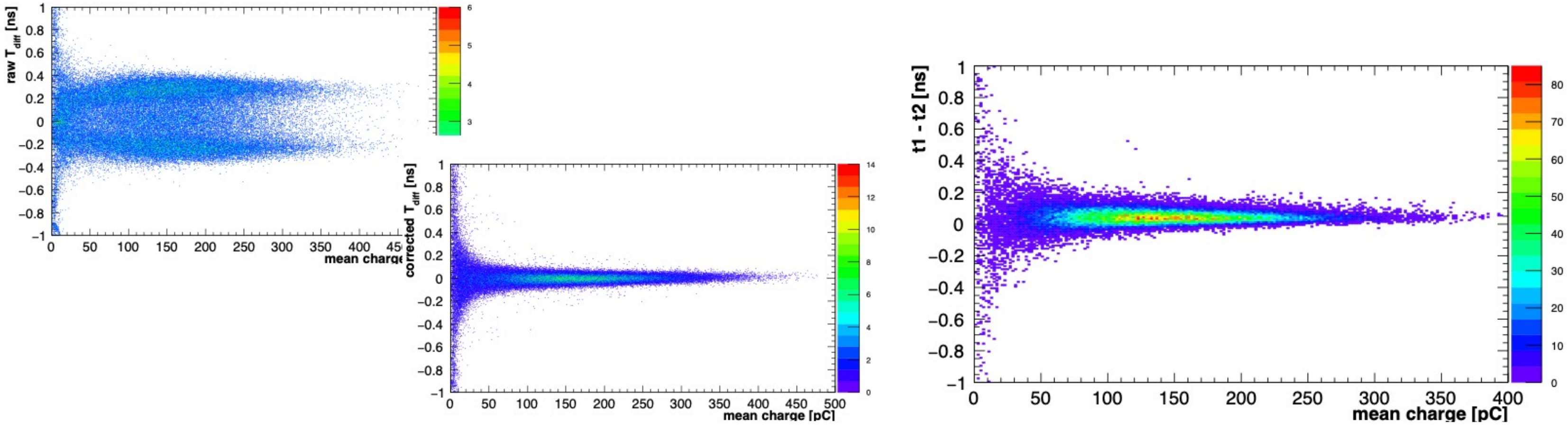
PbF2 → time:charge

- For **FRONT** runs, a clear positional effect of reconstructed time vs beam position is found
- Negligible effect for **BACK** runs
- Cherenkov light propagation is the culprit
- To estimate timing resolution via CH0 and CH1 timing differences, a correction was tried
- deltaT corrected using charge sharing information for **FRONT** runs

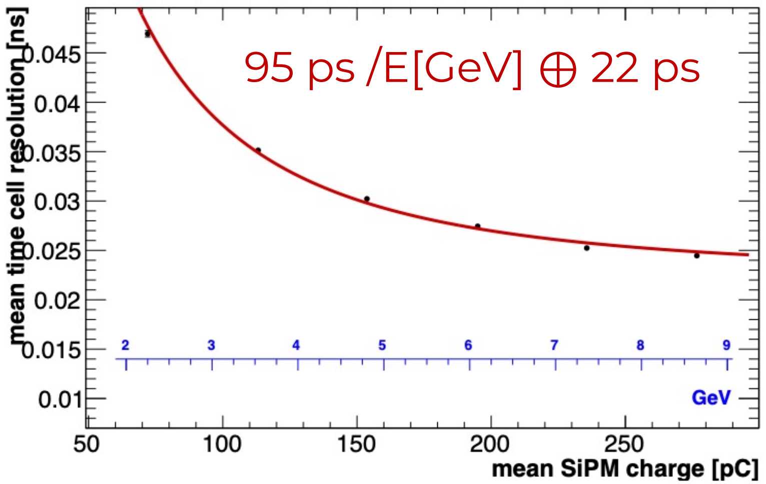


PbF2 → time resolution

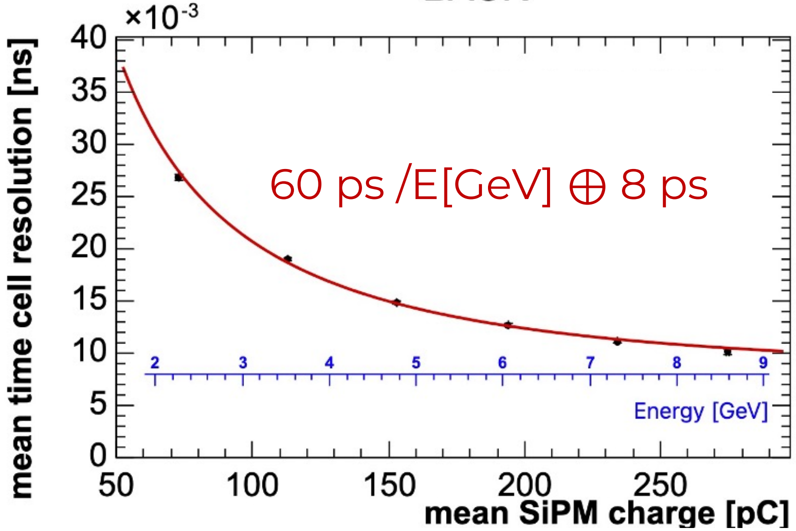
- Timing resolution as sigma of (T1-T2)/2 distributions
- Timing resolution is better for BACK runs, even after correction



FRONT - CORRECTED

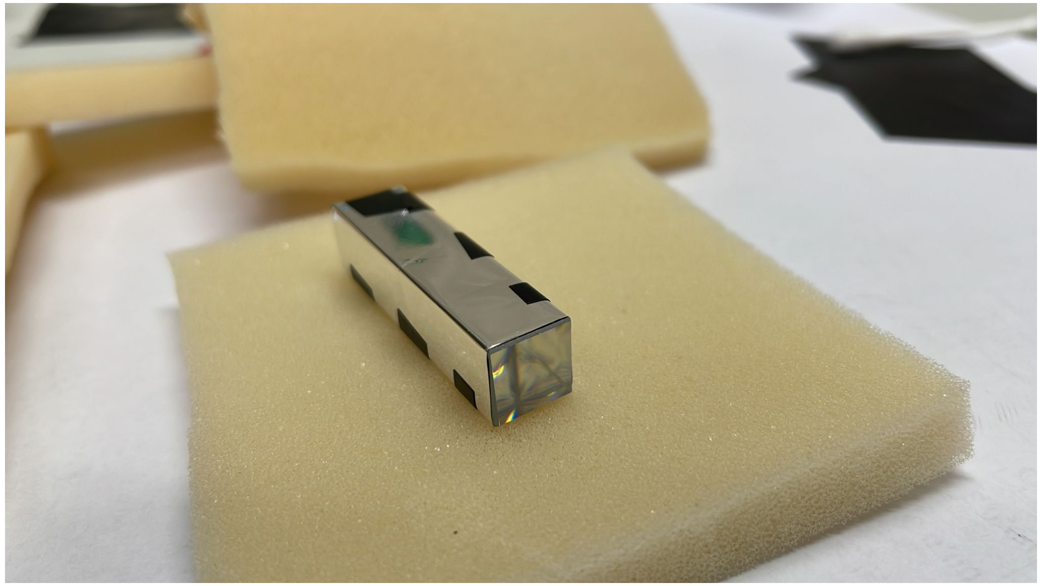


BACK



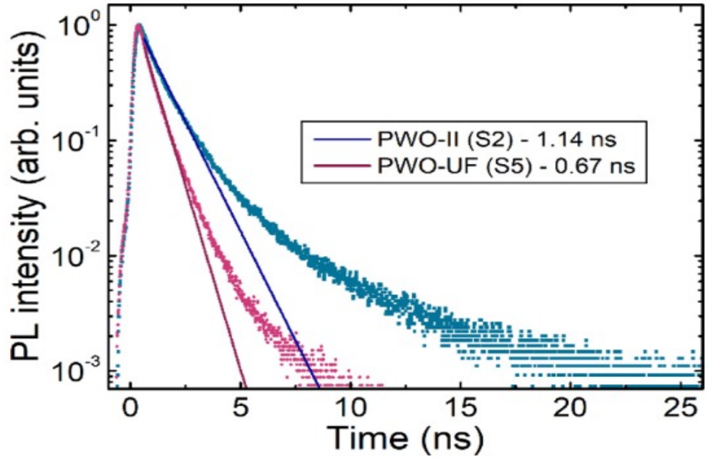
Alternative crystal : PWO-UF

- Alternative crystal choices are being considered
- **Critur → PbWO-UF**
- Excellent density
- Better LY
- Fast response
- 10^7 rad TID resistant → to be validated



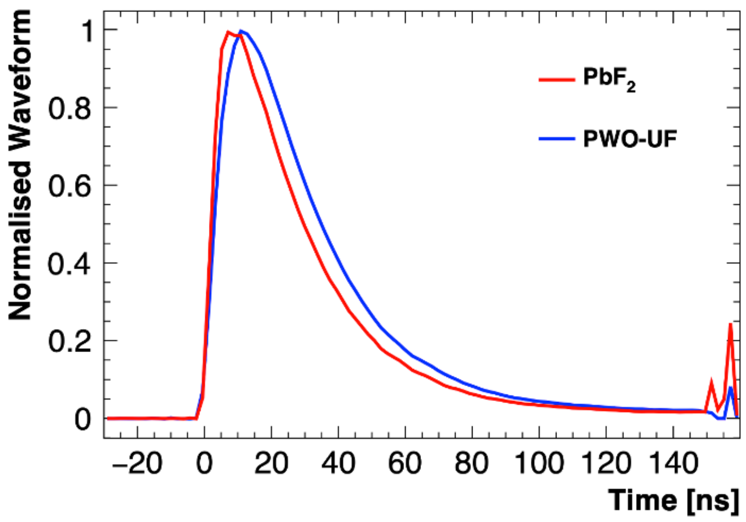
For reference

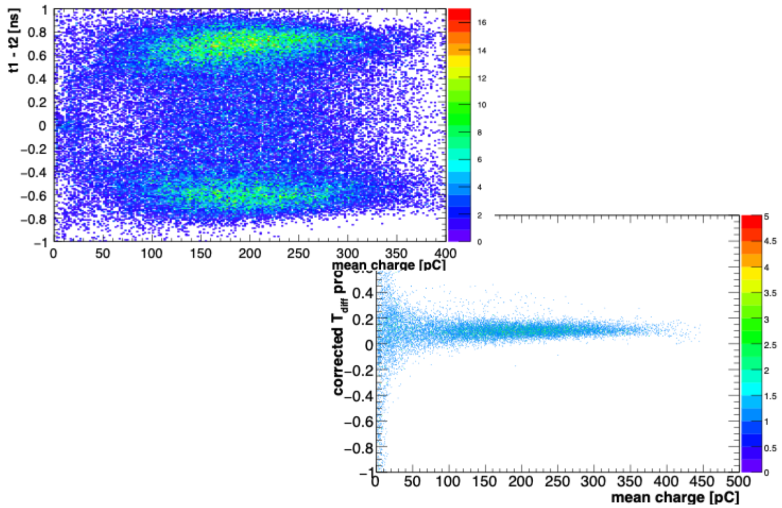
PWO-UF (ultra-fast):
Dominant emission with $\tau < 0.7$ ns
M. Korzhik et al., NIMA 1034 (2022) 166781

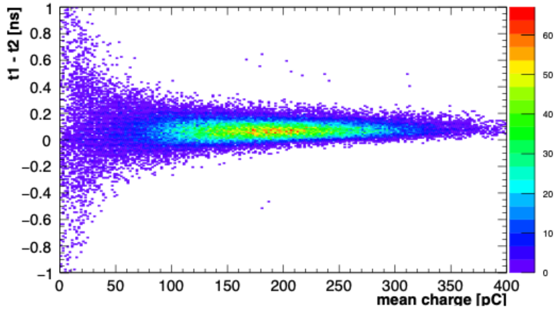


PWO-UF → results

- Same techniques as before used for PWO, similar results
- Timing resolution is worse for PWO, despite almost 2x increase in LO

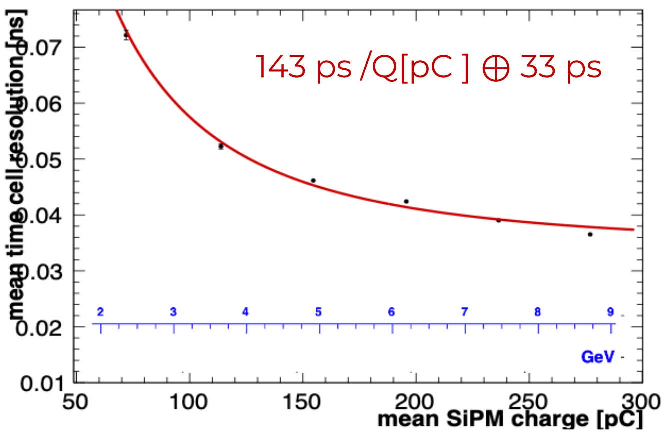


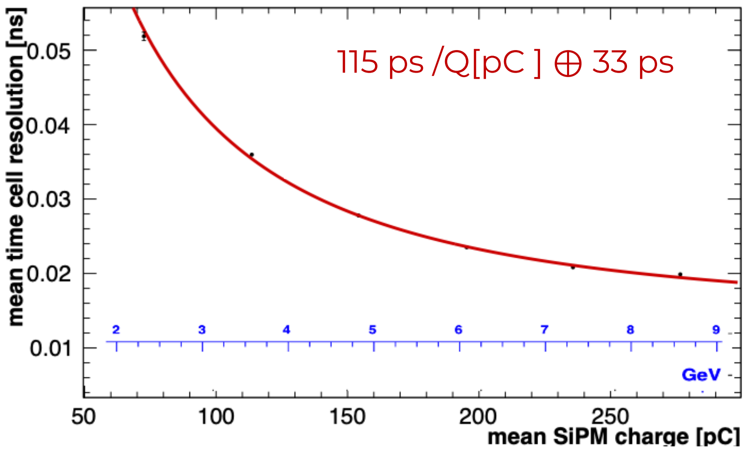




FRONT - CORRECTED

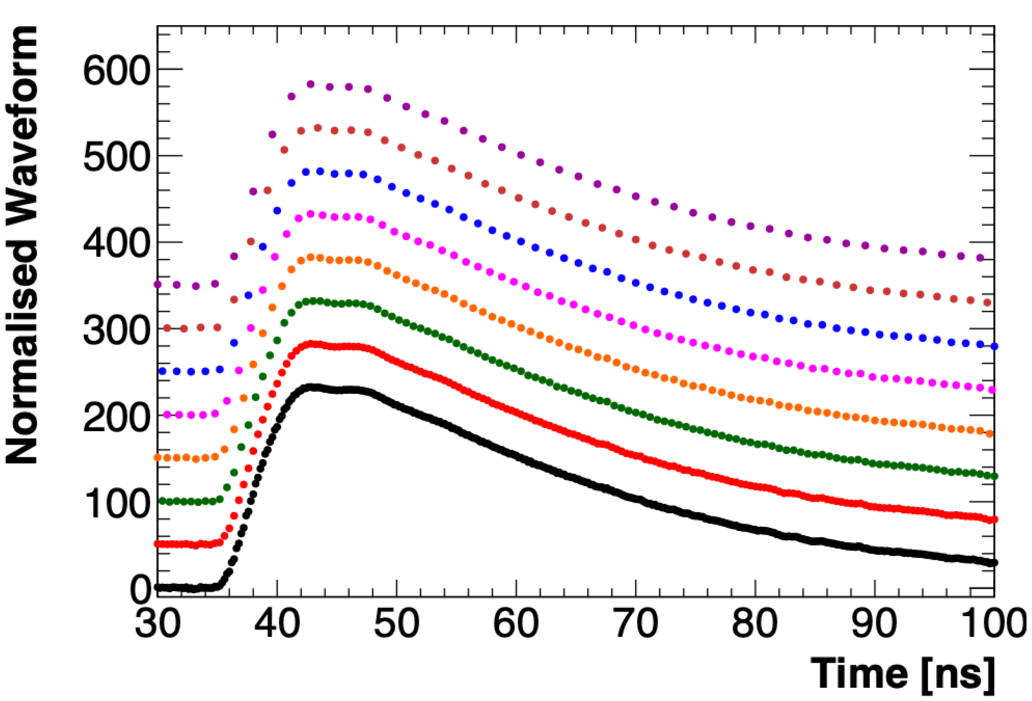
BACK

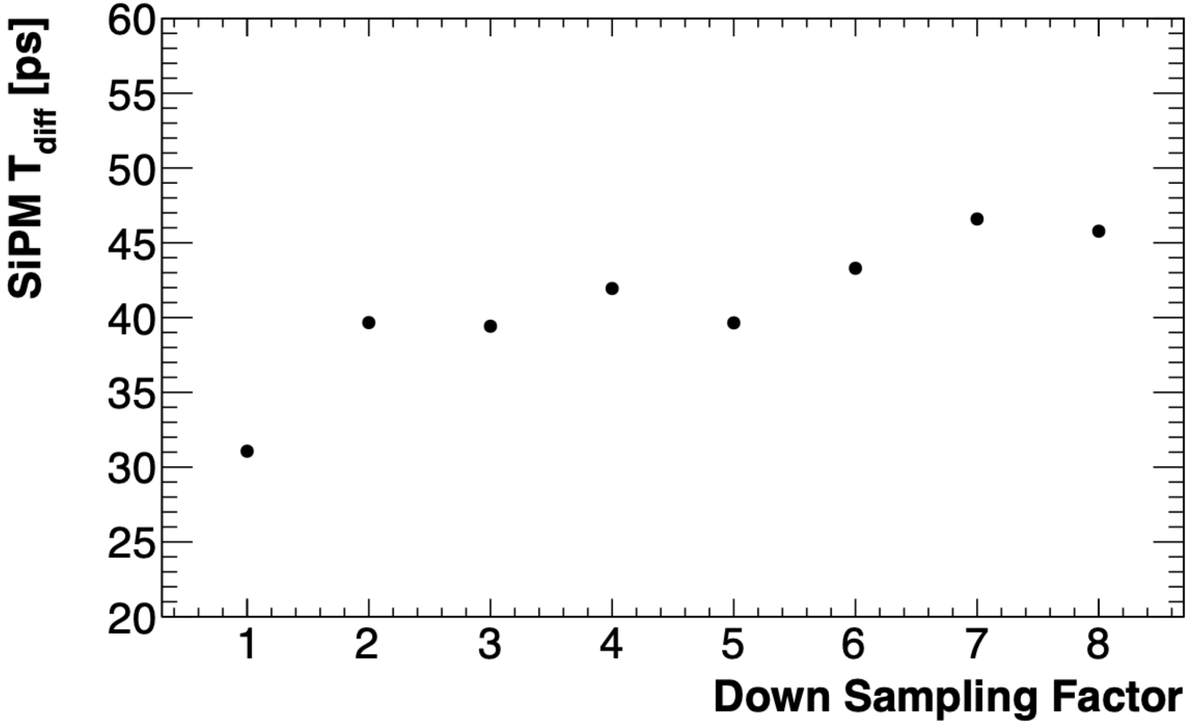




Downsampling

- Run PbF_2 back side
- Waves were down-sampled offline by 8 factors: 1, ½, …, 1/8
- Further invest. needed





Conclusions

Lessons learned

- Timing performance of a single Crilin cell is excellent w/ latest FEE design
- PbF2 still outperforms PWO-UF, despite almost halved LY

- Cherenkov light transport plays a key role for charge and timing measurement
- Waveform shape alteration due to convolution of Cherenkov photons transport time distribution and SiPM+FEE response for PbF2 (less severe effect for PWO)
- Depending on particles path inside crystal, some timing offsets appear and need correction
- SiPM series connection also introduces some effect relative to charge sharing and unbalanced illumination

- Specific crystal wrappings or orientations seem to average out these effects
- Using mean-time and charge information seems to average out light transport effects
- We were only testing a 4 X0 crystal, things will change during full shower development

Lessons yet to be learned

- Geant4 simulation of light transport will verify current hypotheses
- Test of SiPM matrix with laser to check SiPM response (L/R and series connection)
- Further test beams in different orientations and w/ alternative wrapping/finishing options already planned

Next R&D steps

- Proto-1 is under assembly
- Electronics and mechanics have been produced
- 2023 Beam Tests → LNF-BTF (April), CERN-H2 (August)

SPARES

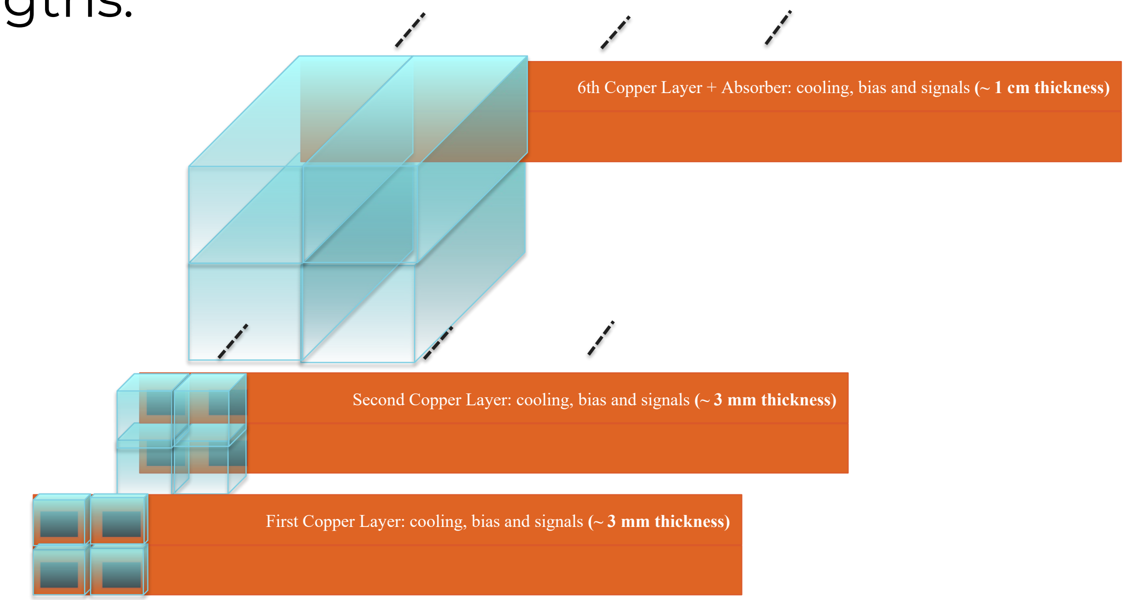
The Lorenzo proposal

- Add a passive pre-shower to mitigate the BIB effect on the first layer

  → O(cm) of Aluminum or other material to minimize the neutrons generation.

The all Ecal group proposal

- Add two or more layers of Crilin with different granularity (wider and longer) to achieve about 3 interaction lengths.



Introduction and Motivation

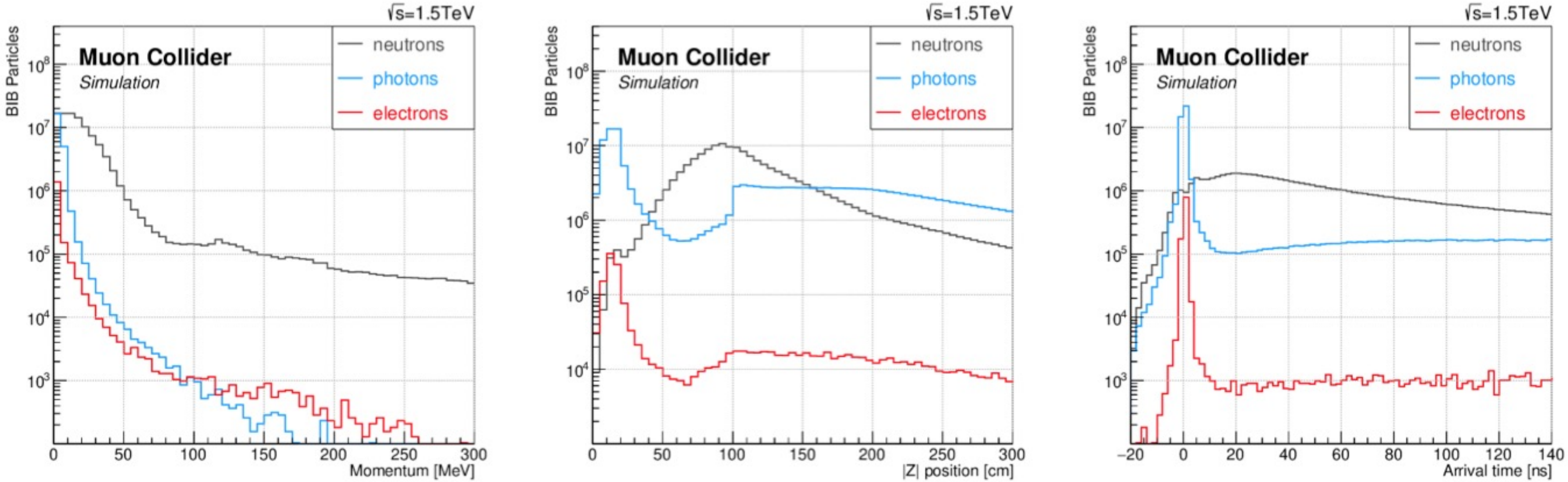
- Muon Colliders (MC) could represent the keystone for accessing the energy frontier of high energy physics

- Great potential, especially in the TeV range:
  - negligible synchrotron radiation (m_μ/m_e~200)→ high collision energy as in hadron colliders;
  - no significant beamstrahlung → improved energy resolution for physics measurements.

- Challenging development due to the instable nature of muons ($\tau_\mu = 2.2\ \mu s$)
  - Decay products of the circulating μ interacting with the machine elements → not so clean environment;
  - $4{\times}10^5$ decays/m at 1.5 TeV with $2{\times}10^{12}$ μ/beam→O(10^{10}) background reach the interaction region and enter the detector: **Beam-Induced Background (BIB).**
    - Very soft momenta;
    - Displaced origin w.r.t. the interaction region;
    - Asynchronous time of arrival w.r.t. the bunch crossing;

Beam induced background (BIB)

- BIB represents the main issues for the detectors;
- Strongly depends on the CM energy and machine design→realistic MC simulation vital to estimate the physics reach;
- Very soft momenta;
- Displaced origin w.r.t. the interaction region;
- Asynchronous time of arrival w.r.t. the bunch crossing;

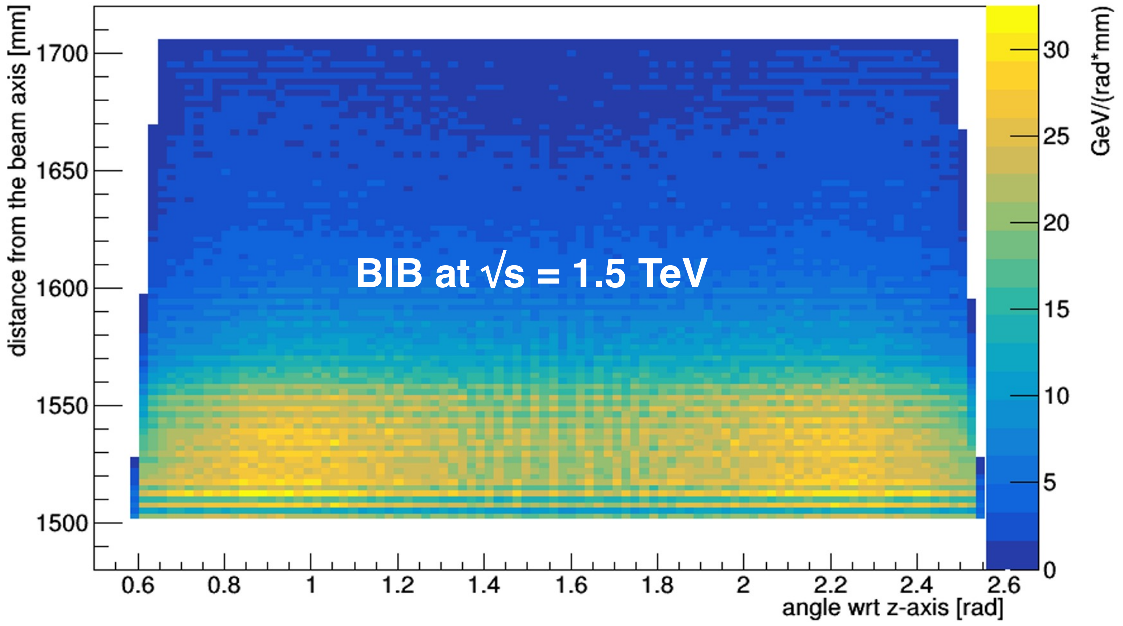


BIB in ECAL

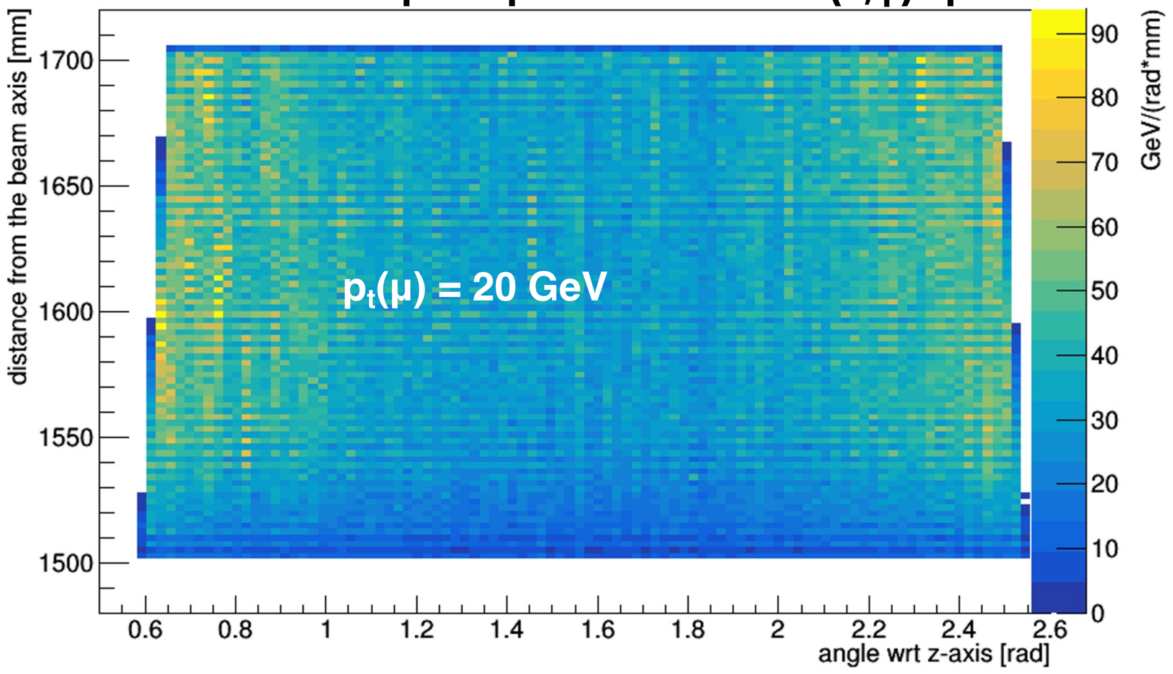
Timing and longitudinal segmentation play a key role in BIB suppression

- At the ECAL barrel surface the BIB flux is 300 particles/cm^2, most of them are photons with <E>=1.7 MeV.
- Different energy release for signal and BIB event → possibility to subtract the BIB from longitudinal measurements

Energy released in ECAL barrel by one BIB bunch crossing

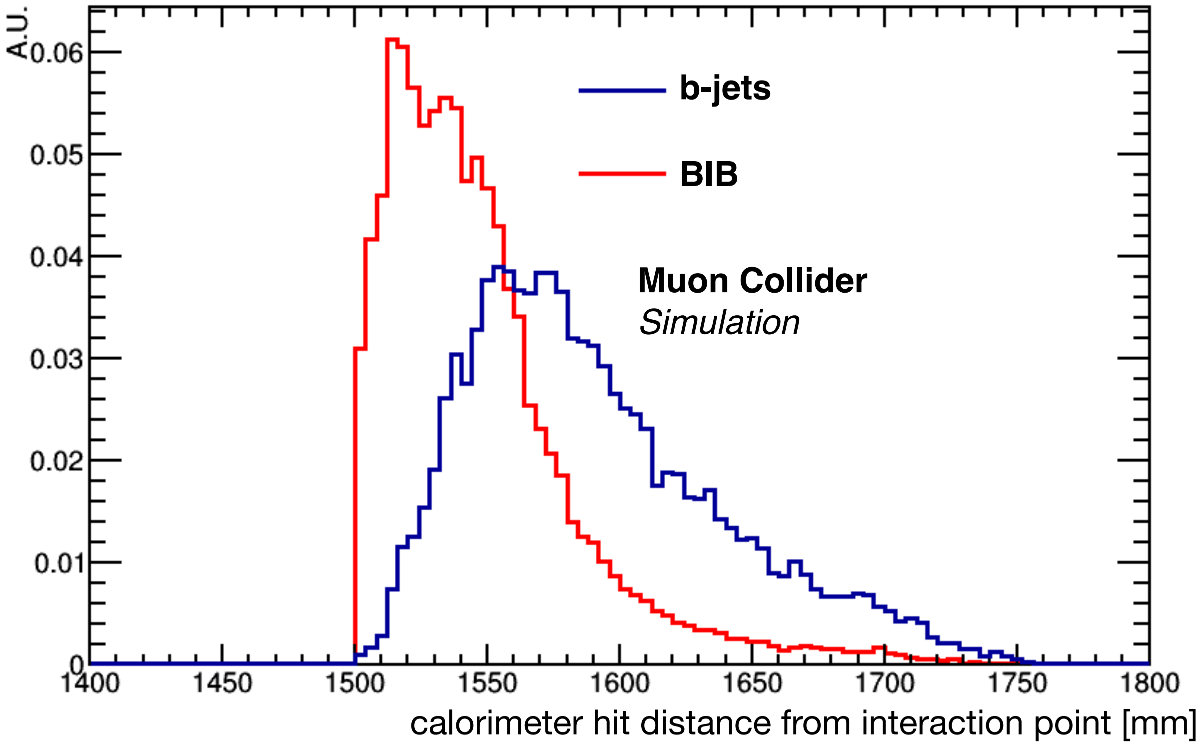


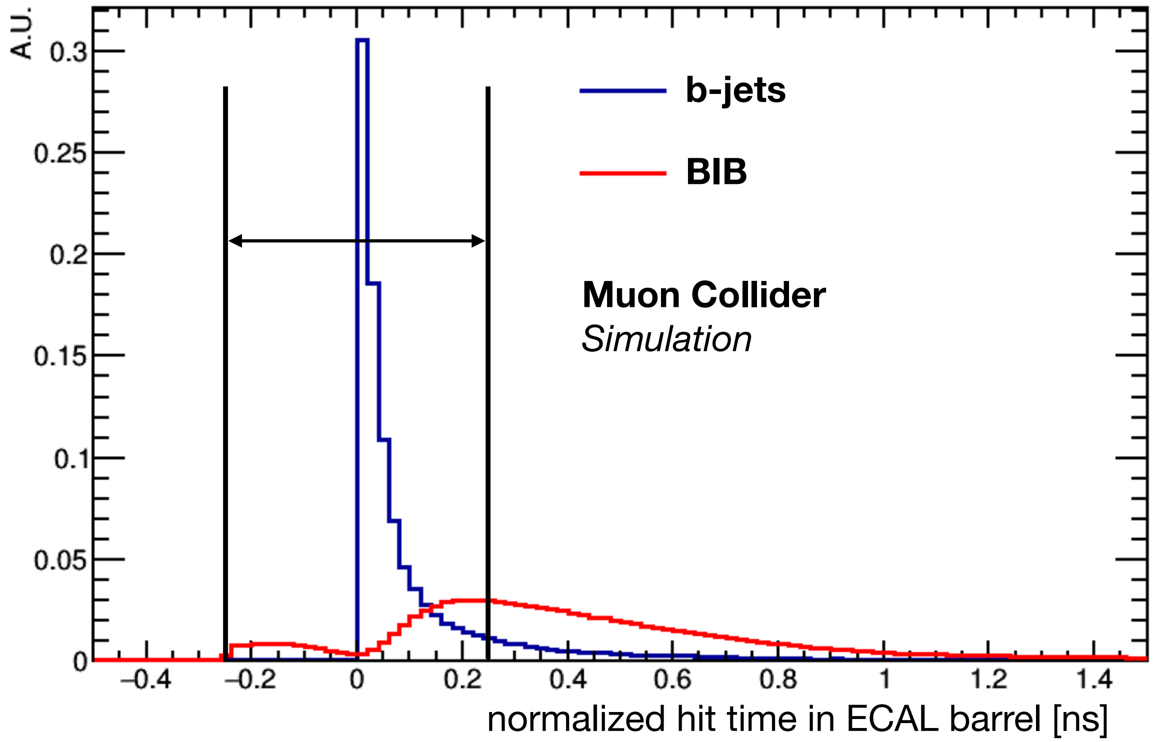
Energy released in ECAL barrel by uniformly distributed prompt muons in the (θ,φ) space



Muon identification

- Muons and BIB leave two different signatures in the ECAL barrel:
  - The BIB produces most of the hits in the first layers of the calorimeter while muons produce a constant density of hits after the first calorimeter layers.
  - Since the BIB hits are out-of-time w.r.t. the bunch crossing, a **measurement of the hit time performed cell-by-cell** can be used to **remove most of the BIB.**

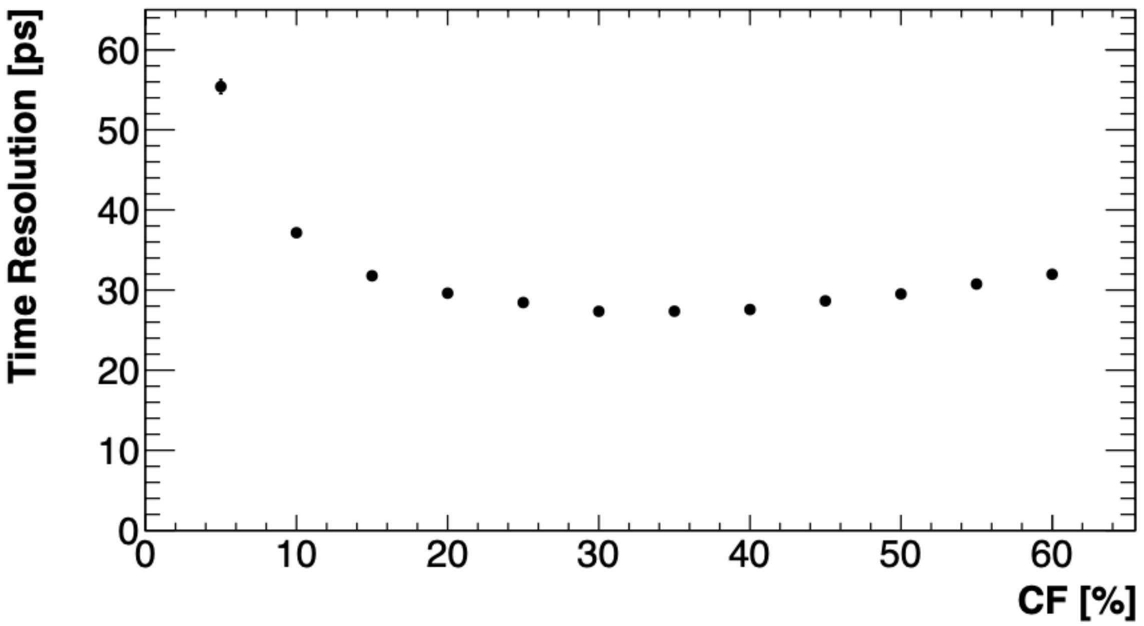




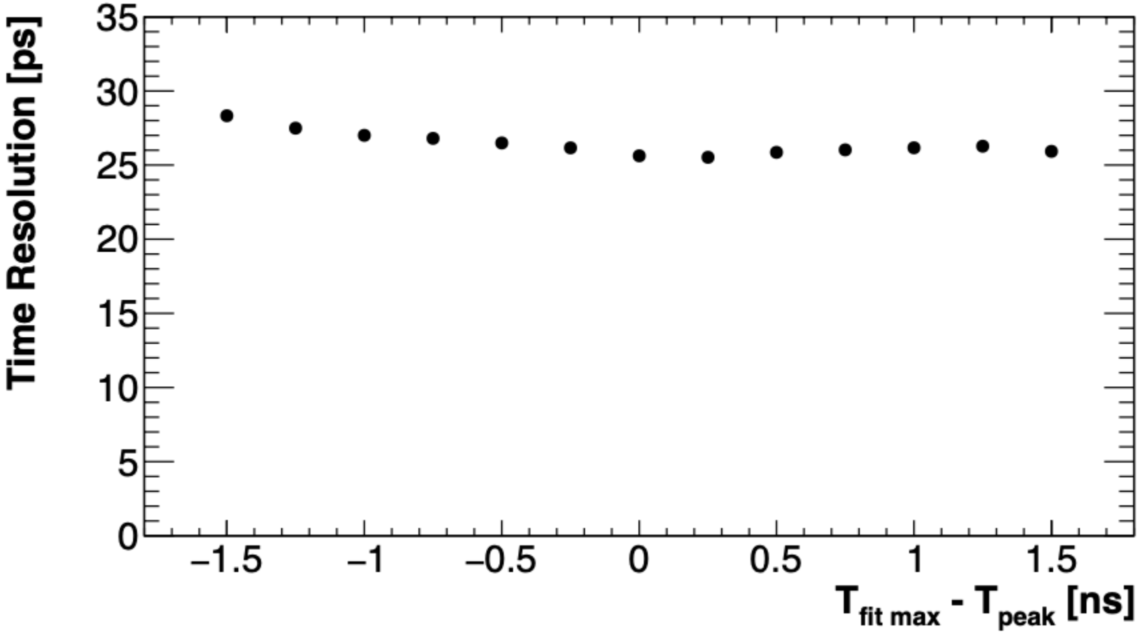
Constant fraction and fit window

We minimized the time resolution scanning in CF and fit window upper limit.

The fit window is given by: $[T_{peak} - 12 \text{ ns}, T_{peak} + T_{fit\,max}]$

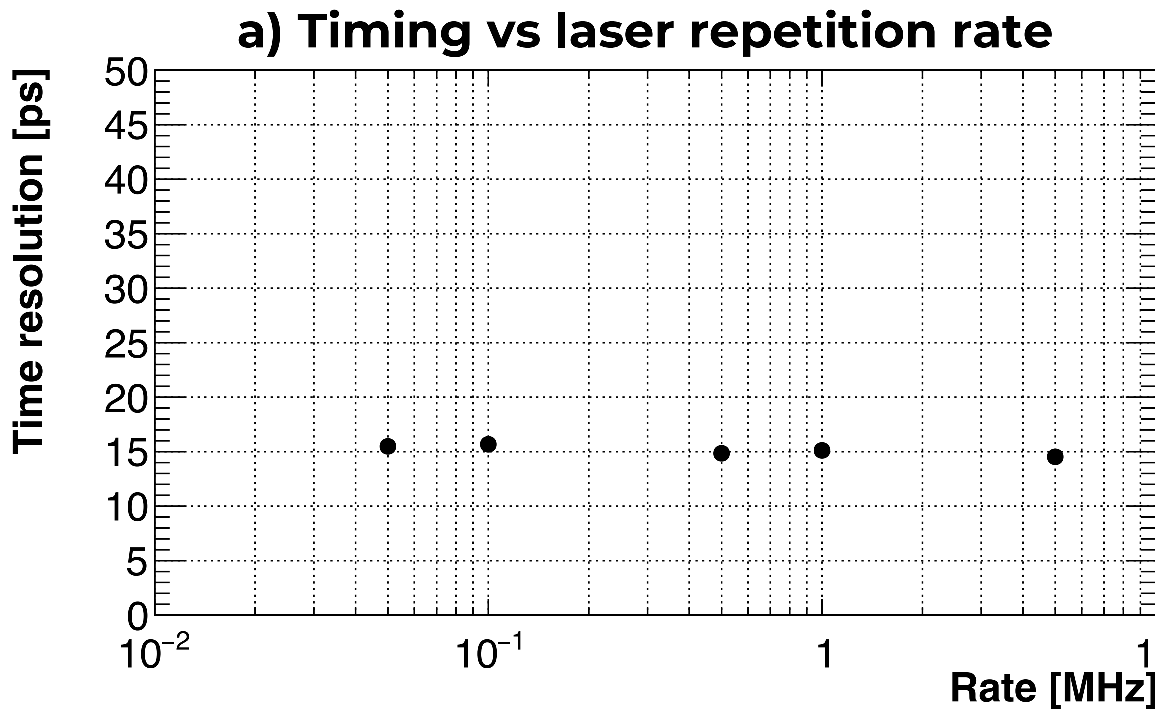


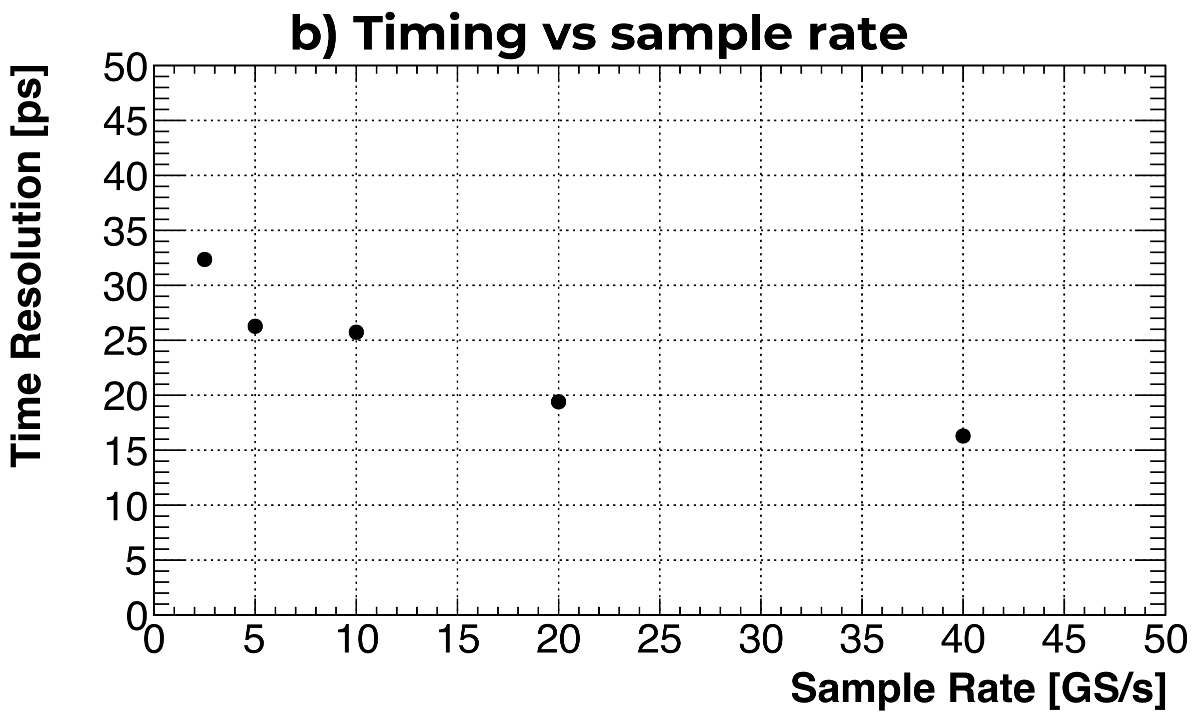
Best constant fraction: 30%



Best $T_{fit\,max} - T_{peak}$: 0.5 ns

Time resolution studies: first results (1)





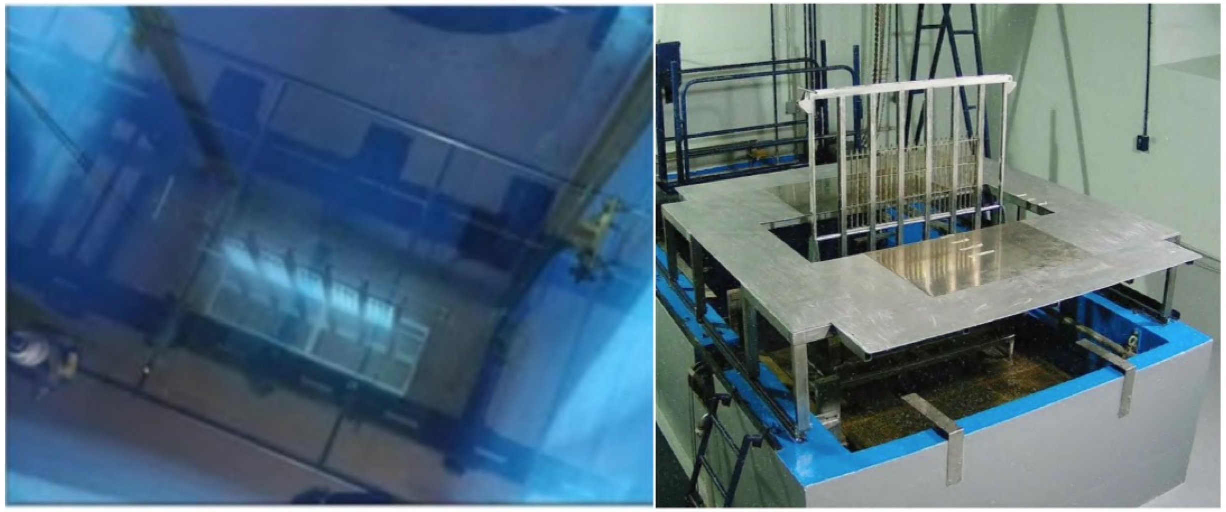
Constant behaviour meaning that the **waveform stays unchanged in the 50 kHz-5MHz range**.

Strong dependence from the sample rate since the **time resolution at 2.5 GS/s is twice the one at 40 GS/s**.

Irradiation sources

Calliope facility:

- pool-type gamma irradiation;
- 25 ^{60}Co source rods producing photons with E_{γ} =1.25 MeV and an activity of 1.97×10^{15} Bq.



Irradiation Step	Dose in air [krad]
I	30.2
II	89.88
III	2082
IV	4031.8
V	4435.5

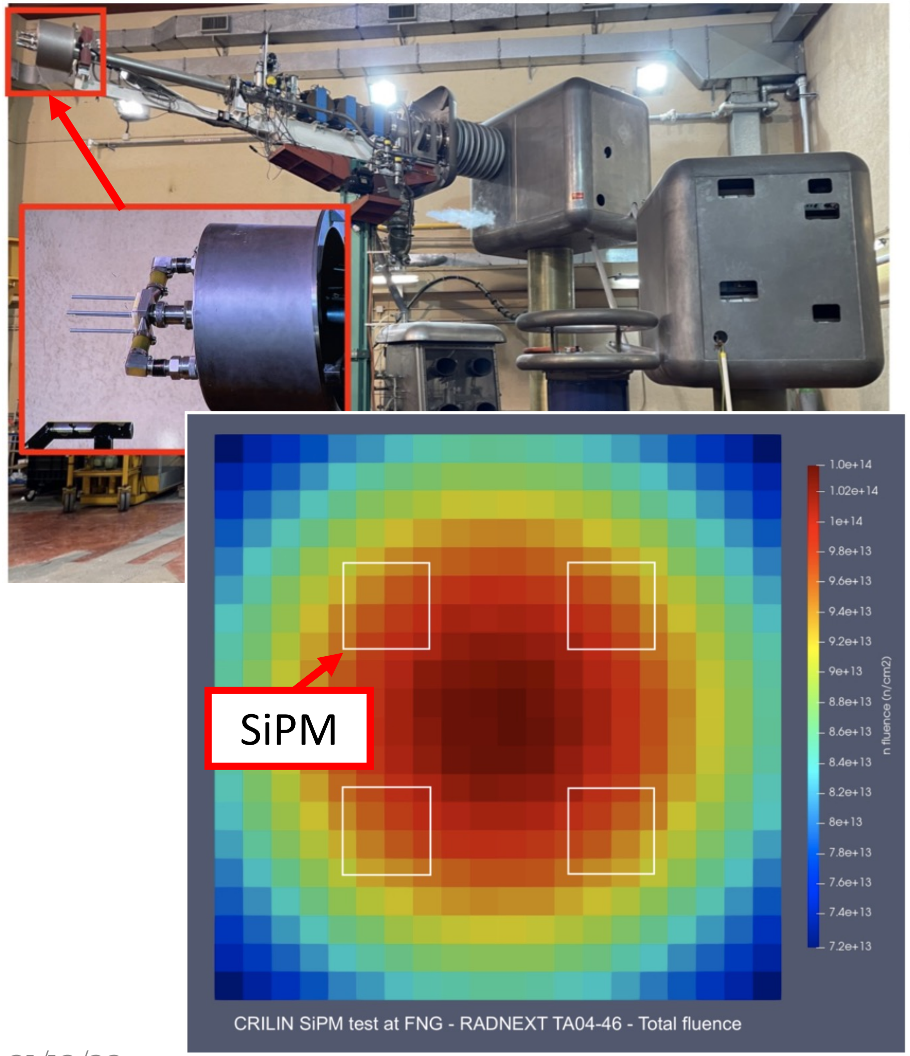
Table 1. Irradiation steps and corresponding total dose absorbed by the crystals

FNG facility:

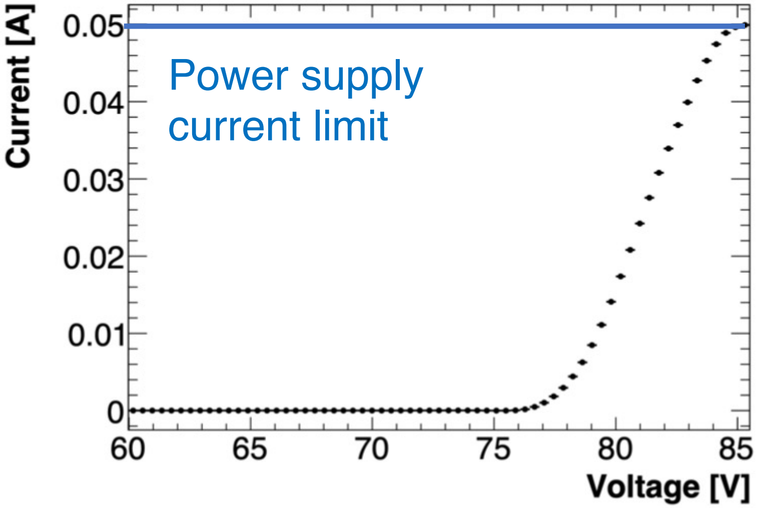
- Neutron source based on T(d,n)α fusion reaction;
- 14 MeV neutrons with a flux up to 10^{12} neutrons/s in steady state or pulsed mode.

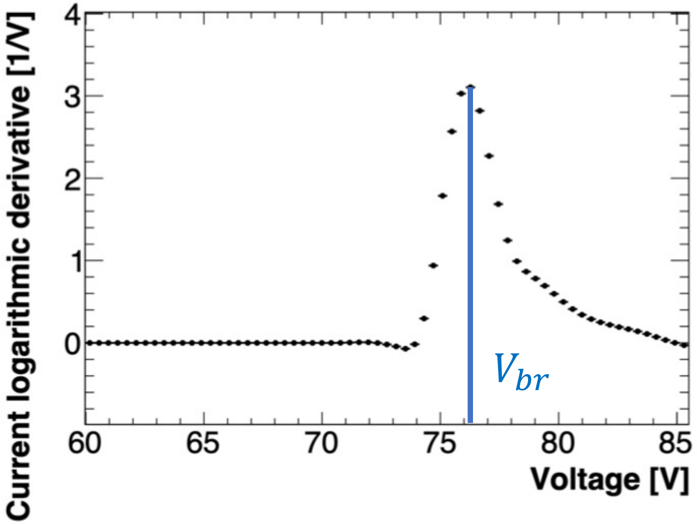
SiPMs Characterisation

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)

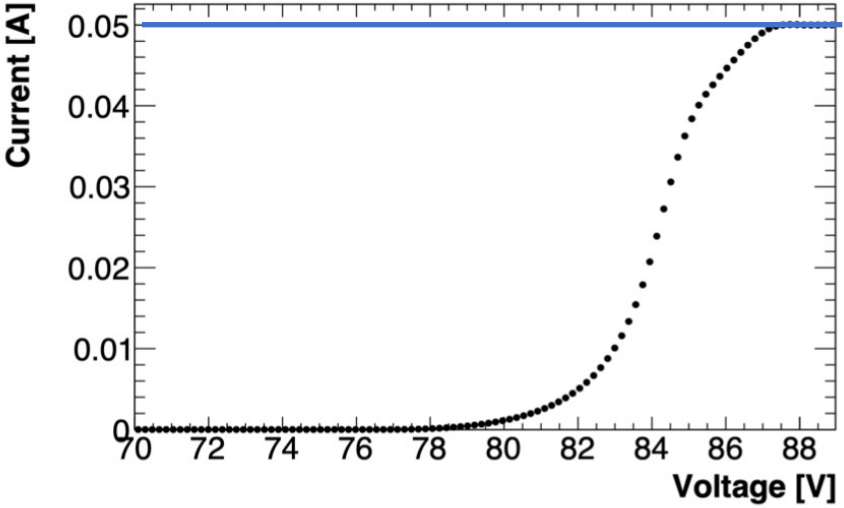


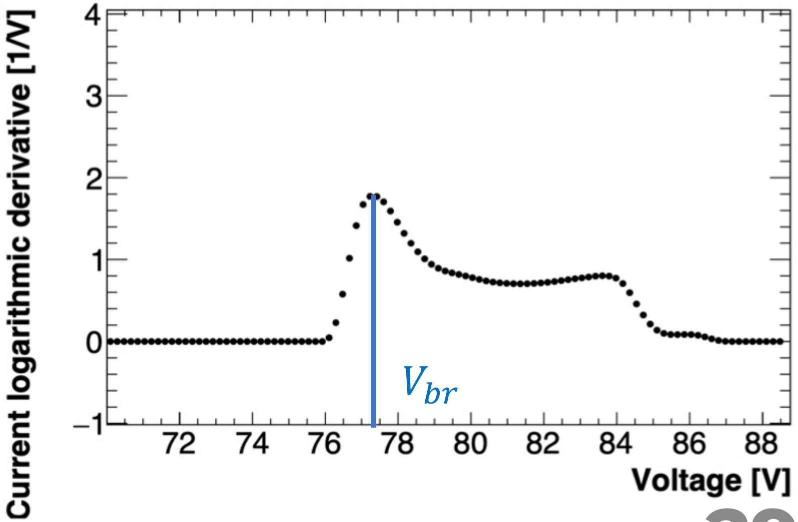
15 μm





10 μm



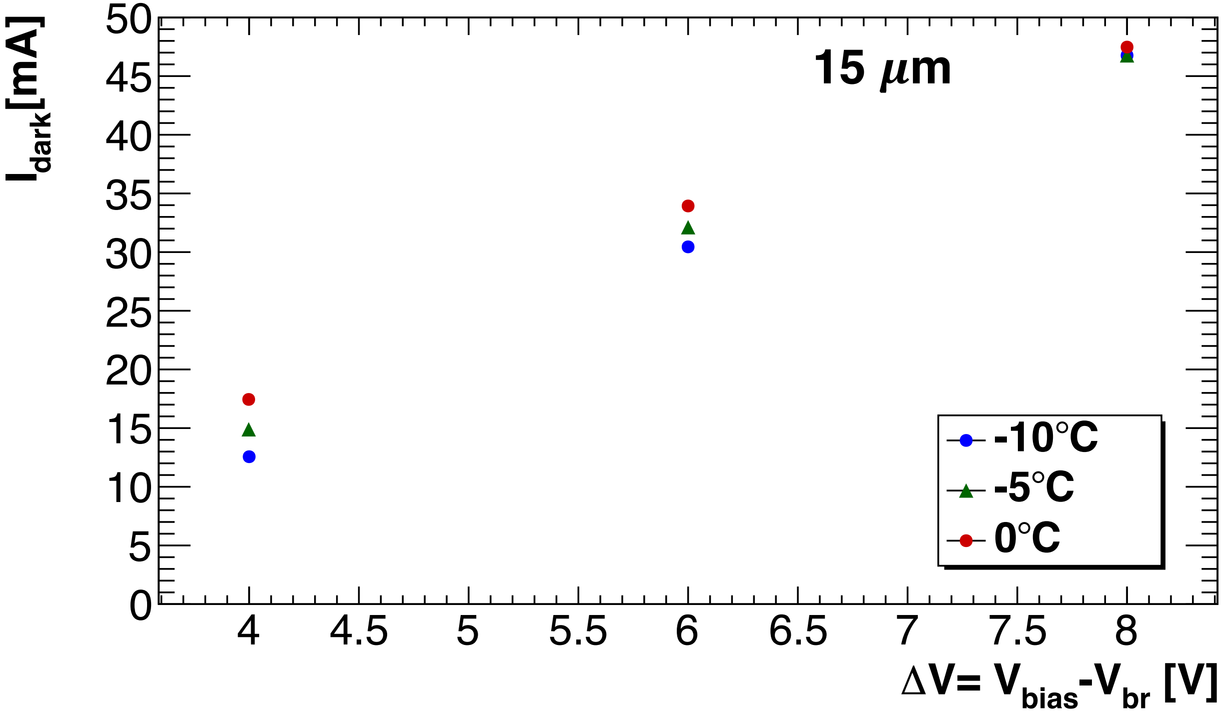


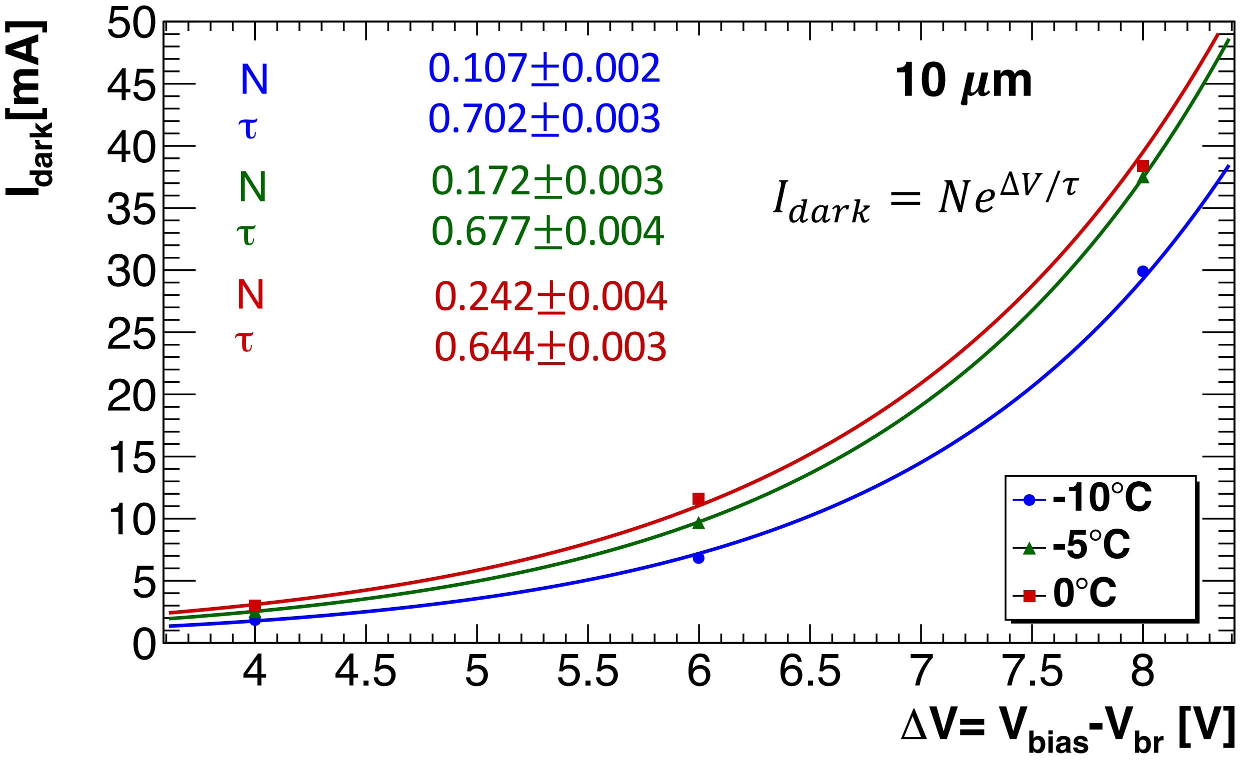
SiPMs Characterisation-2

Extrapolated from I-V curves at 3 different temperatures:

- Currents at different operational voltages.
- Breakdown voltages;

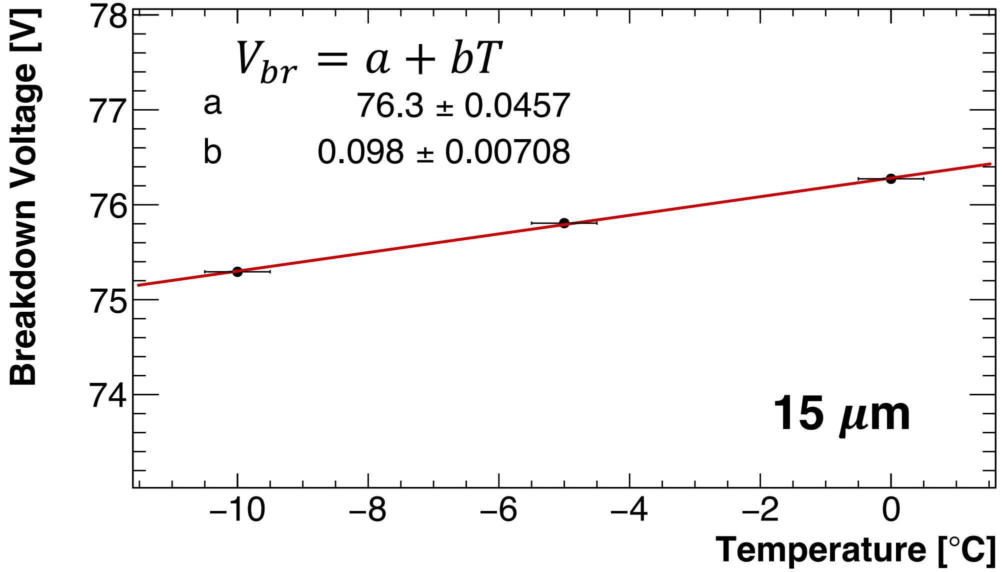
For the expected radiation level **the best SiPMs choice are the 10 μm one** for its minor dark current contribution.





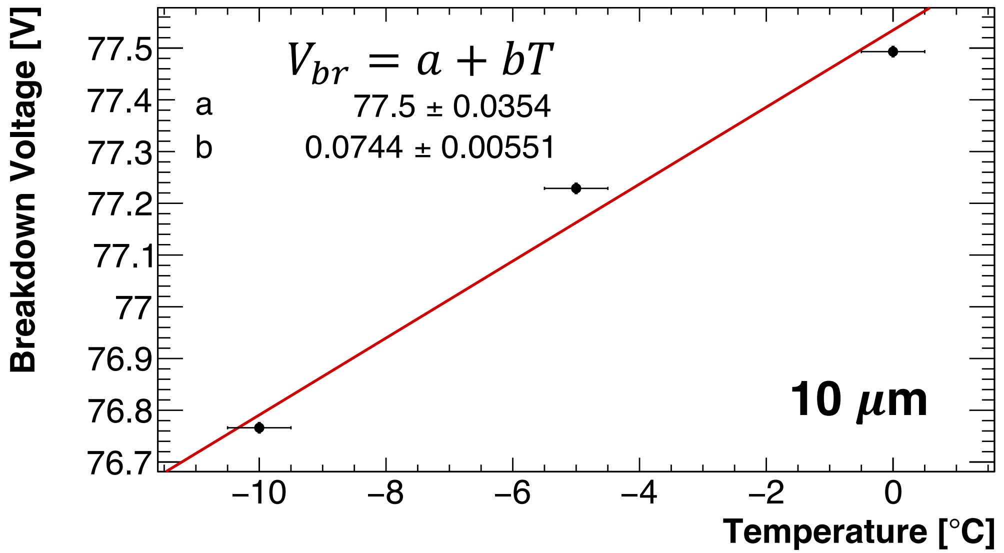
SiPMs Characterisation-3

The percentage variation of the breakdown voltage while the temperature changes of 1°C: for the **15 μm** SiPM is **9.8%/°C** and for the **10 μm** one is **7.3%/°C.**



15 μm

Temperature [°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



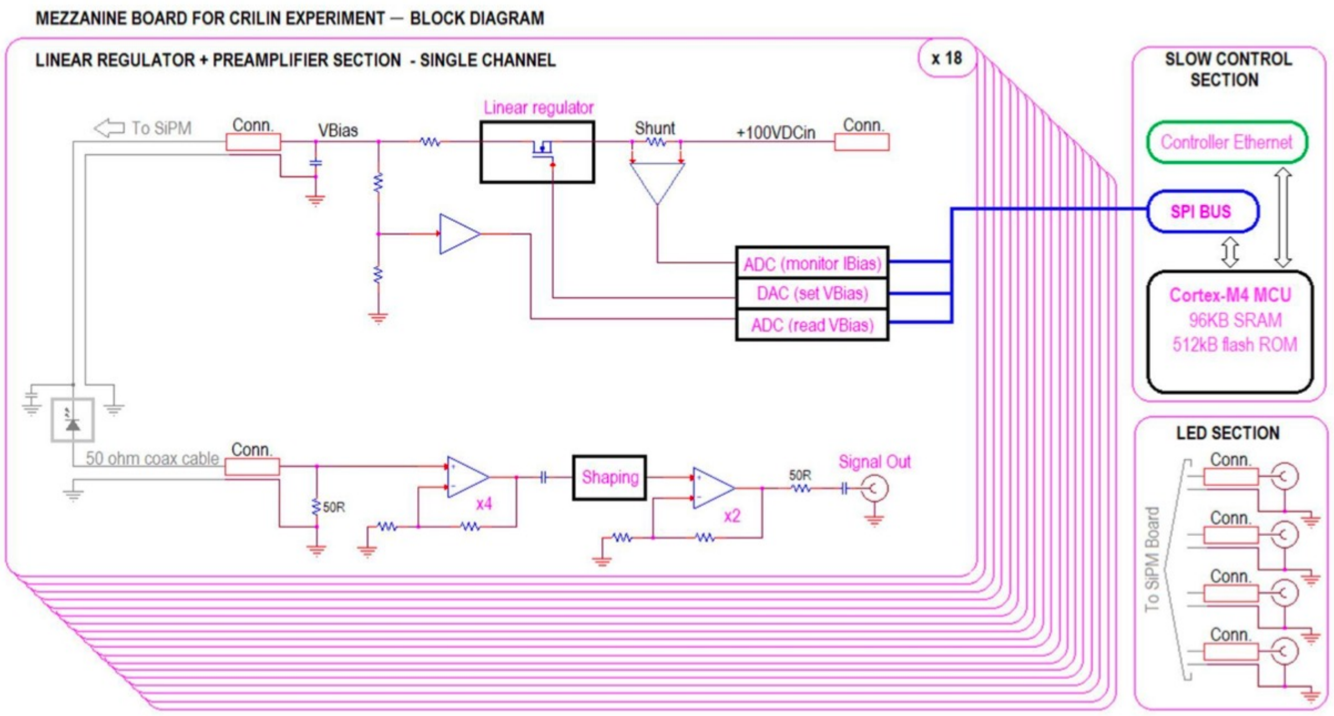
10 μm

Temperature [°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

Electronics – Mezzanine Board

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 Processors.



Mezzanine board CAD

Further thoughts on single-crystal studies

We have data for good measurements of time resolution

- CRILIN electronics has extremely good time performance in laboratory, confirmed at test beam
- MCP time reference, σ_t = 30 ps
- Digitization at 5 GHz
- Good signal shape

Can obtain light yield measurements with mips and high-energy electrons from this data

Particularly interested in systematics of light collection with small crystals of high refractive index

- On-line analysis suggests collimation effects disappear with backside illumination
- Time resolution better with backside illumination?
- Need modeling by simulation
- Implications for detector design?