The CRILIN Calorimeter: an alternative solution for the Muon Collider barrel

C. Cantone, S. Ceravolo, E. Di Meco, E. Diociaiuti, P. Gianotti, A. Liedl, D. Paesani, **I. Sarra** – LNF INFN

F. Colao – ENEA Frascati

D. Lucchesi, L. Sestini – INFN Sezione di Padova

A. Saputi – INFN Sezione di Ferrara

N. Pastrone – INFN Sezione di Torino

D. Tagnani – INFN Sezione di Roma 3

G. Pezzullo – Yale University

CERN - MUON Collider Collaboration Meeting (11-14 October 2022)

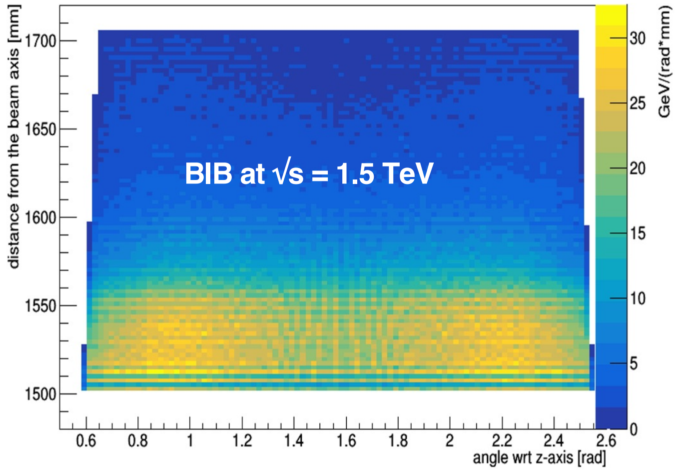
-

Beam Induced Background

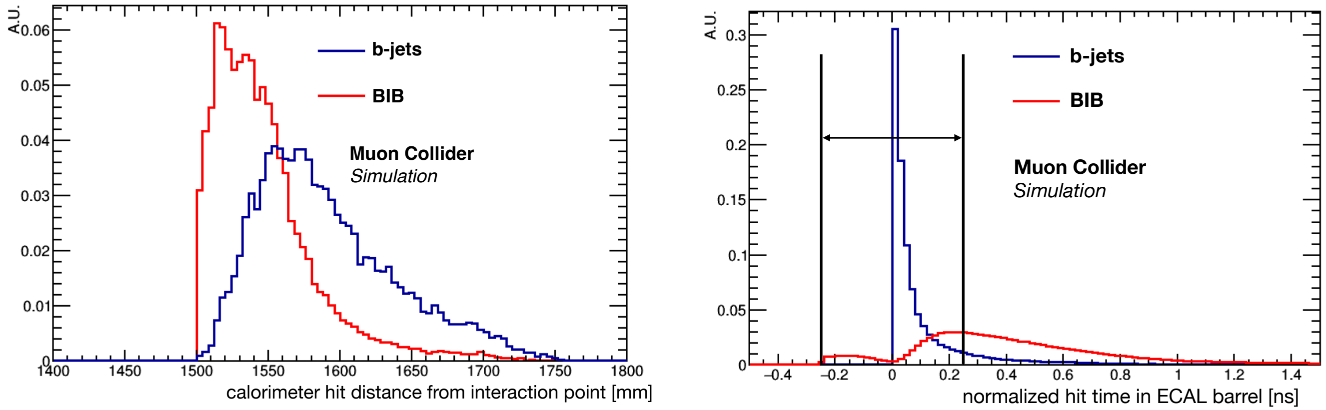
Timing and longitudinal segmentation play a key role in BIB suppression

- 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



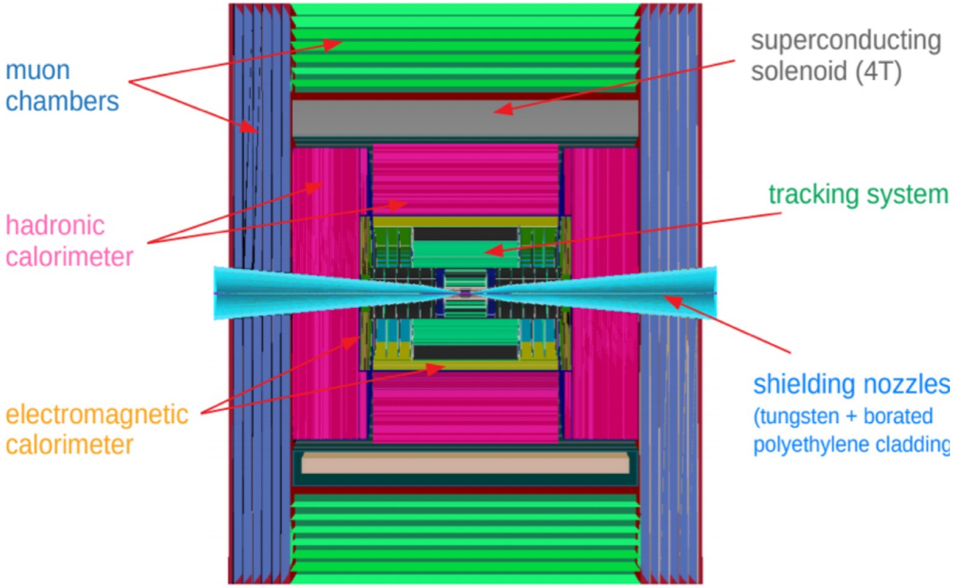
- The BIB produces most of the hits in the first centimeters of the calorimeter
- Since the BIB hits are out-of-time w.r.t. the bunch crossing, a **measurement of the hit time performed cell-by-cell** can be used to **remove most of the BIB:** → **fast response** (small integration window) is essentially to **reduce energy contribution** from BIB

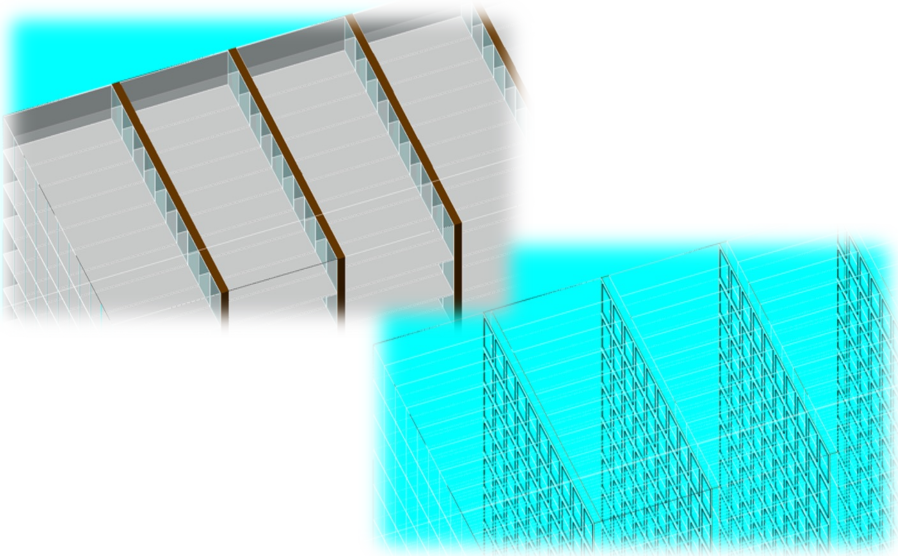


Bartosik, Nazar, et al. "Simulated Detector Performance at the Muon Collider." arXiv preprint arXiv:2203.07964 (2022).

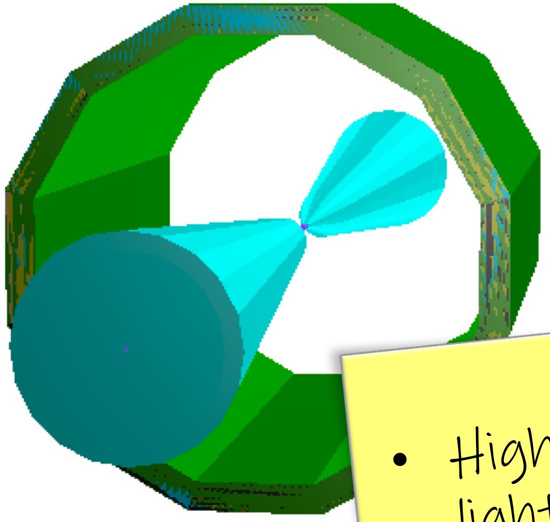
Crilin: an alternative solution

- Actual design of the ECAL: 40 layers of 1.9 mm W absorber + silicon pad sensors (~64M channels for the Barrel)
  - 5x5 mm^2 cell granularity
  - 22 X_0 (1 λ_i)
- Crilin (Crystal calorimeter with longitudinal information) represent a **valid** and **cheaper backup solution**
  - Based **on Lead Fluoride** (PbF_2) crystals readout by **2 series of two UV-extended 10µm pixel SiPMs each.**
  - Crystal dimensions are 10x10x40mm^3 and the surface area of each SiPM is 3x3 mm^2, to closely match the crystal surface.
  - Modular architecture based on stackable submodules





Crilin: a backup solution



e ECAL: 40 layers of 1.9 mm W
ad sensors
ularity

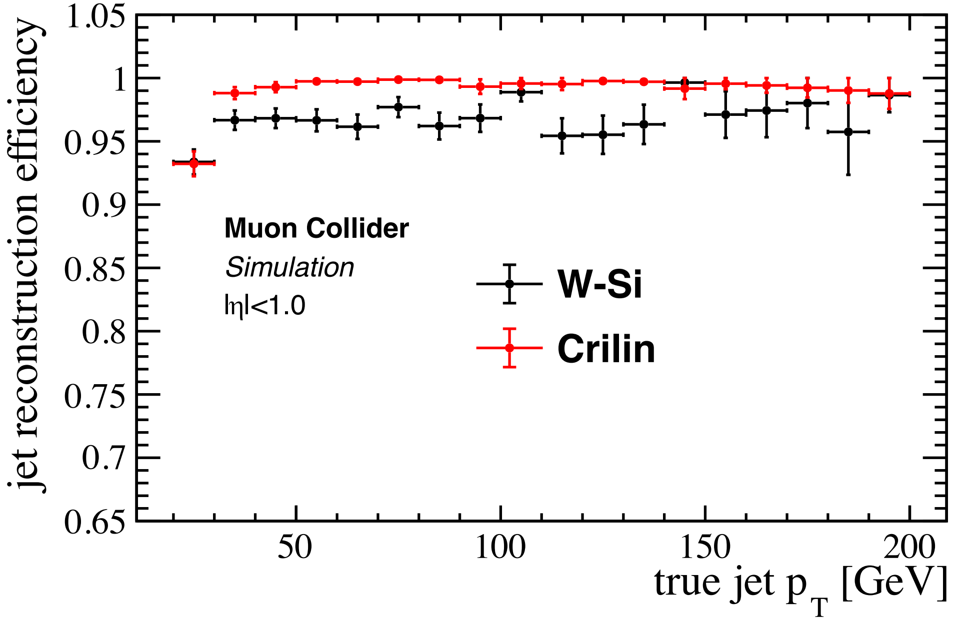
al
er

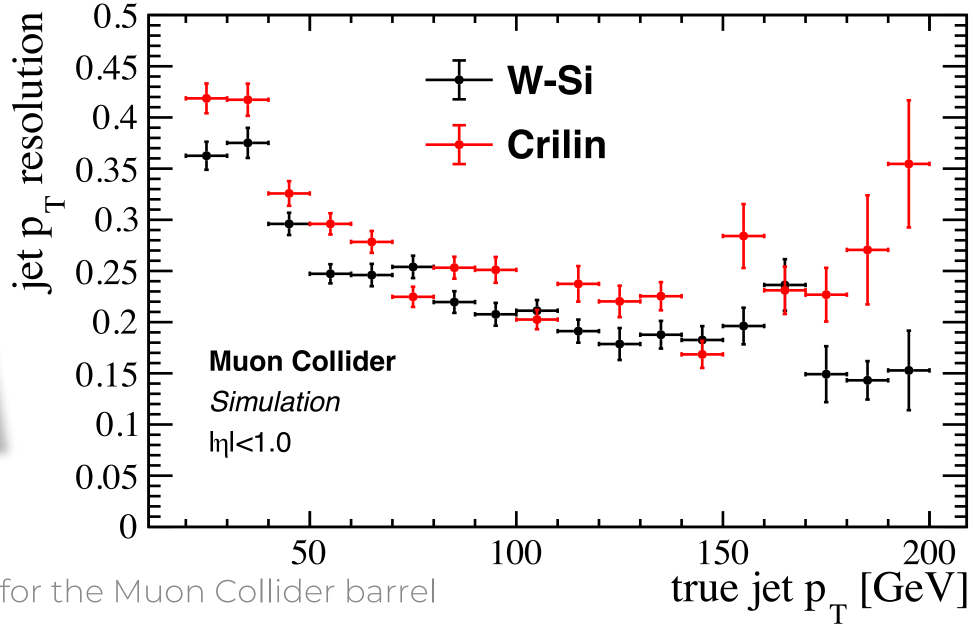
Based on
2 series o
each.

– Modular
submodul
crystals;

– Crystal di
surface are
match the

- High response speed (Cherenkov light is instantaneous w.r.t particle passage)
- Reduced signal width→ excellent ability to resolve temporally close events at high rates
- Good light collection (~ 1 pe/ MeV)
- Good resistance to radiation
- Fine granularity and scalable SiPM dimensions

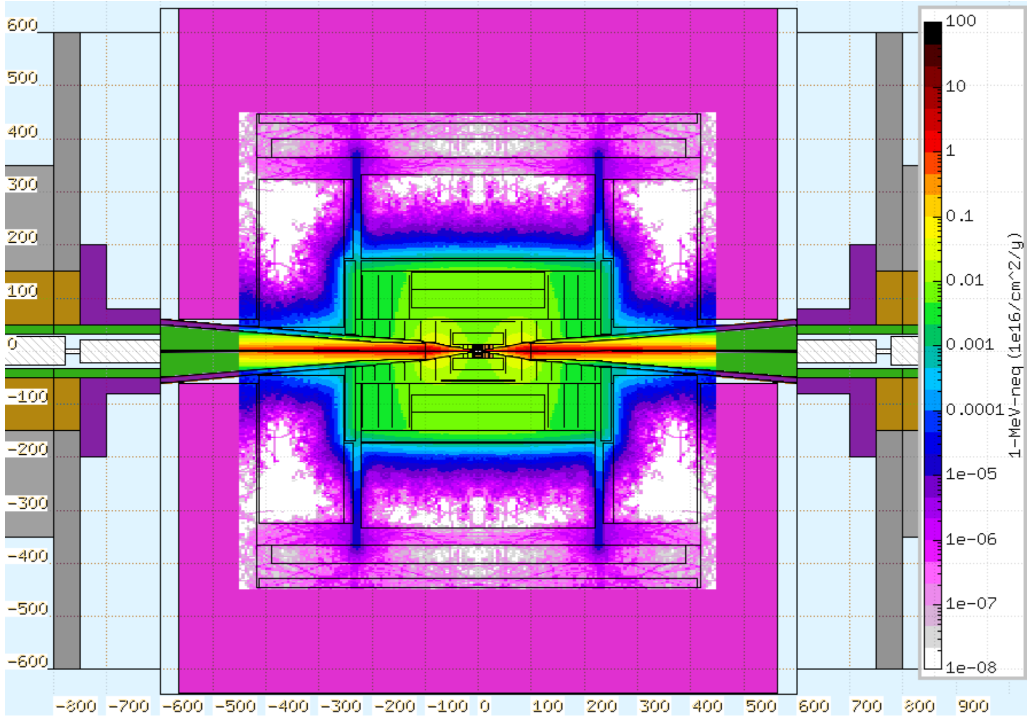




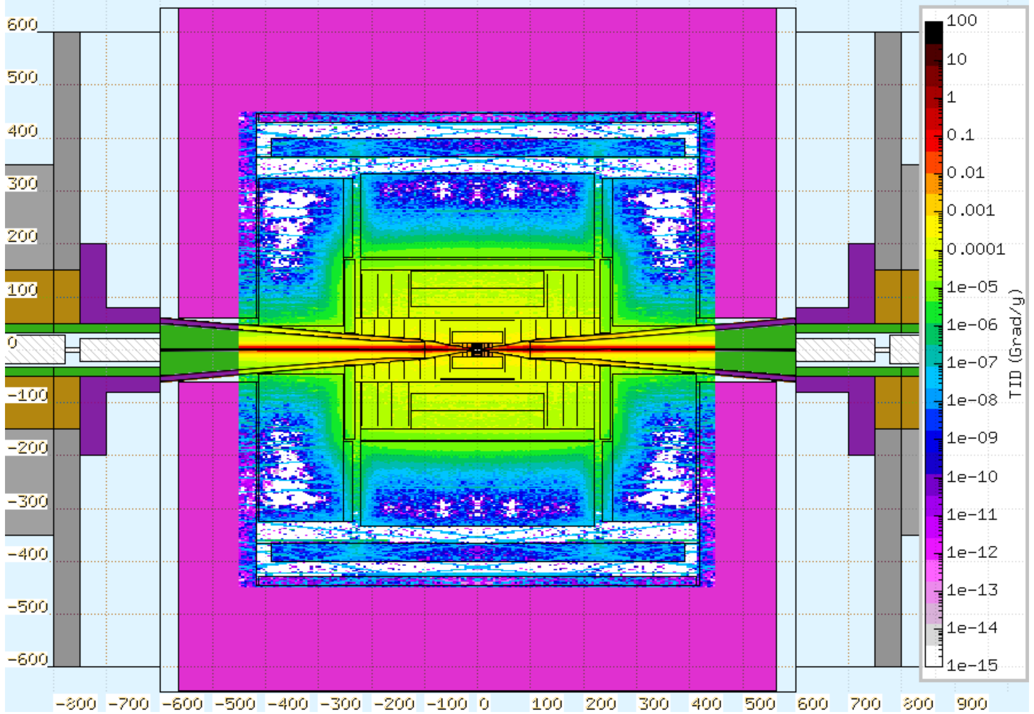
Radiation environment

- FLUKA simulations implementing the BIB yielded were carried out at $\sqrt{s} = 1.5\ \mathrm{TeV}$
- assuming 200 days of operation during a year in the ecal region
  - the neutron (1-MeV-eq) fluence is ~ 10^{14} cm^{-2} / year
  - The TID is ~ 100krad/year

1 MeV neutron equivalent



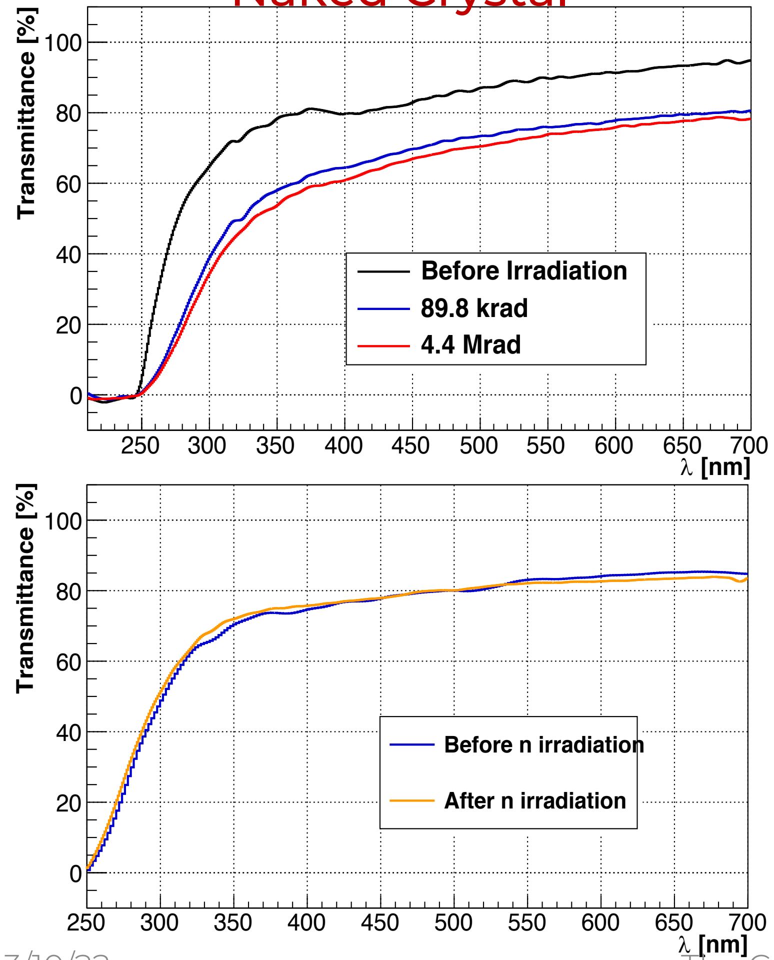
Total Ionizing dose



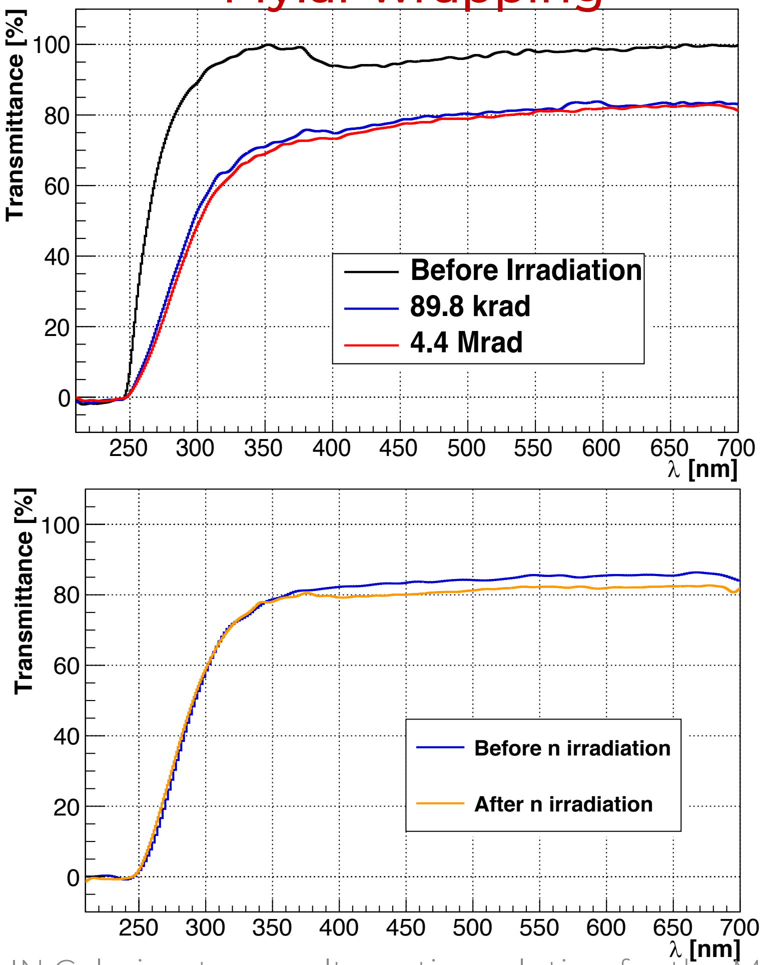
Crystal radiation hardness

- Radiation hardness of two PbF_2 crystals(5x5x40 mm^3) checked for TID (up to **4.4 Mrad** @ Calliope, Enea Casaccia) and neutrons (14 MeV neutrons from Frascati Neutron Generator, Enea Frascati, up to **10^{13} n/cm^2**)

Naked Crystal



Mylar wrapping



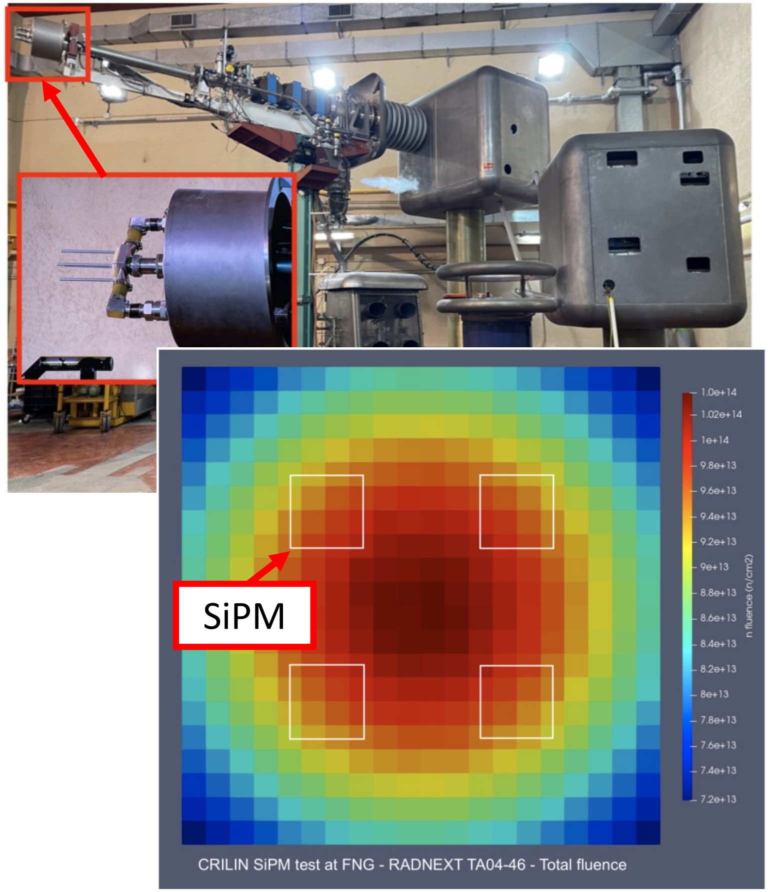
- After a TID ~ 80 krad no significant decrease in transmittance → saturation effect caused by the damage mechanism

- Transmittance after n irradiation evaluated after 14 days show no deterioration → possible natural annealing

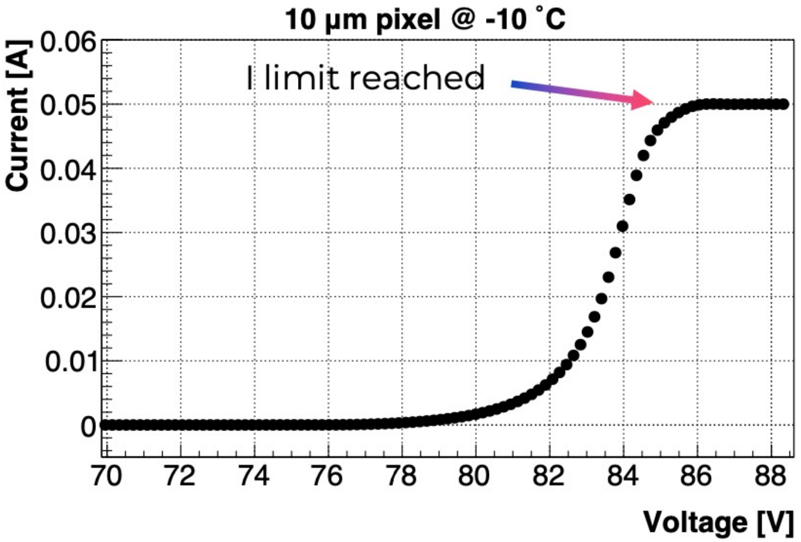
SiPM radiation hardness

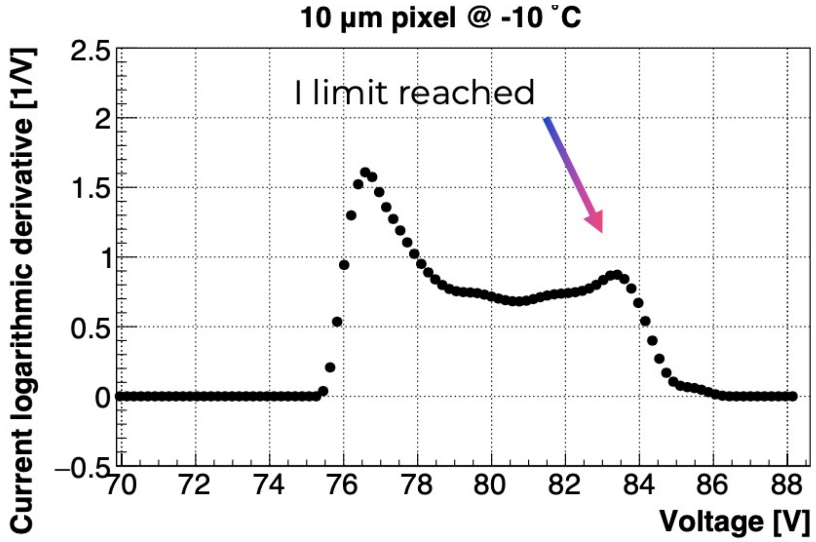
The main SiPM damage due to n irradiation is related to the increase of the dark current

- 80 hours neutron irradiation (@FNG,ENEA Frascati) up to 10^{14} n/cm^2 for a series of two 10(15) μm SiPMs



CRILIN SiPM test at FNG - RADNEXT TA04-46 - Total fluence

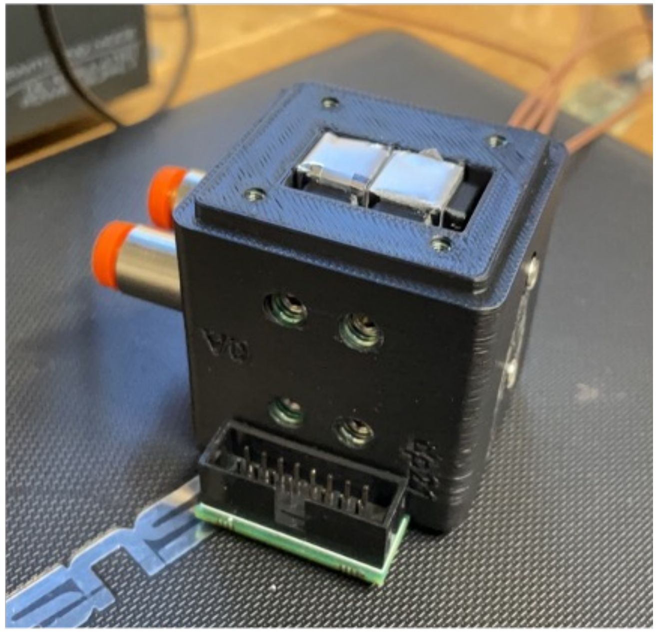




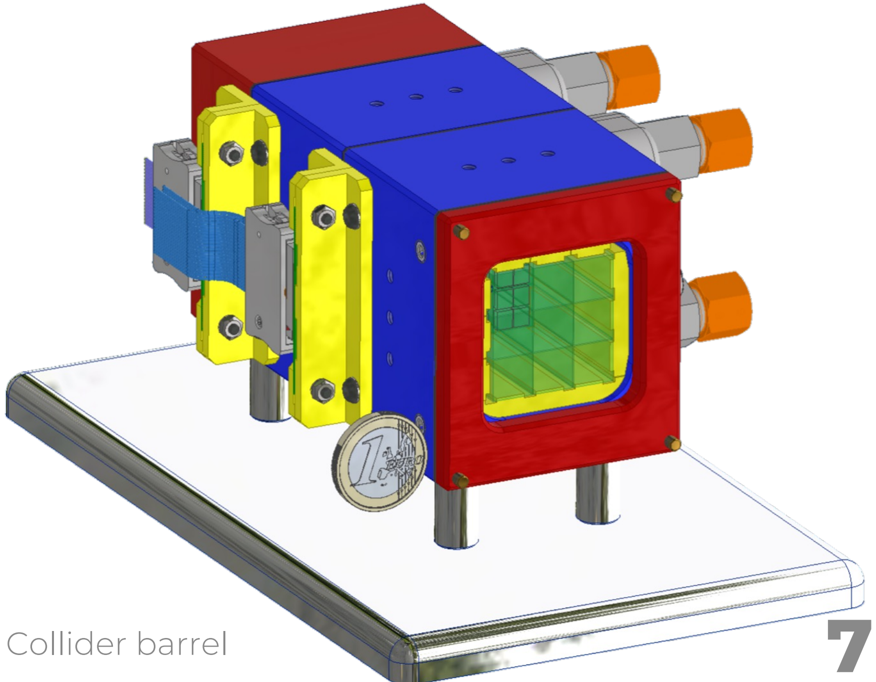
Temperature[°C] ±0.5	V_{br} [V] ±0.06	I(V_{br}+4V) [mA] ±0.006	I(V_{br}+6V) [mA] ±0.006	I(V_{br}+8V) [mA] ±0.006
-10	76.58	2.188	8.193	35.137
-5	77.09	3.003	11.512	40.484
0	77.42	3.555	13.909	40.560

Crilin prototype

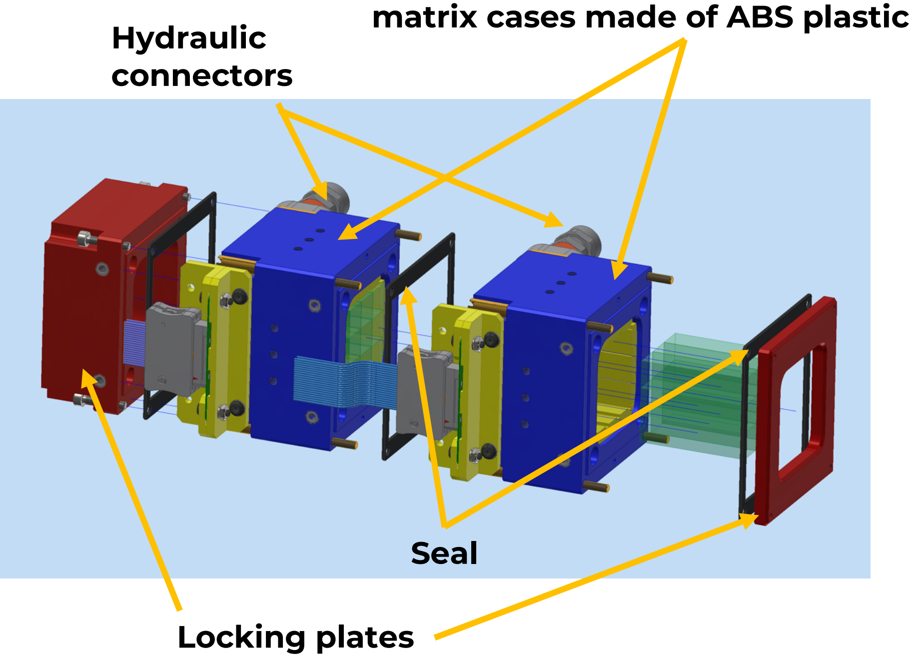
- **Proto-0**: 1 module composed of 2 crystals readout by 4 SiPMs
  - validate the design choices characterizing in detail the response of crystals and photosensors,
  - Good results from 2 Test Beam @H2 facility,CERN, in 2021 and 2022



- **Proto-1:** 2 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.
  - SiPMs are connected via 50-ohm micro-coaxial transmission lines to a microprocessor-controlled Mezzanine Board which provides signal amplification and shaping, along with all slow control



Mechanics and cooling system



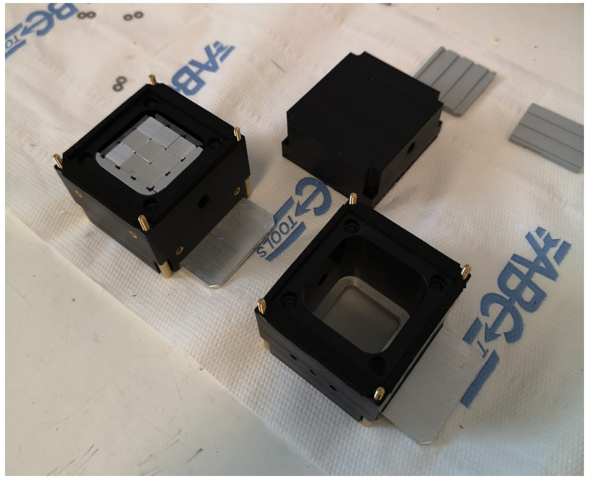
Hydraulic connectors

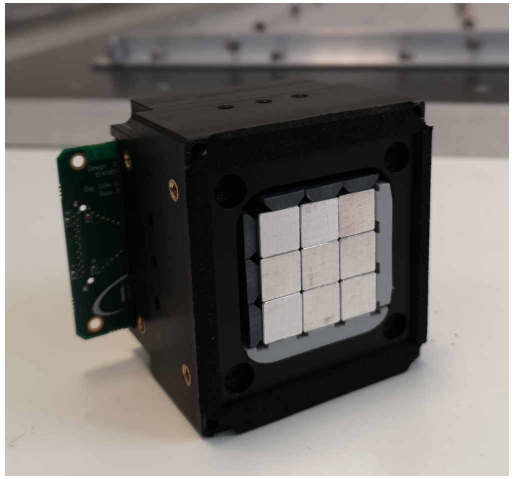
matrix cases made of ABS plastic

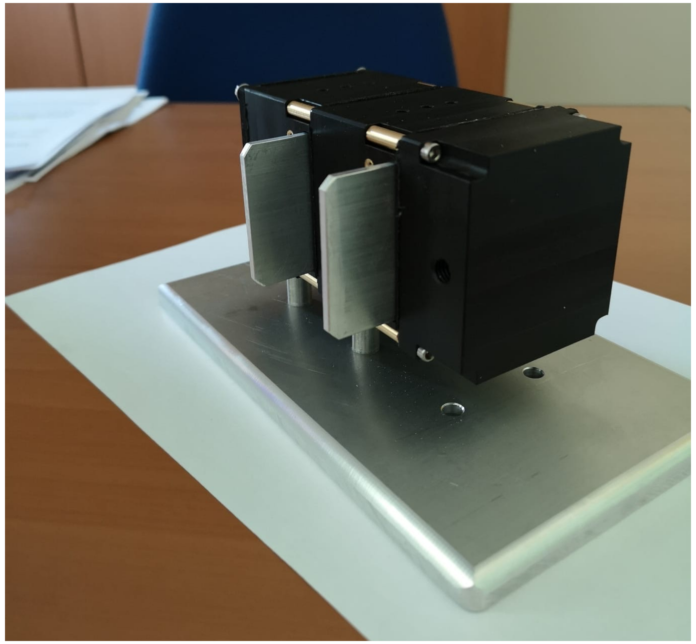
Seal

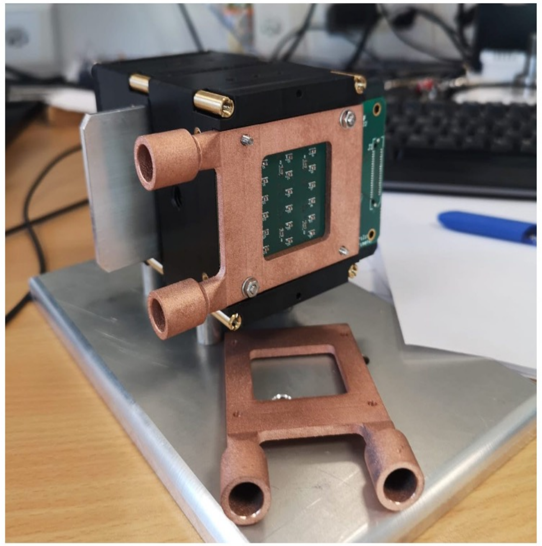
Locking plates

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









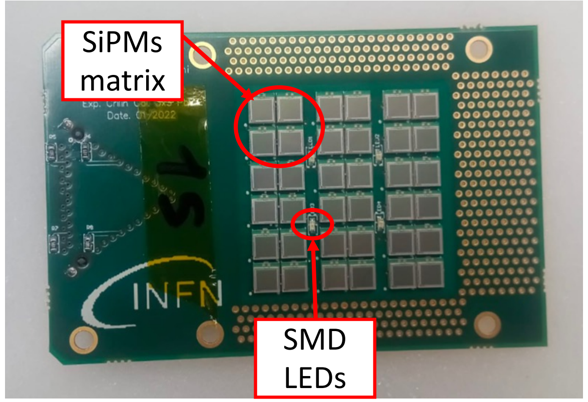
Copper exchanger

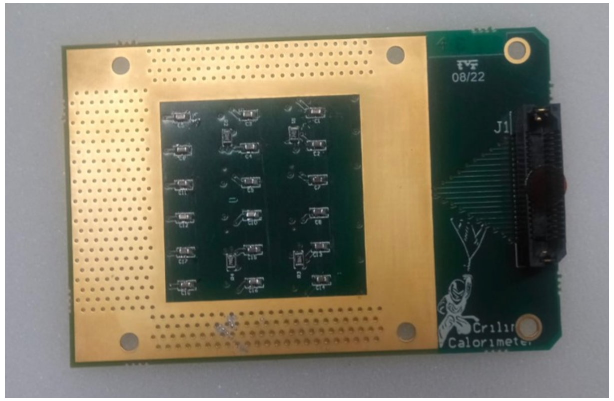
Electronics
SiPMs Board and FEE/Controller

The SiPMs board is made of:

- 36 **10 μm Hamamatsu SiPMs**

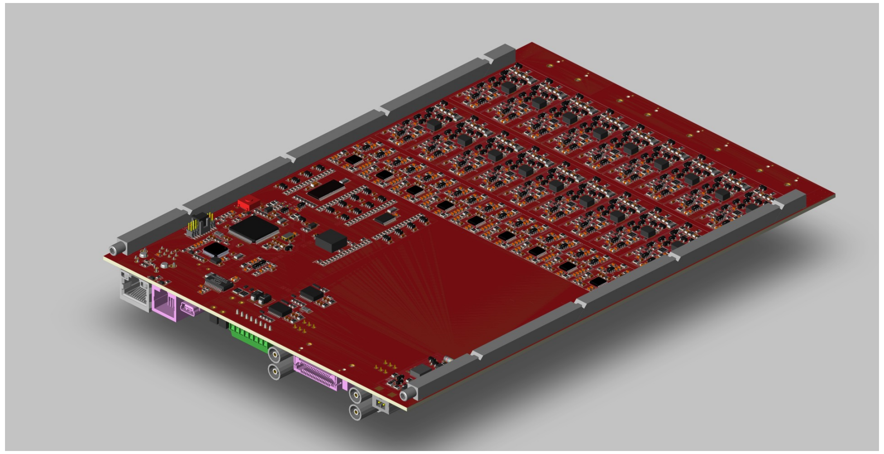
  ⟶ each crystal has **two separate readout channels connected in series**.

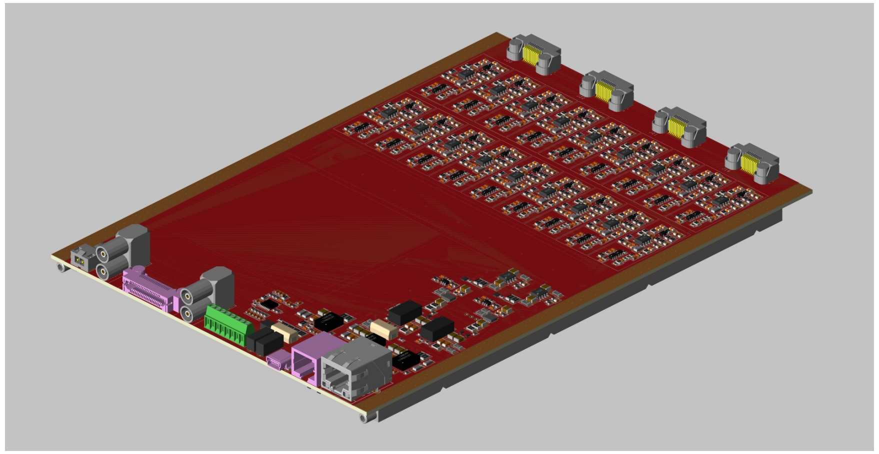




- Four SMD blue LEDs nested between the photosensor packages.

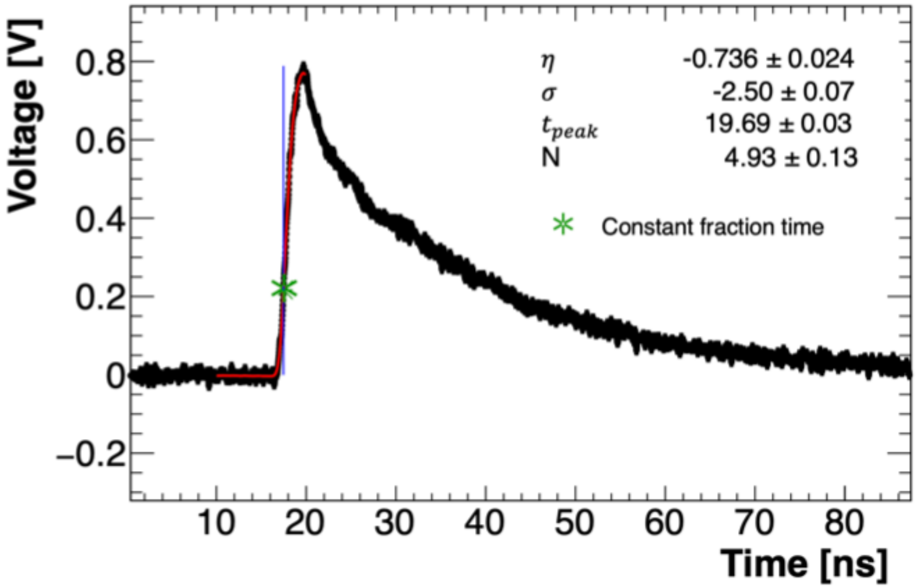
- Controller - 18 Front End electronics channels → under production

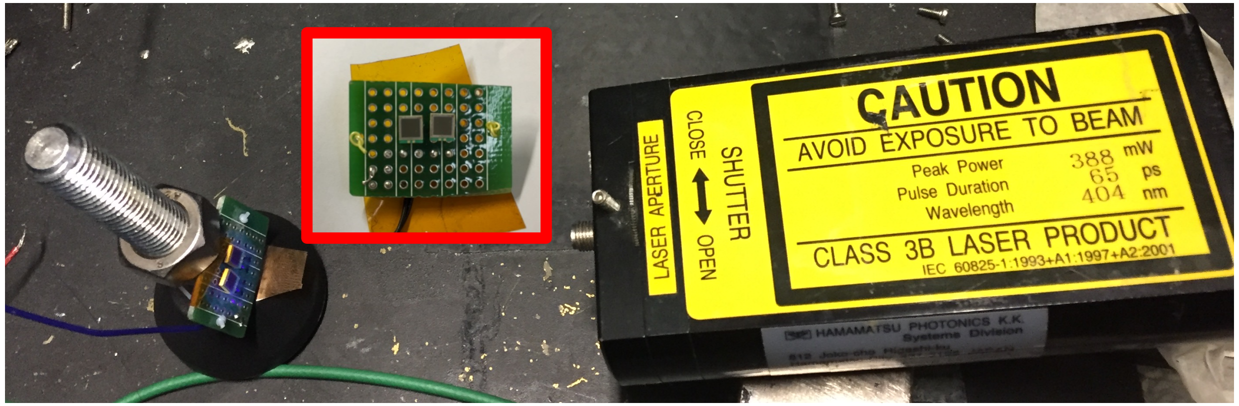




Time resolution studies: the setup

- Two 15 μm SiPM in serial connection + prototype of FEE electronics
- Picosecond UV laser source with variable intensity
- Signals digitized at 40 Gsps
- Three sets of measurements:
  - a) Fixed laser pulse amplitude (1 Volt), 40 Gsps, laser repetition rate from 50 kHz up to 5 MHz;
  - b) Fixed laser pulse amplitude (1 V), 100 kHz laser repetition rate, sampling rate: (2.5 -40) Gsps
  - c) Sampling rate: 40 Gsps, laser repetition rate: 100 kHz, variable laser pulse amplitude

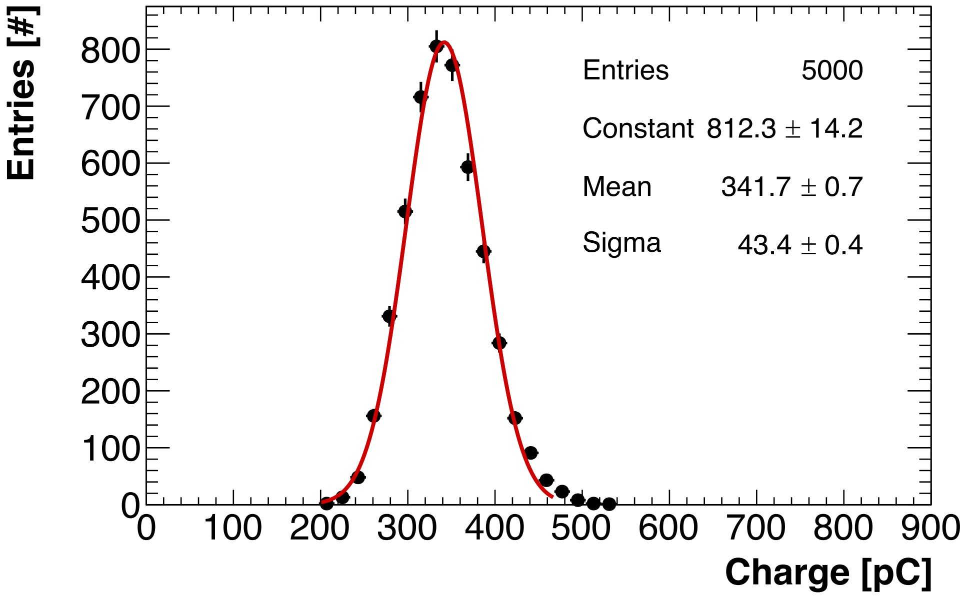


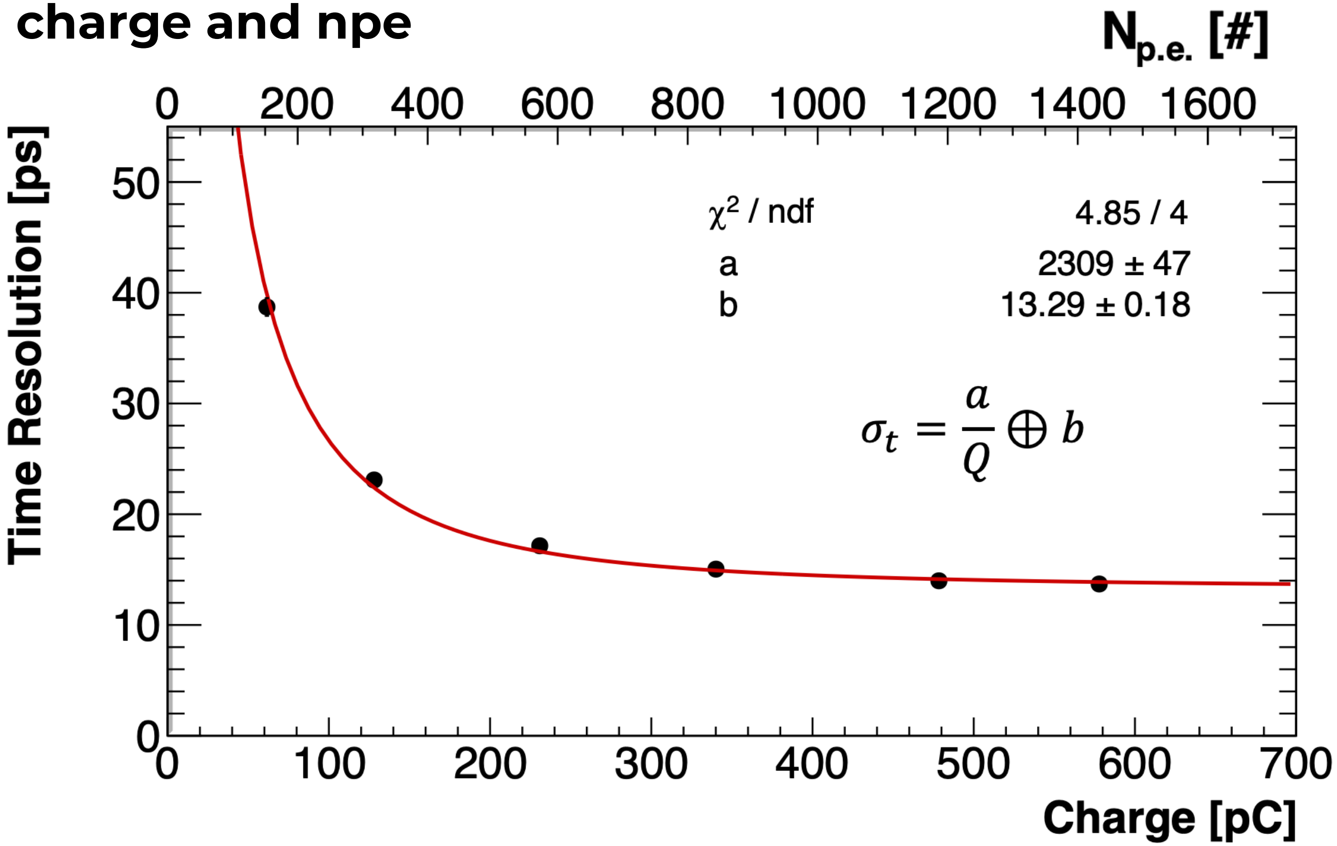


- Dynamic range: (0-2)V
- Fast rising edge ~ 2 ns;
- Full width of ~ 70 ns;
- Timing reconstruction performed **using Constant Fraction method** (~30% of Peak amplitude) on a lognormal fit.

Time resolution studies: laser results

Timing vs mean charge and npe

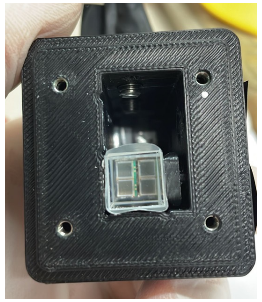


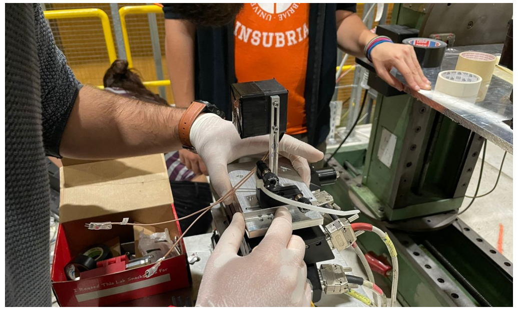


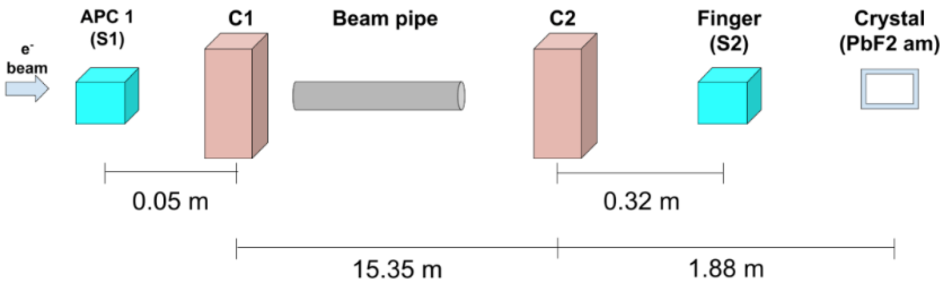
- A resulting **13 ps constant term** contribution to timing resolution was evaluated on fitted data.
- Npe obtained using $N_{p.e.} = \frac{Q}{G_{FEE} \times G_{SiPM} \times e}$, with $G_{FEE} = 7$ and $G_{SiPM} = 3.6 \times 10^5$
- **σ_t << 100 ps** can be expected for energy deposits greater than 1 GeV

Test beam: PbF_2 and PWO

- Validate CRILIN readout electronics and readout scheme
- Study systematics of light collection in small crystals with high *n*
- Measure time resolution achievable for PbF_2 and PWO-UF



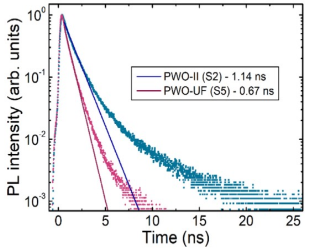




- 80 GeV electrons beam
- Tracking with C1 C2 silicon strips
- Start trigger with S2 scintillator
- Signals digitized at **5 GS/s**

For reference

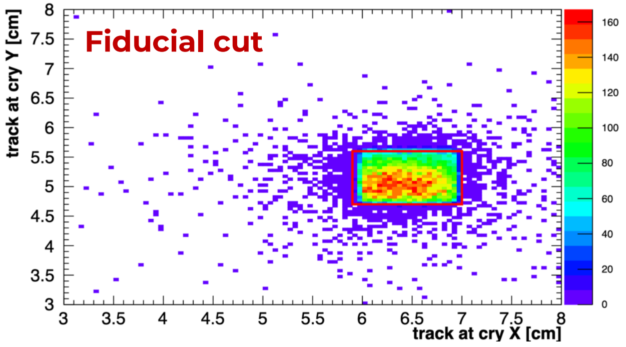
PWO-UF (ultra-fast):
Dominant emission with $\tau < 0.7$ ns
M. Korzhik et al., NIMA 1034 (2022) 166781



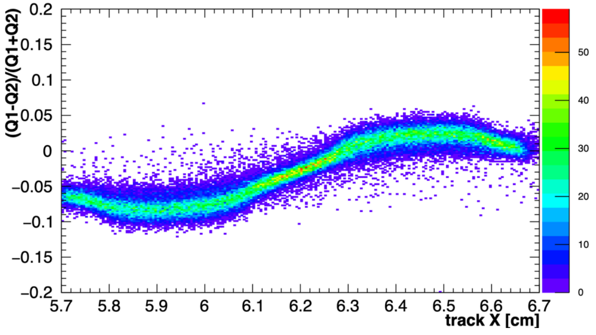
Very Preliminary (last week test beam, thanks Daniele!)

PbF2 + Mylar

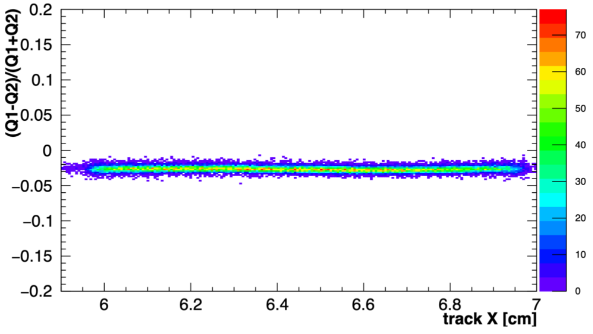
Deposited energy vs 1 single particle in C1 and C2

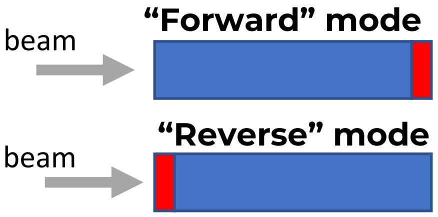


Light propagation "Forward" mode



Light propagation "Reverse" mode





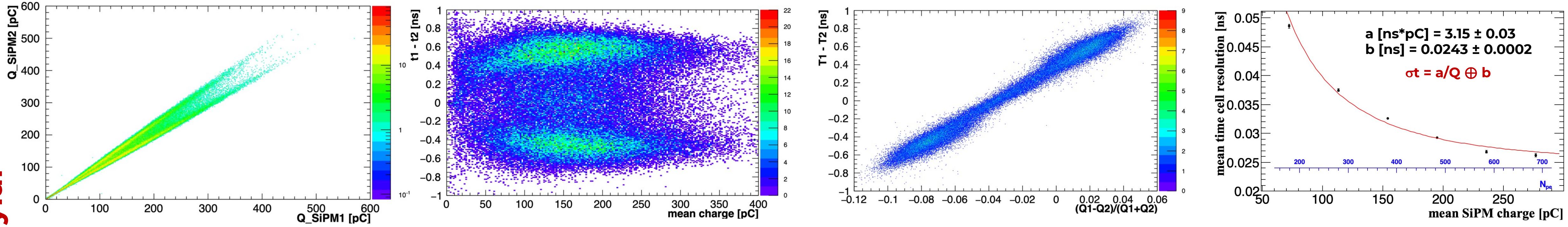
Test beam: PbF_2

Very Preliminary

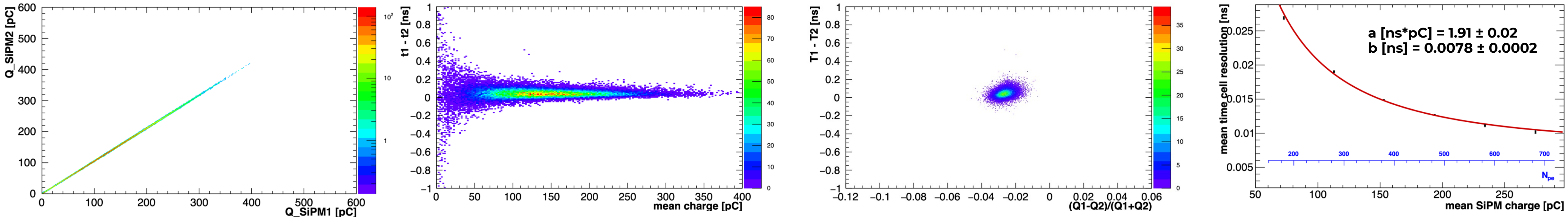
PbF2 + Mylar

"Forward" mode

Charge S1 vs Charge S2 **Time S1 – Time S2 vs Mean Charge** **Time S1 – Time S2 vs Asimmetry** **Time Resolution per charge slices after asymmetry correction**



"Reverse" mode



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

- On-line analysis suggests collimation effects disappear with backside illumination
- We will repeat the "forward" mode with lapped crystals

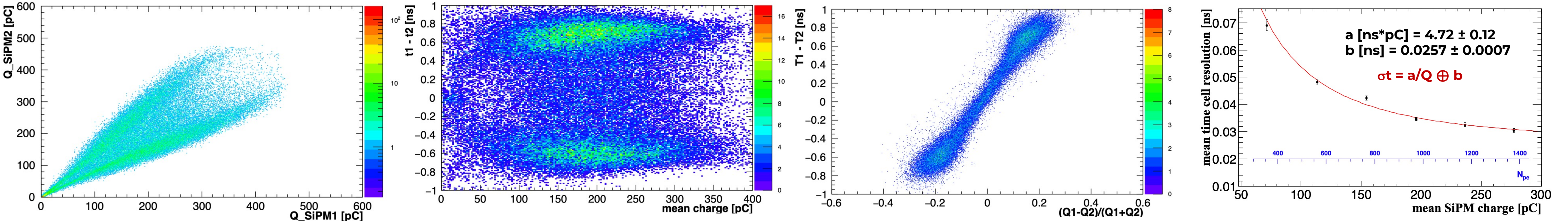
Test beam: PWO-UF

Very Preliminary

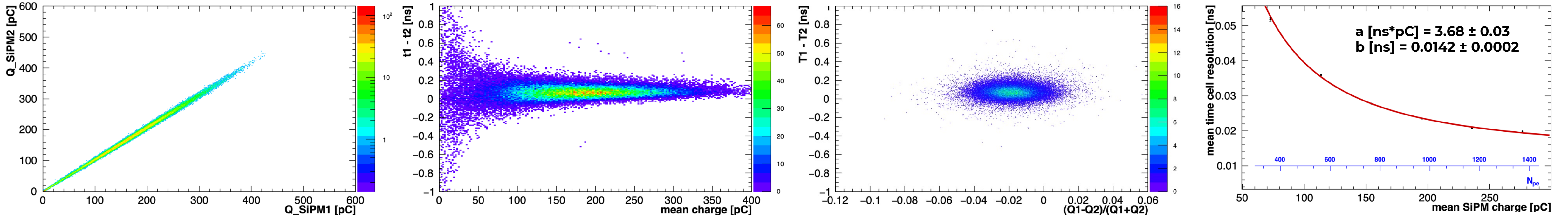
-6 dB (a factor 2) attenuator on both channels

"Forward" mode

Charge S1 vs Charge S2 **Time S1 – Time S2 vs Mean Charge** **Time S1 – Time S2 vs Asimmetry** **Time Resolution per charge slices after asymmetry correction**



"Reverse" mode



PbWO-UF seems work very well

- A factor ~more in LY respect to the PbF2
- Similar timing performances

Conclusions

- Crilin(a) is a semi-homogeneous calorimeter with longitudinal segmentation and excellent timing resolution;

- It represents a good compromise between homogeneous and sampling calorimeter and is well quoted as alternative solution to W-Si ECAL for future MC

- Before the construction of the Proto-1 (3x3 matrix) tests on single components have been performed:
  - Irradiation studies both with neutrons and photons on PbF_2 crystals(b) indicated no significant damages up to 80 krad TID and 10^{13} n/cm^2 fluence(b);
  - Neutron irradiation up to 10^{14} n/cm^2 on SiPMs is ok with 10 um pixel devices

- Proto-0 shows electronics has extremely good time performance in laboratory, confirmed at test beam

- Proto-1 is going to be assembled by the end of 2022 and a test beam with 500 MeV at the Beam Test Facility of the LNF as well as higher energy beam at CERN

(a) Ceravolo, S et al., "Crilin: A CRystal calorImeter with Longitudinal InformatioN for a future Muon Collider" – JINST 17 (2022): P09033

(b) Cemmi, A., et al. "Radiation study of Lead Fluoride crystals" - Journal of Instrumentation 17.05 (2022): T05015.

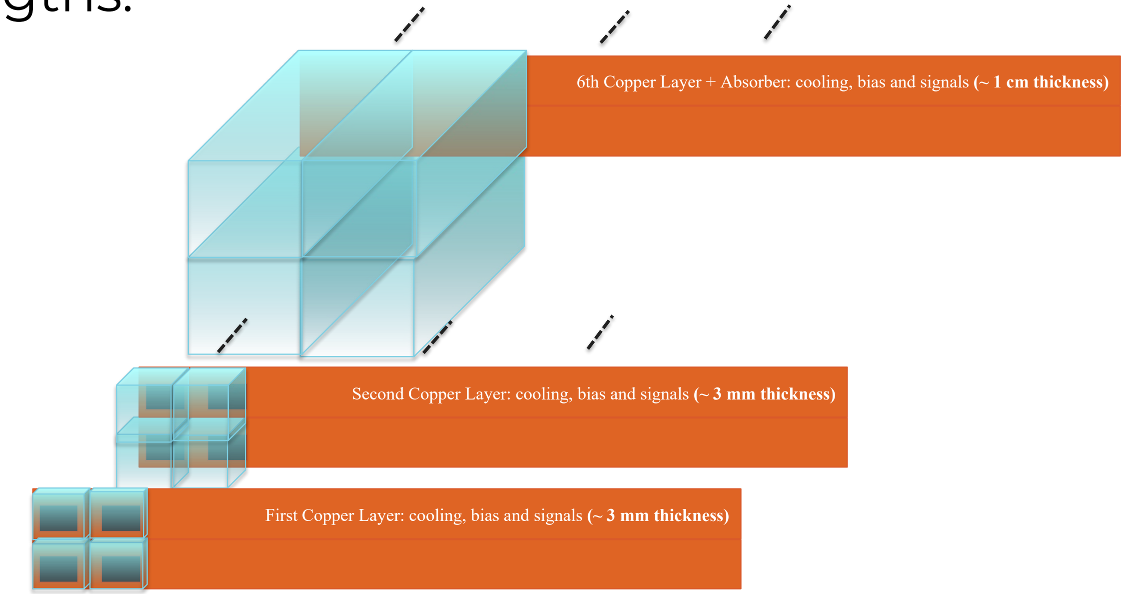
The Lorenzo proposal

- 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.



SPARES

Introduction and Motivation

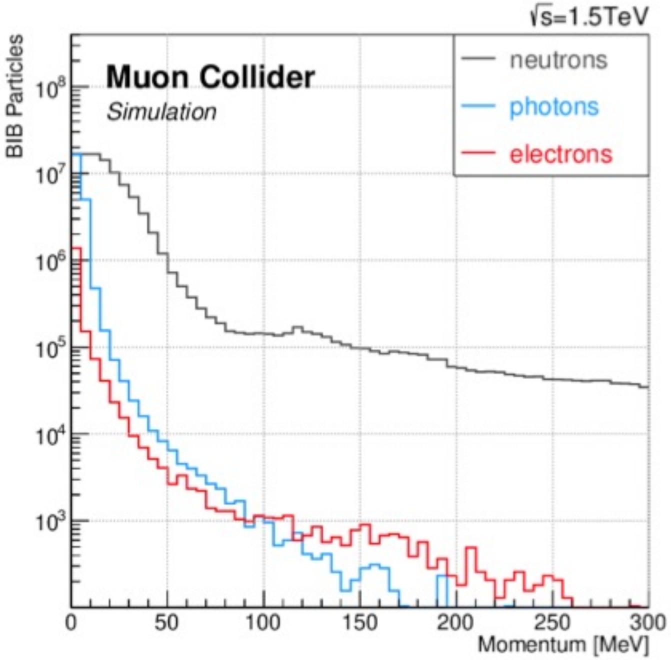
- Muon Colliders (MC) could represent the keystone for accessing the energy frontier of high energy physics

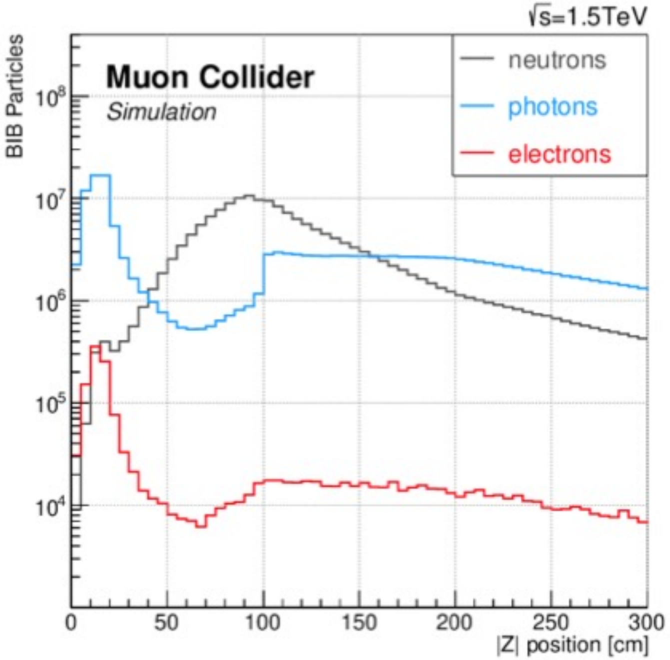
- Great potential, especially in the TeV range:
  - negligible synchrotron radiation ($m_\mu/m_e \sim 200$)→ high collision energy as in hadron colliders;
  - no significant beamstrahlung → improved energy resolution for physics measurements.

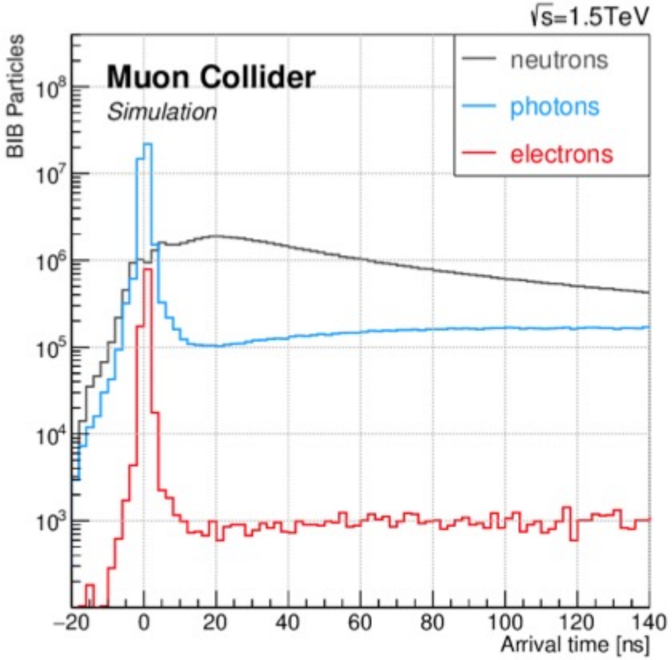
- Challenging development due to the instable nature of muons ($\tau_\mu = 2.2\ \mu s$)
  - Decay products of the circulating μ interacting with the machine elements → not so clean environment;
  - 4×10^5 decays/m at 1.5 TeV with 2×10^{12} μ/beam→$O(10^{10})$ background reach the interaction region and 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;





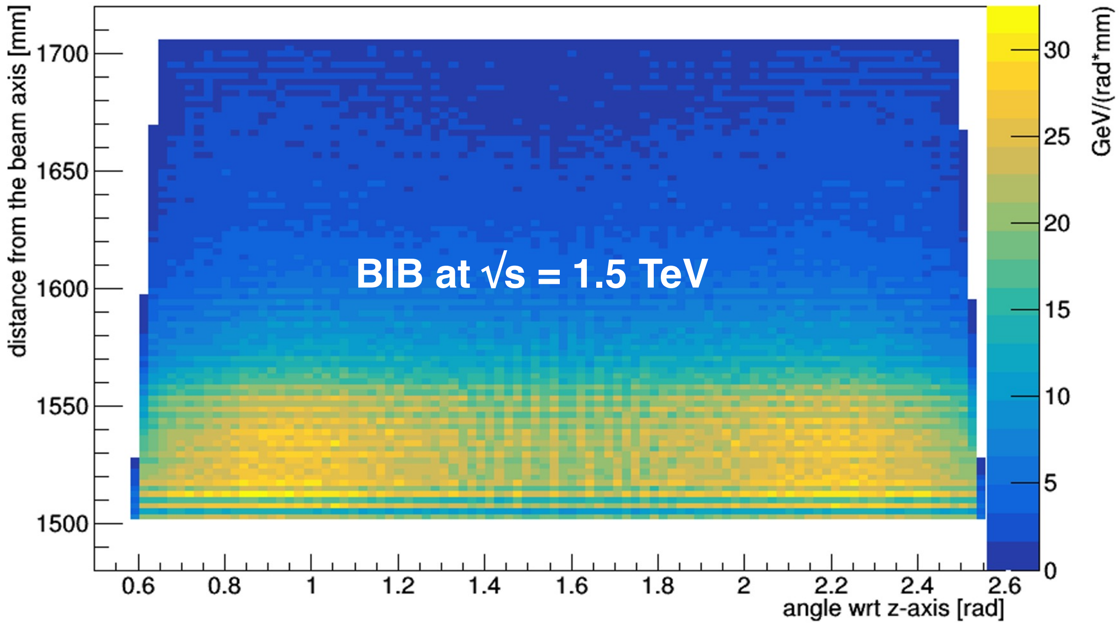


BIB in ECAL

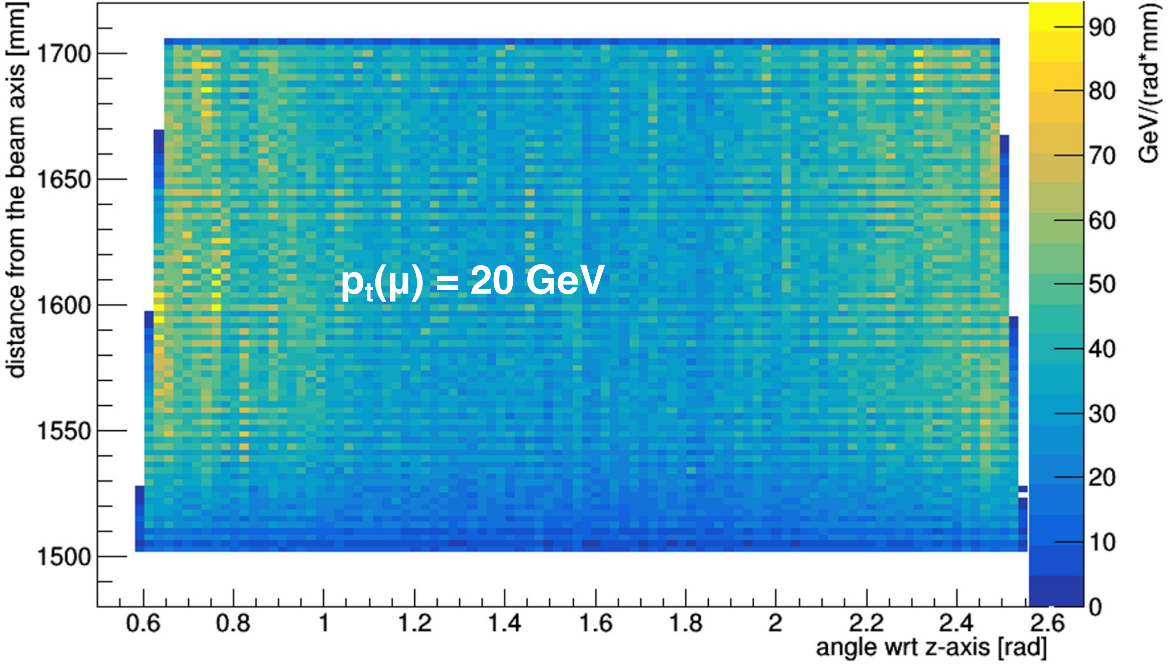
Timing and longitudinal segmentation play a key role in BIB suppression

- 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

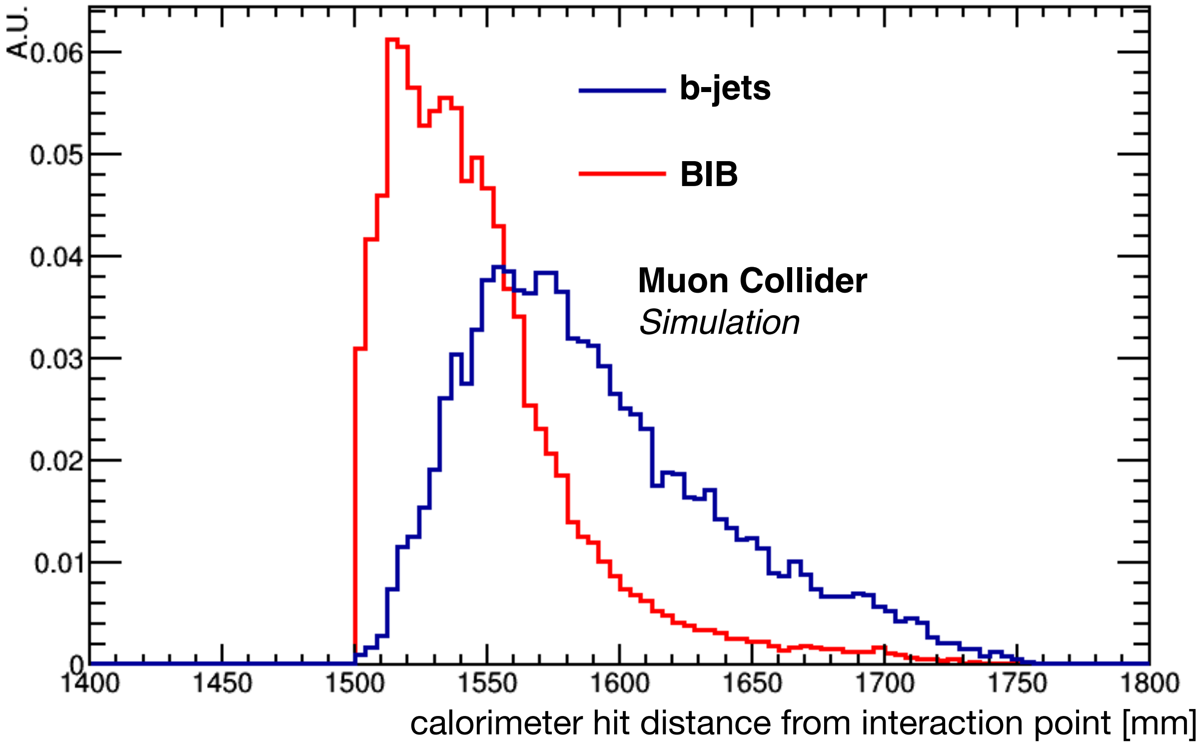


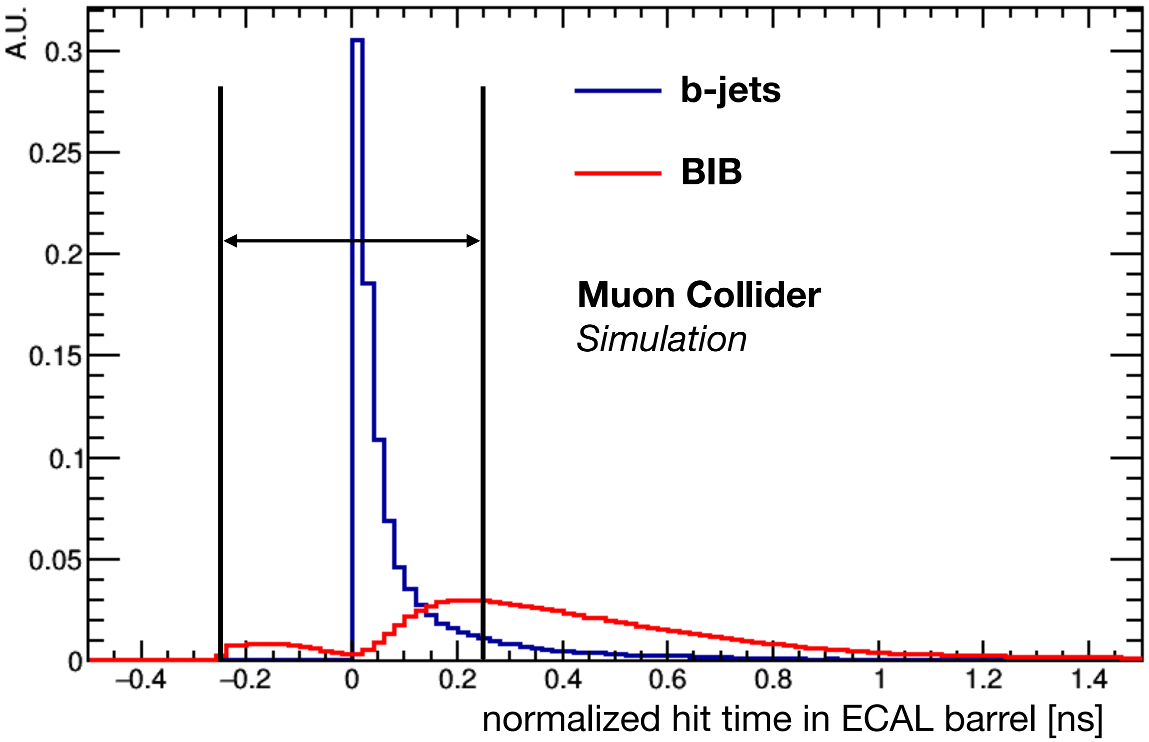
Energy released in ECAL barrel by uniformly distributed prompt muons in the (θ,φ) space



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.**

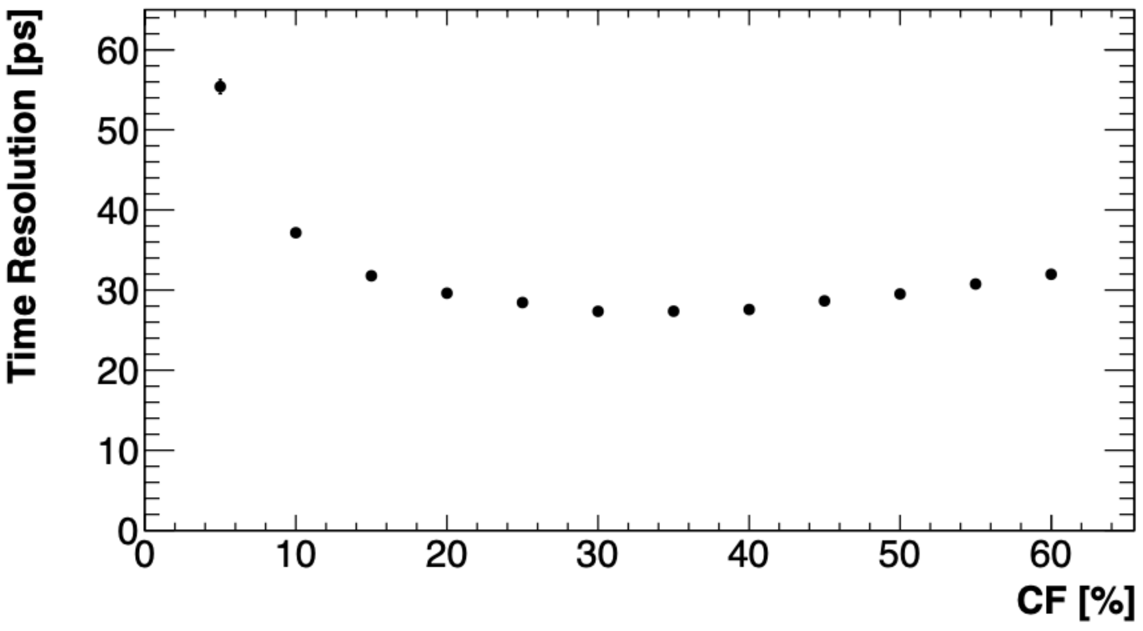




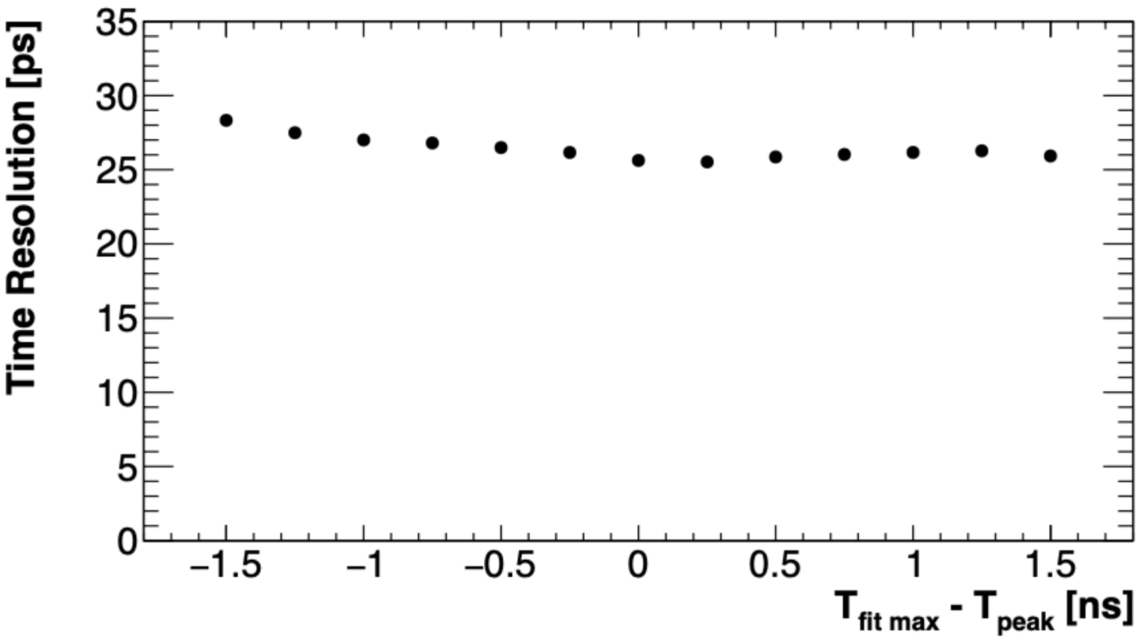
Constant fraction and fit window

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

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

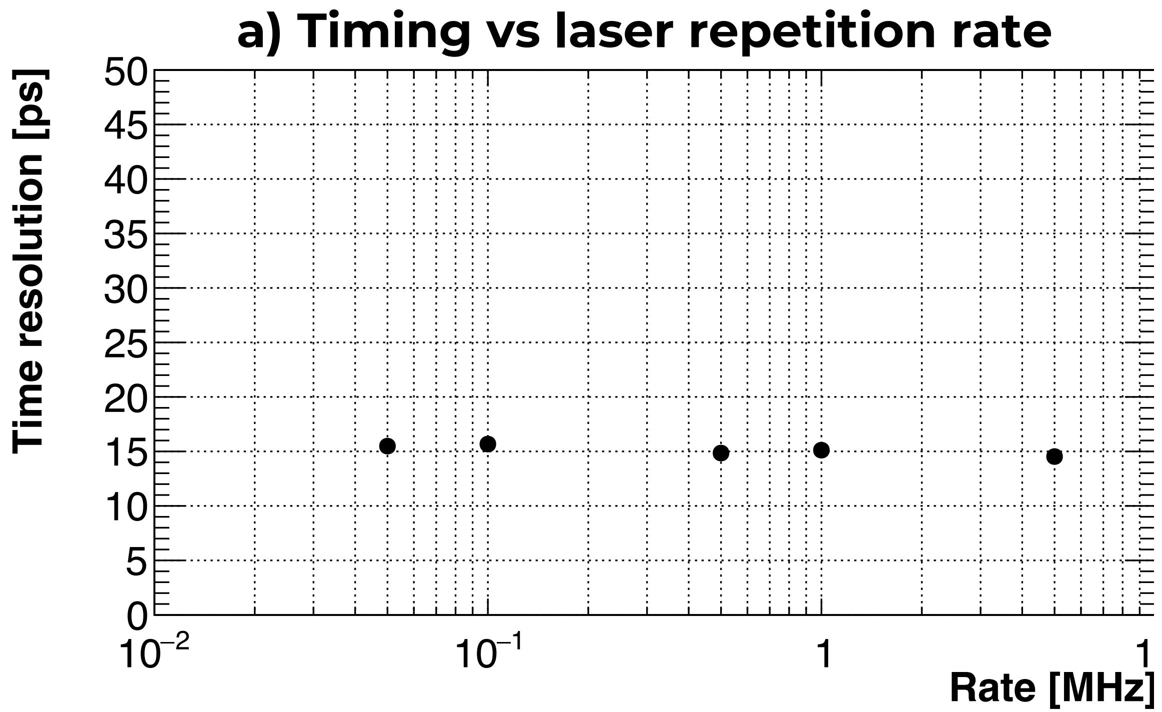


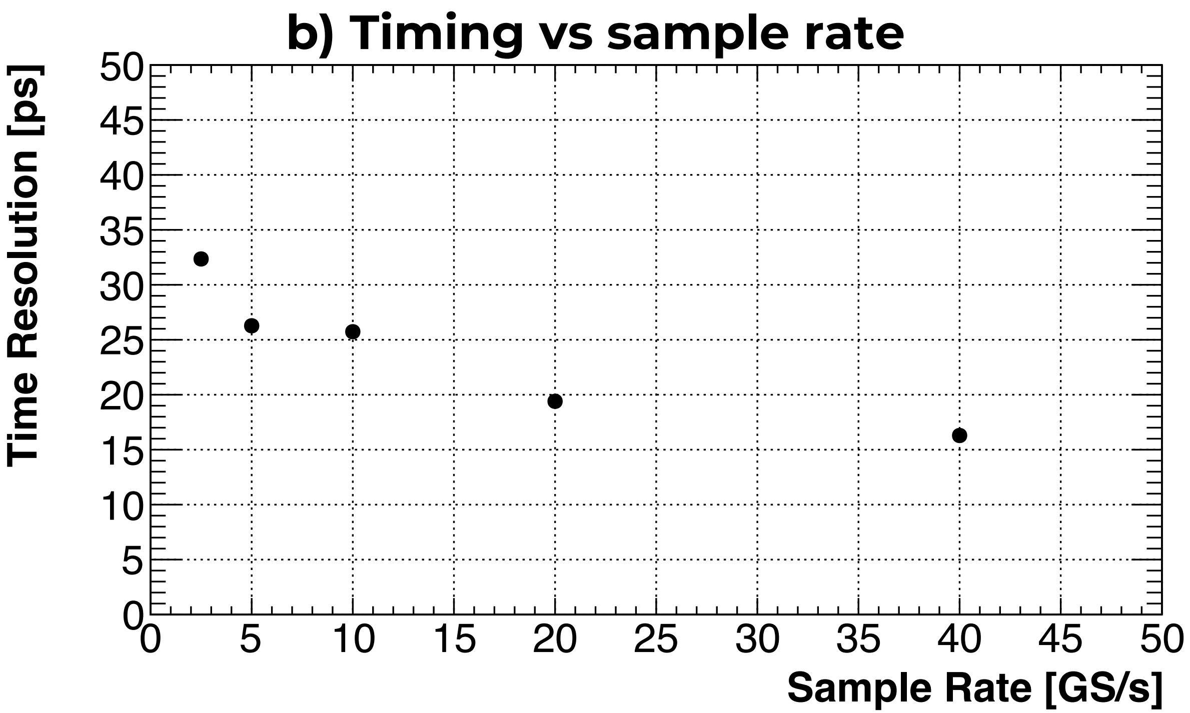
Best constant fraction: 30%



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

Time resolution studies: first results (1)


a) Timing vs laser repetition rate


b) Timing vs sample rate

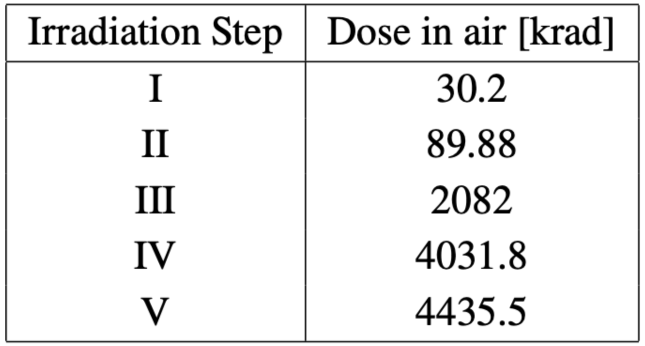
Constant behaviour meaning that the **waveform stays unchanged in the 50 kHz-5MHz range**.

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

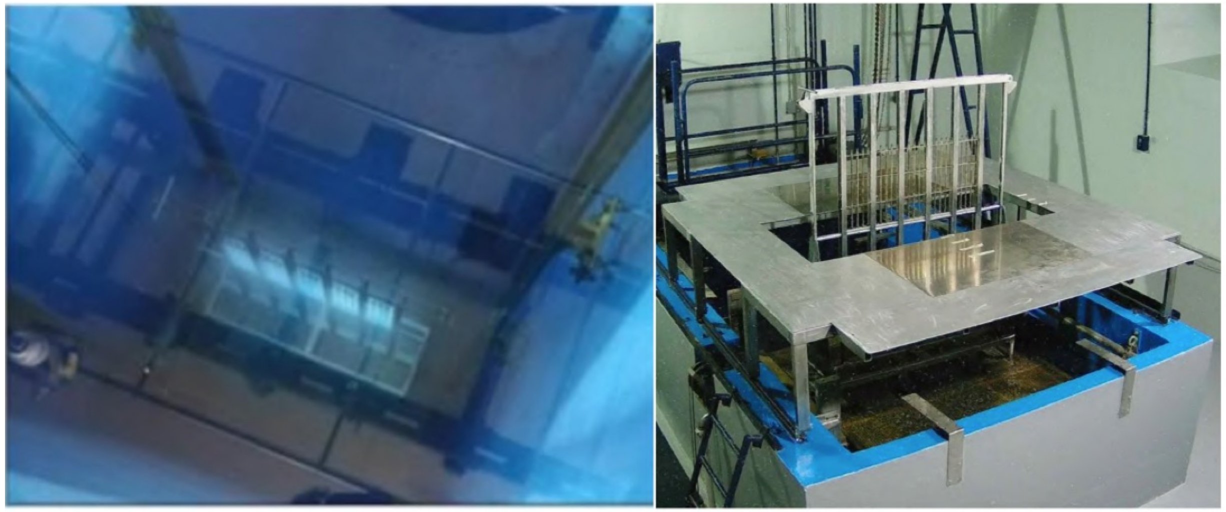
Calliope facility:

- 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

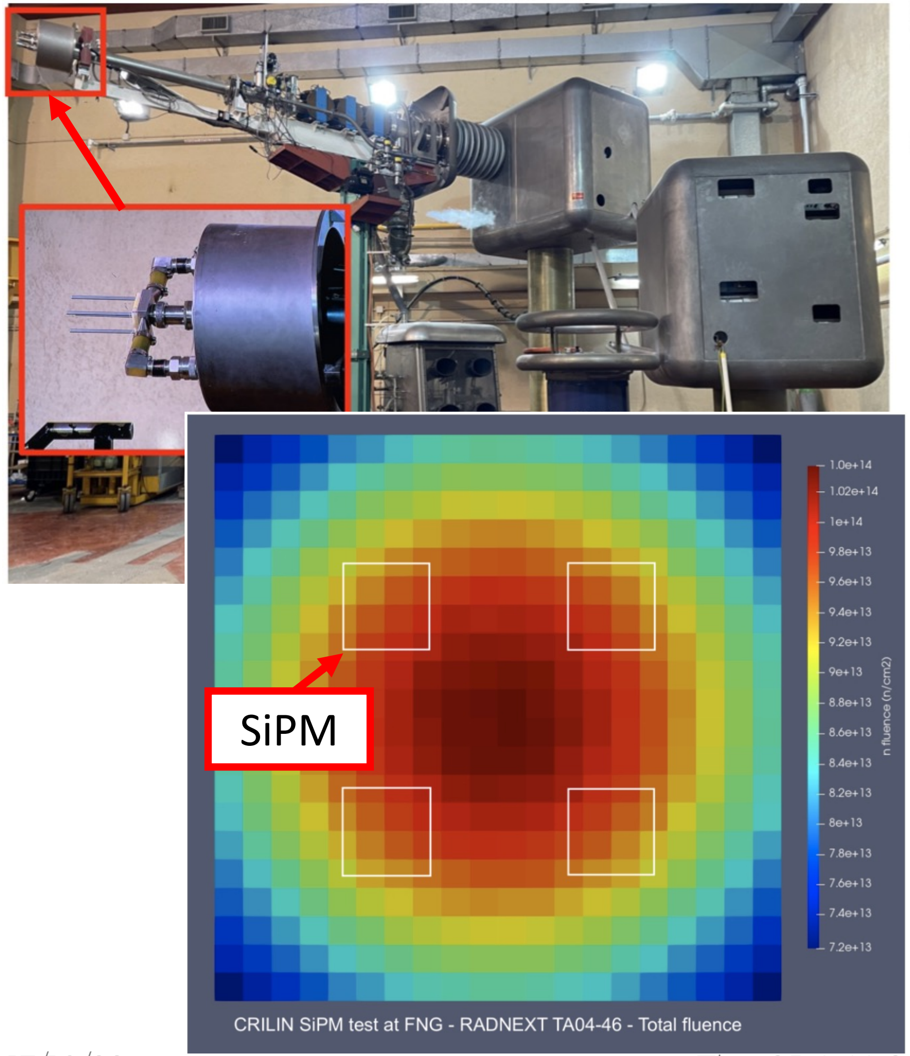


FNG facility:

- 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.

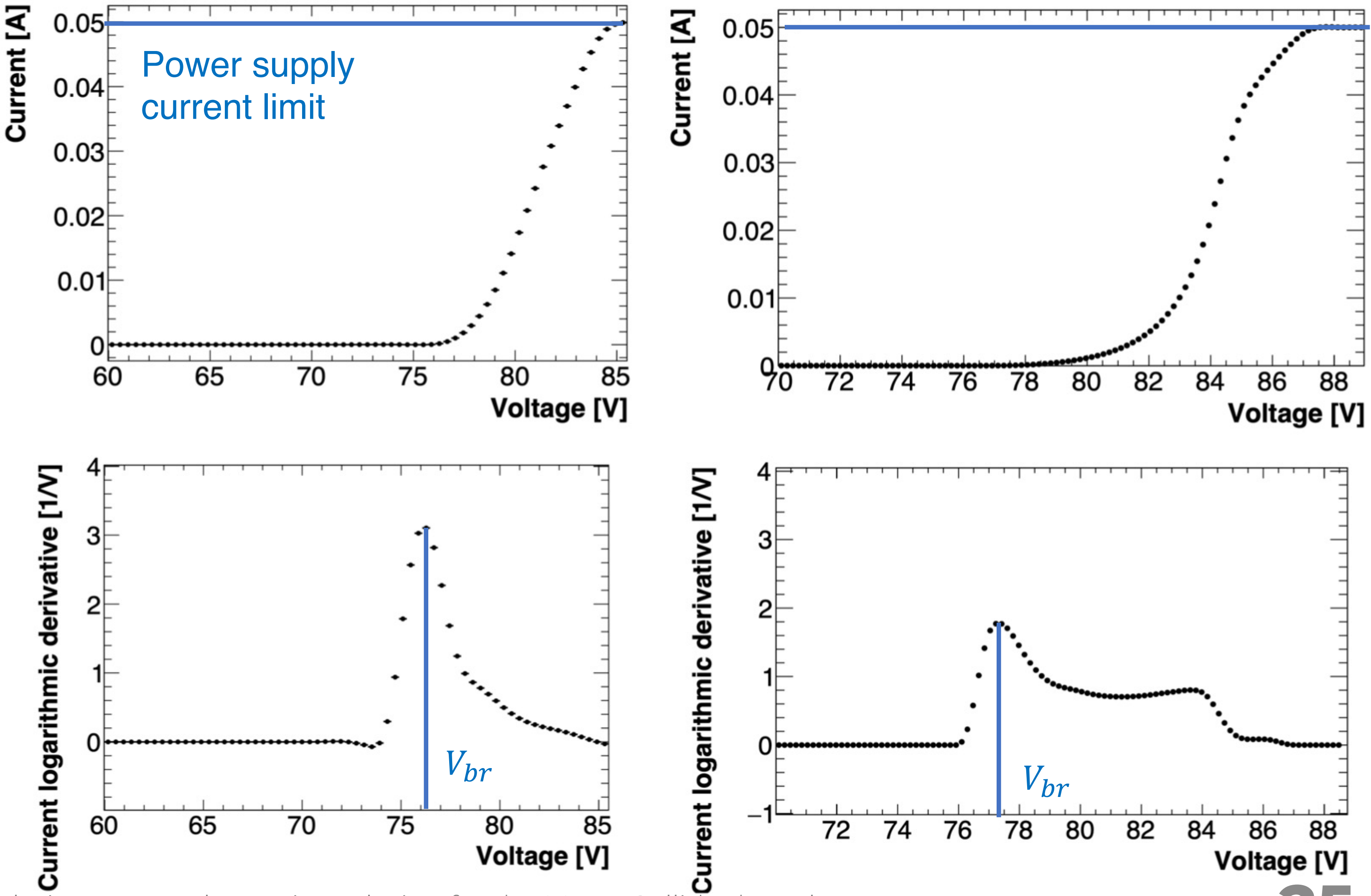
SiPMs Characterisation

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)



CRILIN SiPM test at FNG - RADNEXT TA04-46 - Total fluence

15 μm **10 μm**

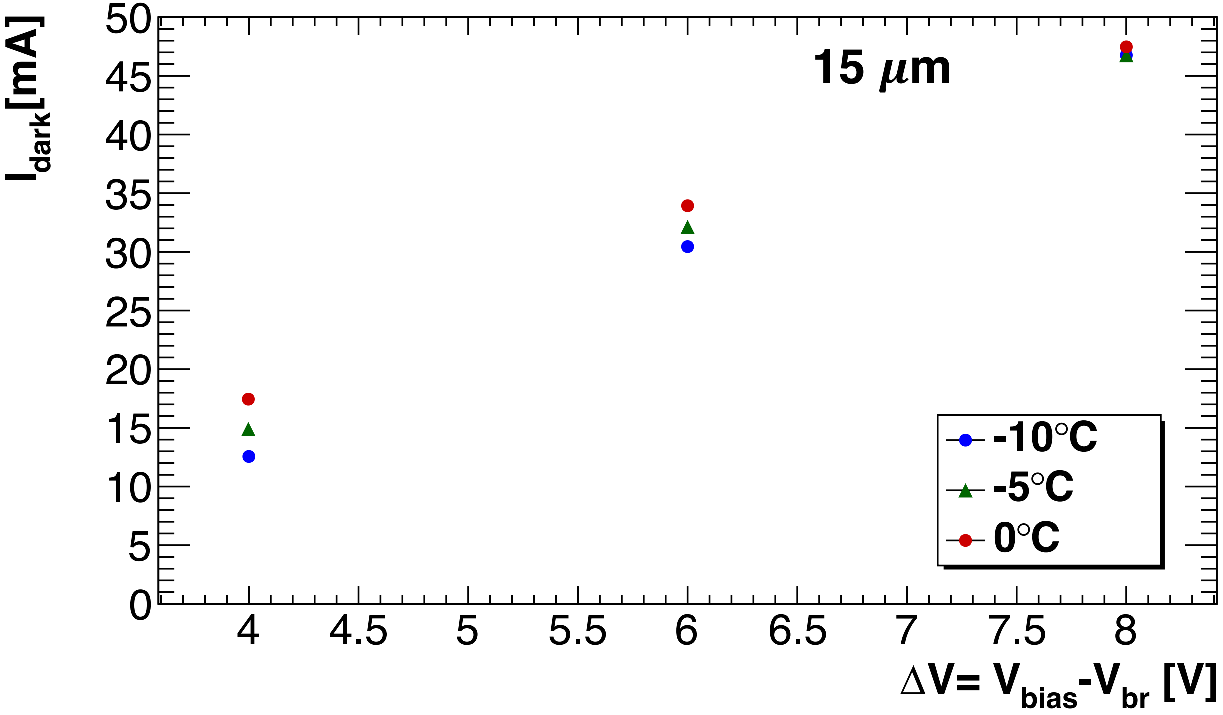


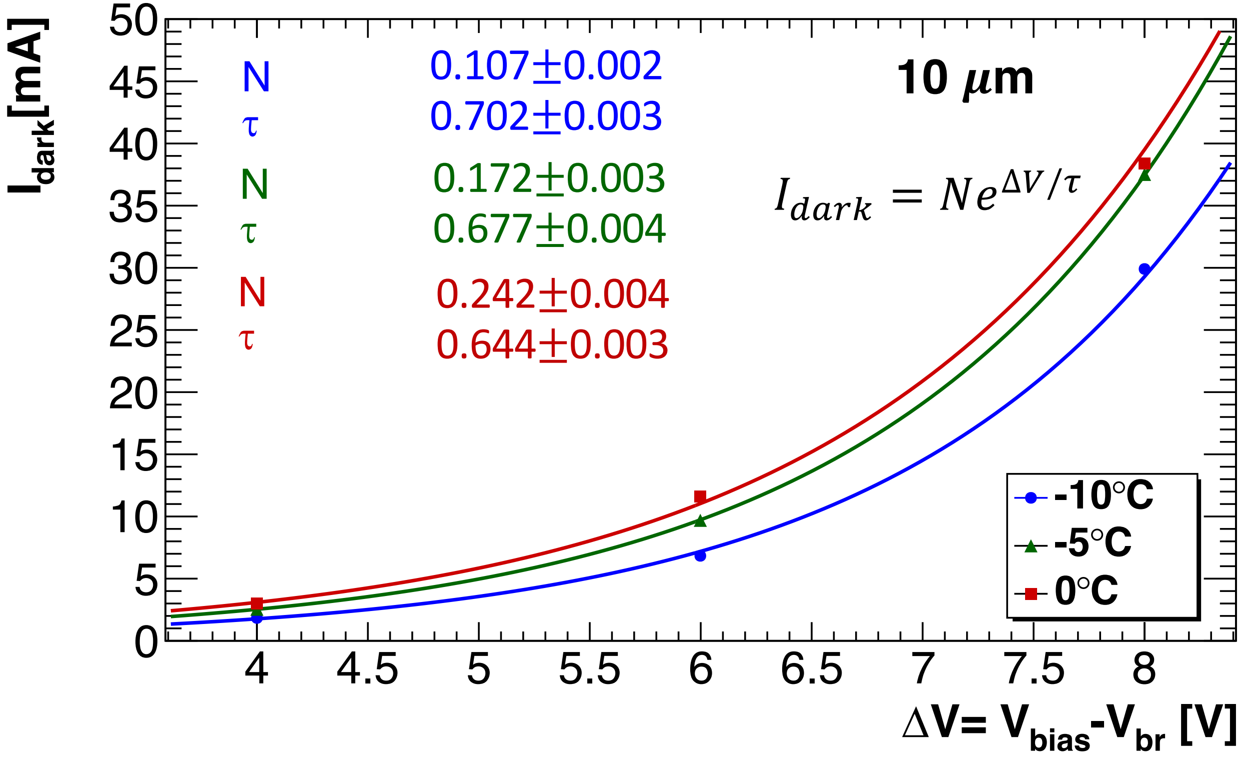
SiPMs Characterisation-2

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

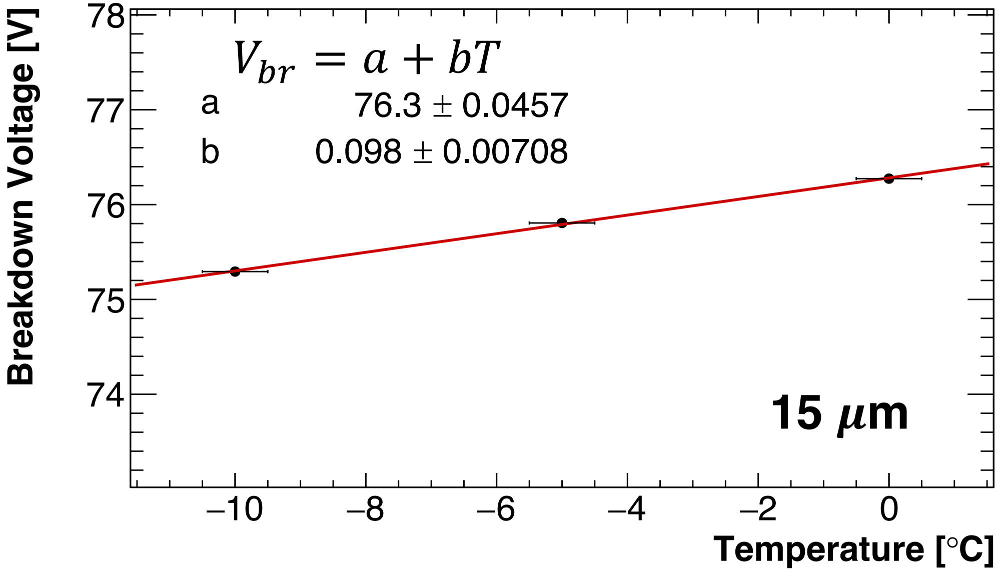
The percentage variation of the breakdown voltage while the temperature changes of 1°C: for the **15 μm** SiPM is **9.8%/°C** and for the **10 μm** one is **7.3%/°C.**

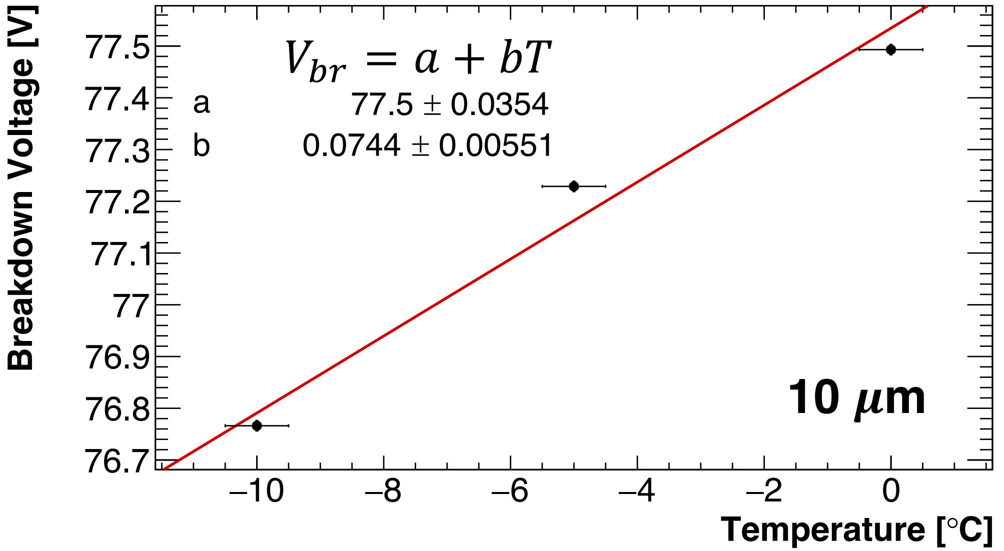
15 μm

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

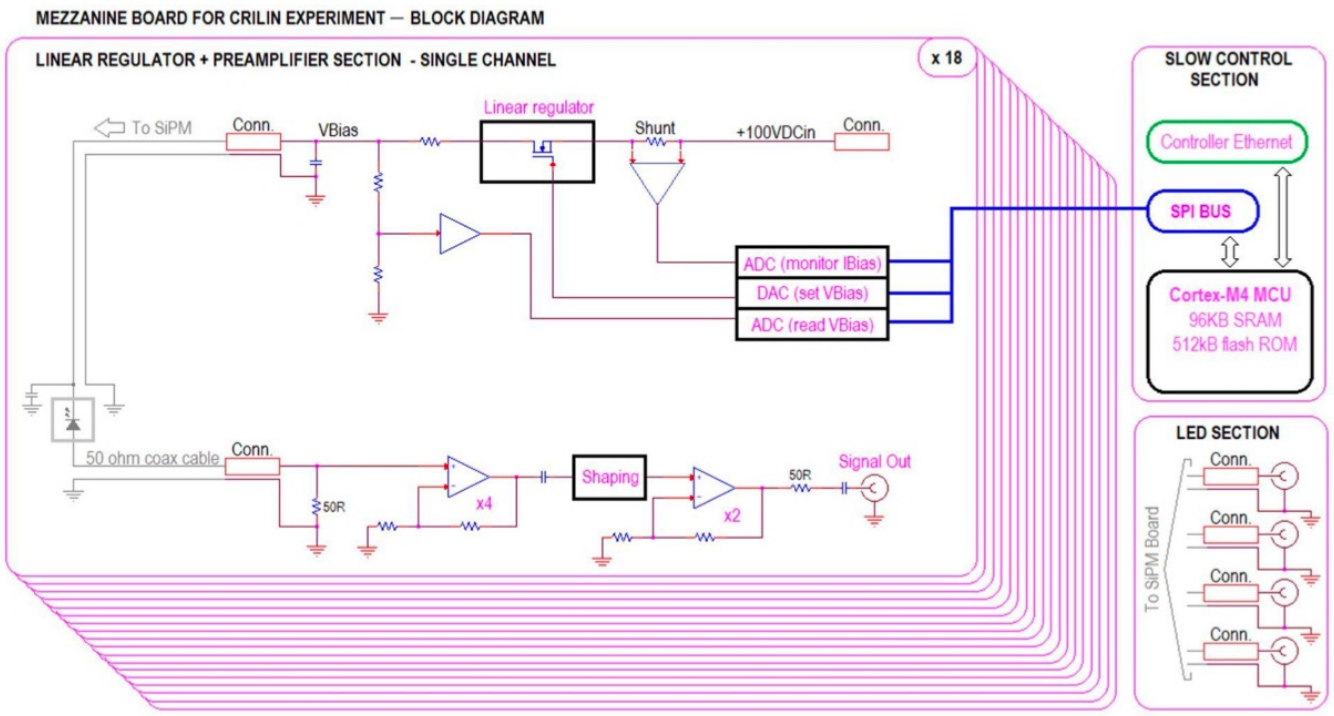




Electronics – Mezzanine Board

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?