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

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International MUON Collider Collaboration

ICHEP 2022 BOLOGNA

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.

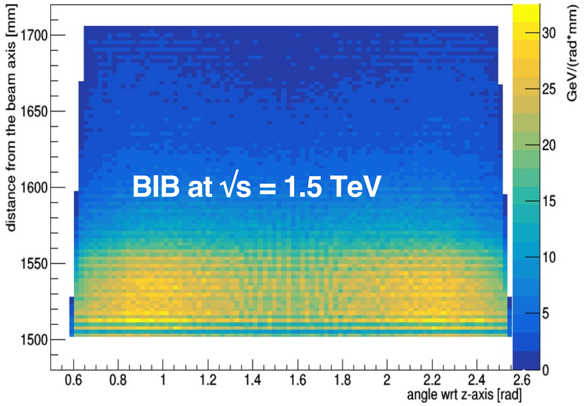
- Challenging development due to the instable nature of muons (τ_μ = 2.2 μs)
  - Decay products of the circulating μ interacting with the machine elements → not so clean environment;
  - $4{\times}10^5$ decays/m at 1.5 TeV with $2{\times}10^{12}$ μ/beam→O(10^{10}) background reach the interaction region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

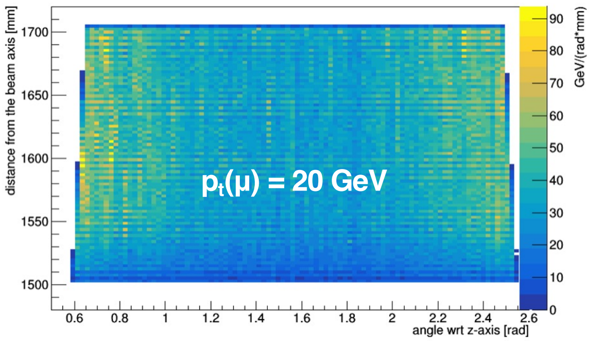
Timing and longitudinal segmentation play a key role in BIB suppression

- 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

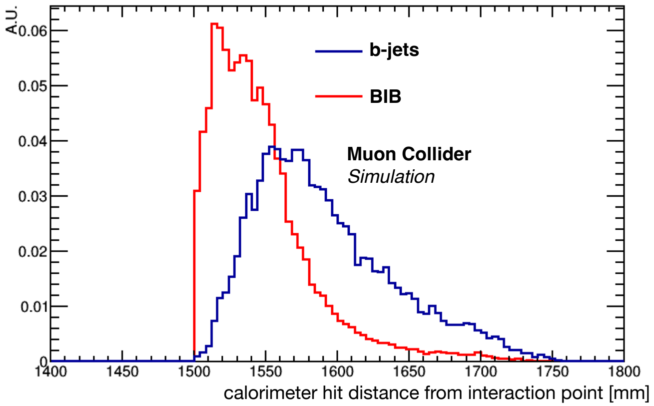
Energy released in ECAL barrel by one BIB bunch crossing

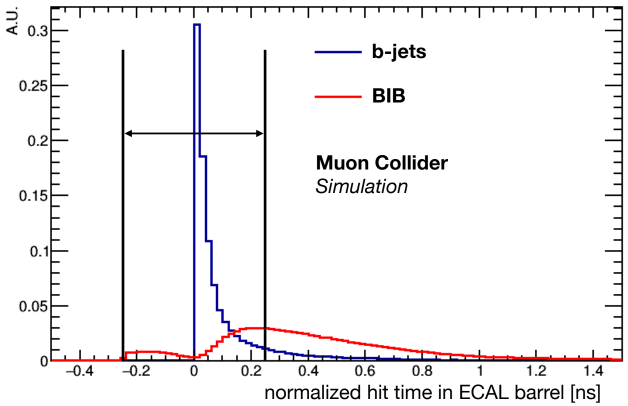


Energy released in ECAL barrel by uniformly distributed prompt muons in the (θ,φ) space



- 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;**
- **fast response** (small integration window) is essentially to **reduce energy contribution** from BIB

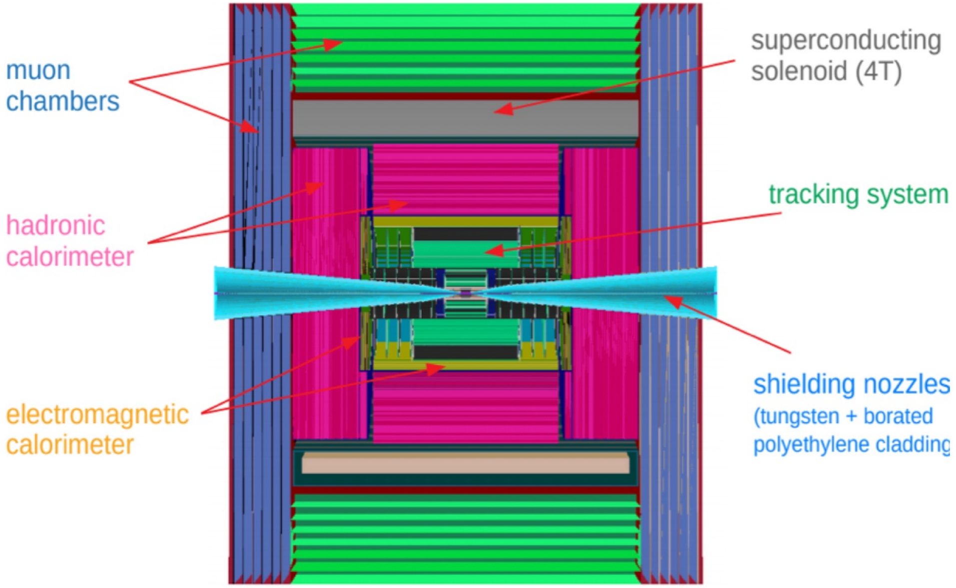


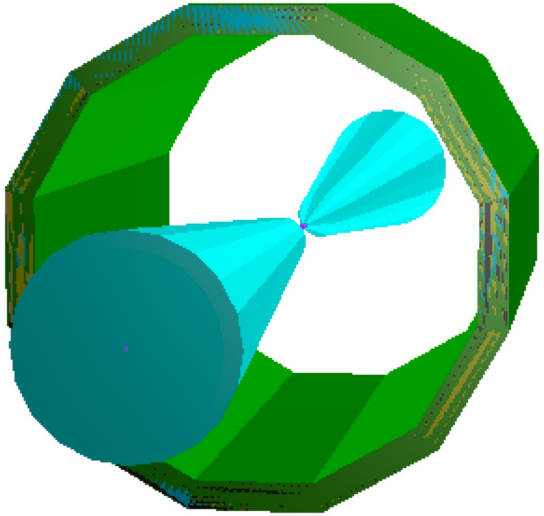


Bartosik, Nazar, et al. "Simulated Detector Performance at the Muon Collider." arXiv preprint arXiv:2203.07964 (2022).

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 15μm 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

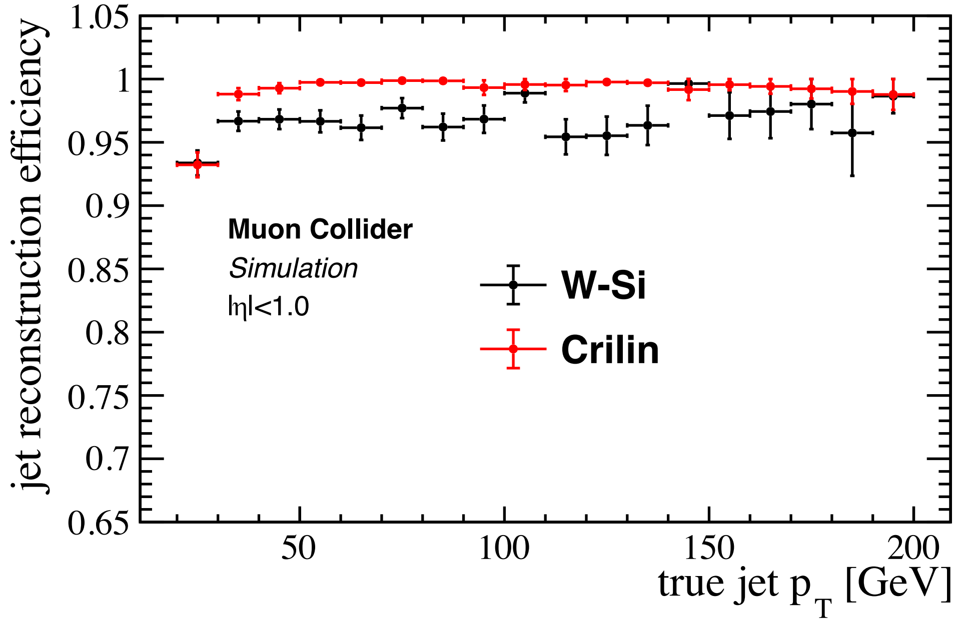


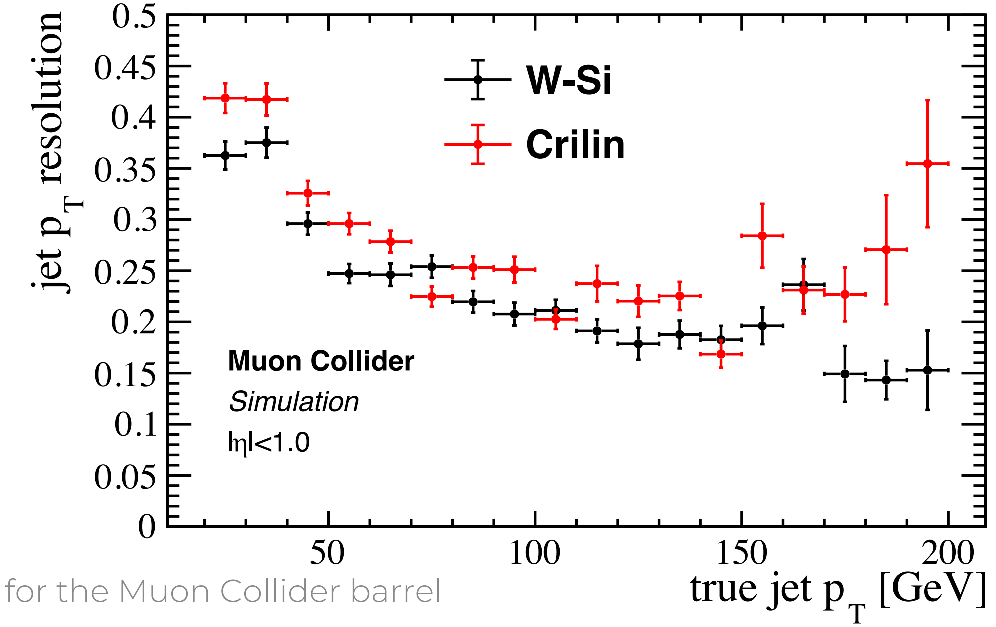


Crilin barrel design for a Muon Collider

Crilin: an alternative solution

- 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

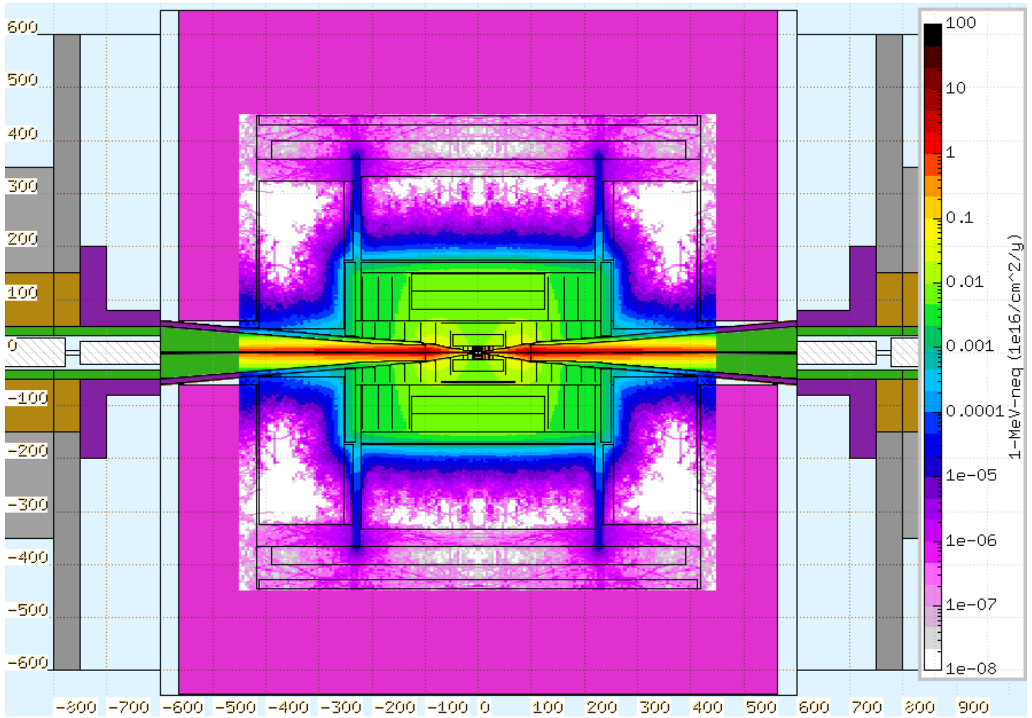




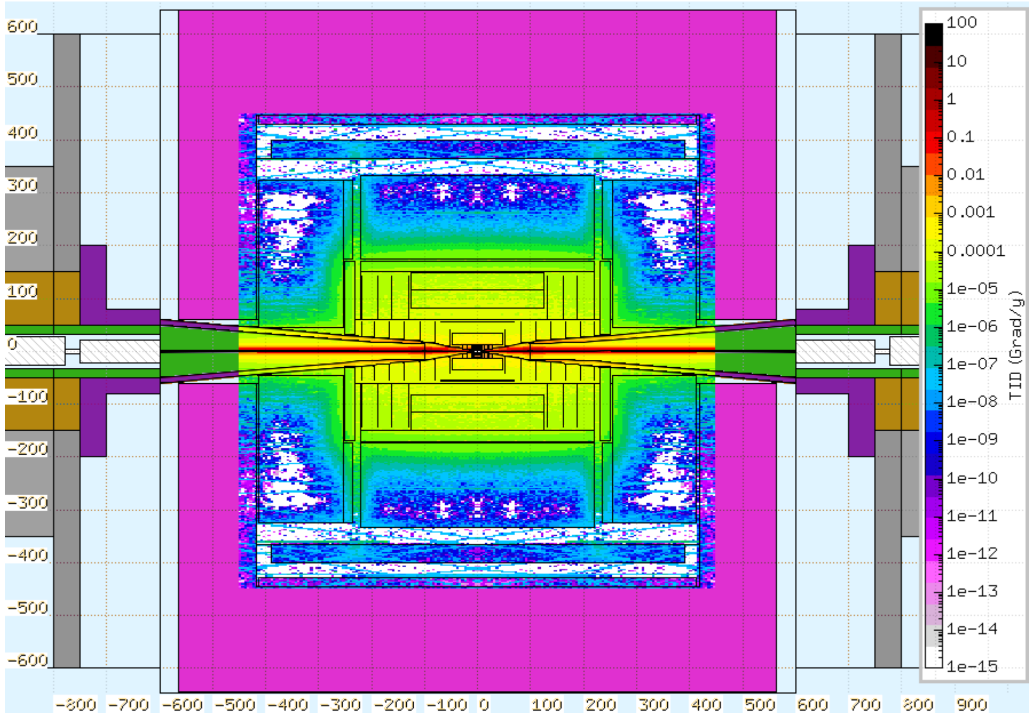
Radiation environment

- FLUKA simulations implementing the BIB yielded were carried out at $\sqrt{s} = 1.5$ 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 ~ 10^{-4} Grad/year

1 MeV neutron equivalent

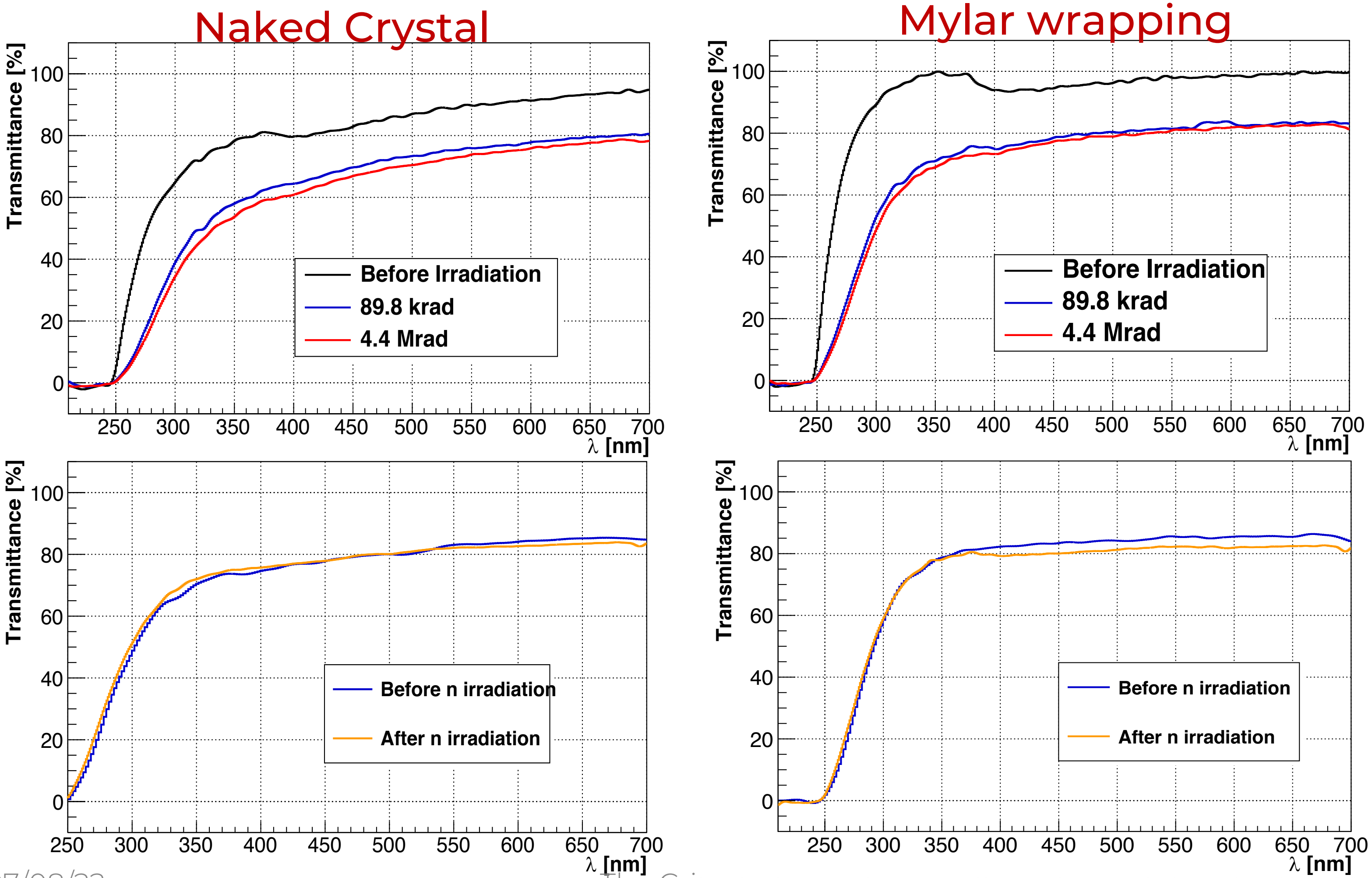


Total Ionizing dose



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/cm²**)



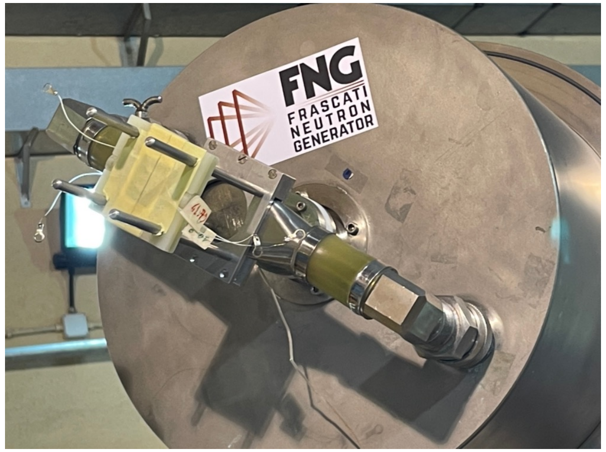
- After a TID ~ 80 krad no significant decrease in transmittance → saturation effect caused by the damage mechanism

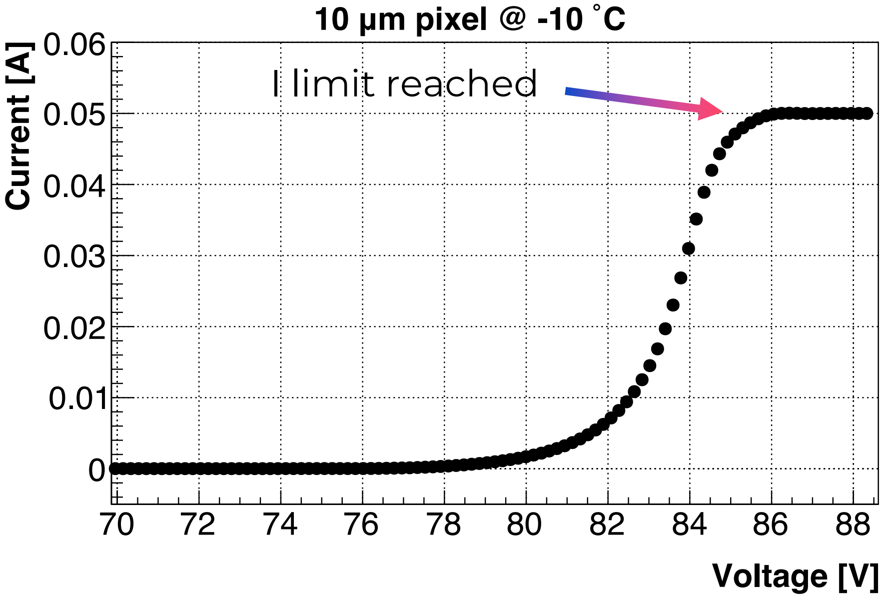
- Transmittance after n irradiation evaluated after 14 days show no deterioration → possible natural annealing

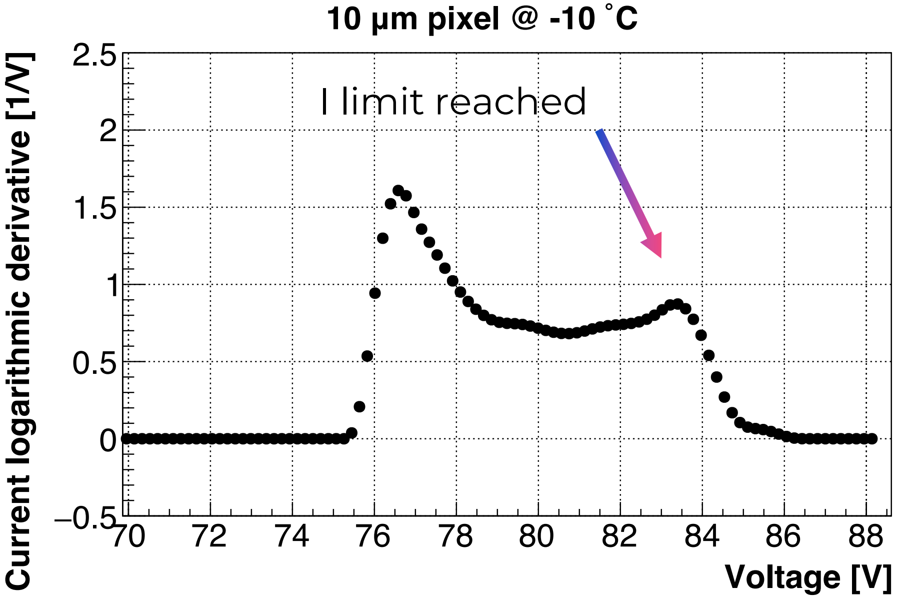
SiPM radiation hardness

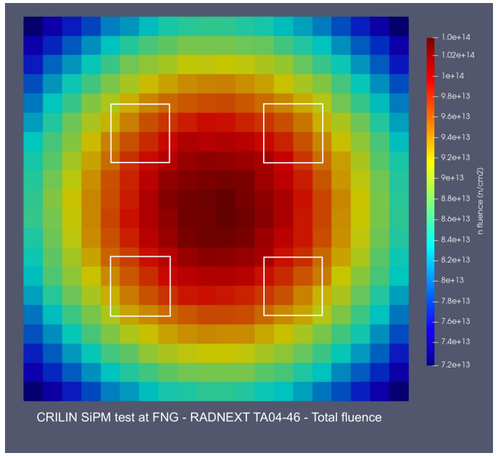
The main SiPM damage due to n irradiation is related to the increase of the dark current

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





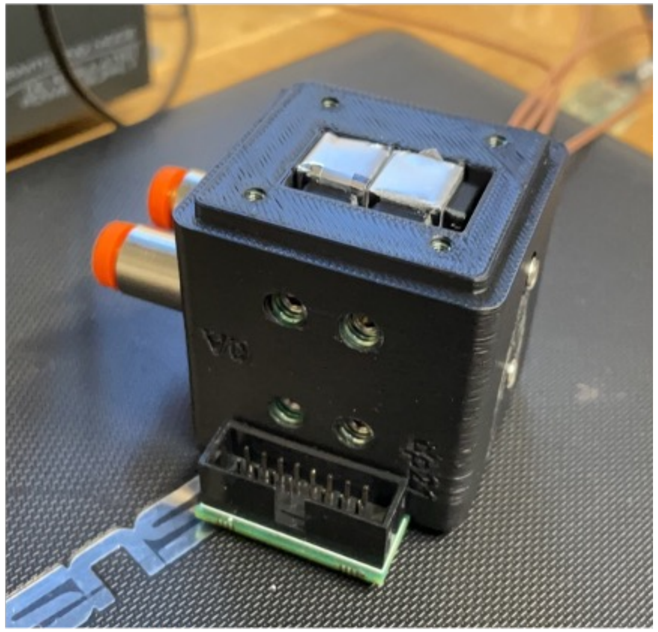




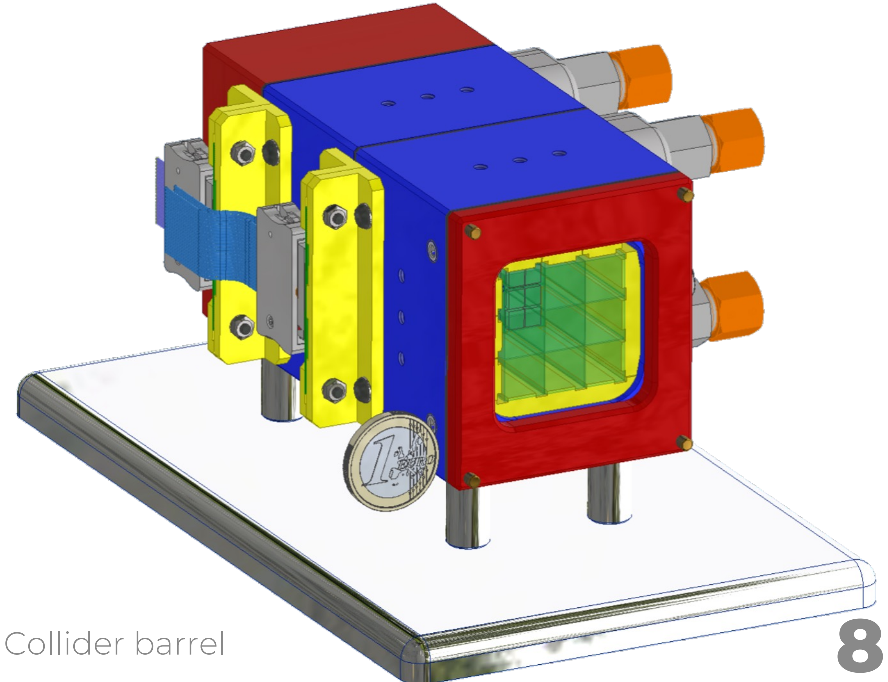
Temperature[°C] ±0.5	V_{br} [V] ±0.06	I(V_{br}+4V) [mA] ±0.006	I(V_{br}+6V) [mA] ±0.006	I(V_{br}+8V) [mA] ±0.006
-10	76.58	2.188	8.193	35.137
-5	77.09	3.003	11.512	40.484
0	77.42	3.555	13.909	40.560

Crilin prototype

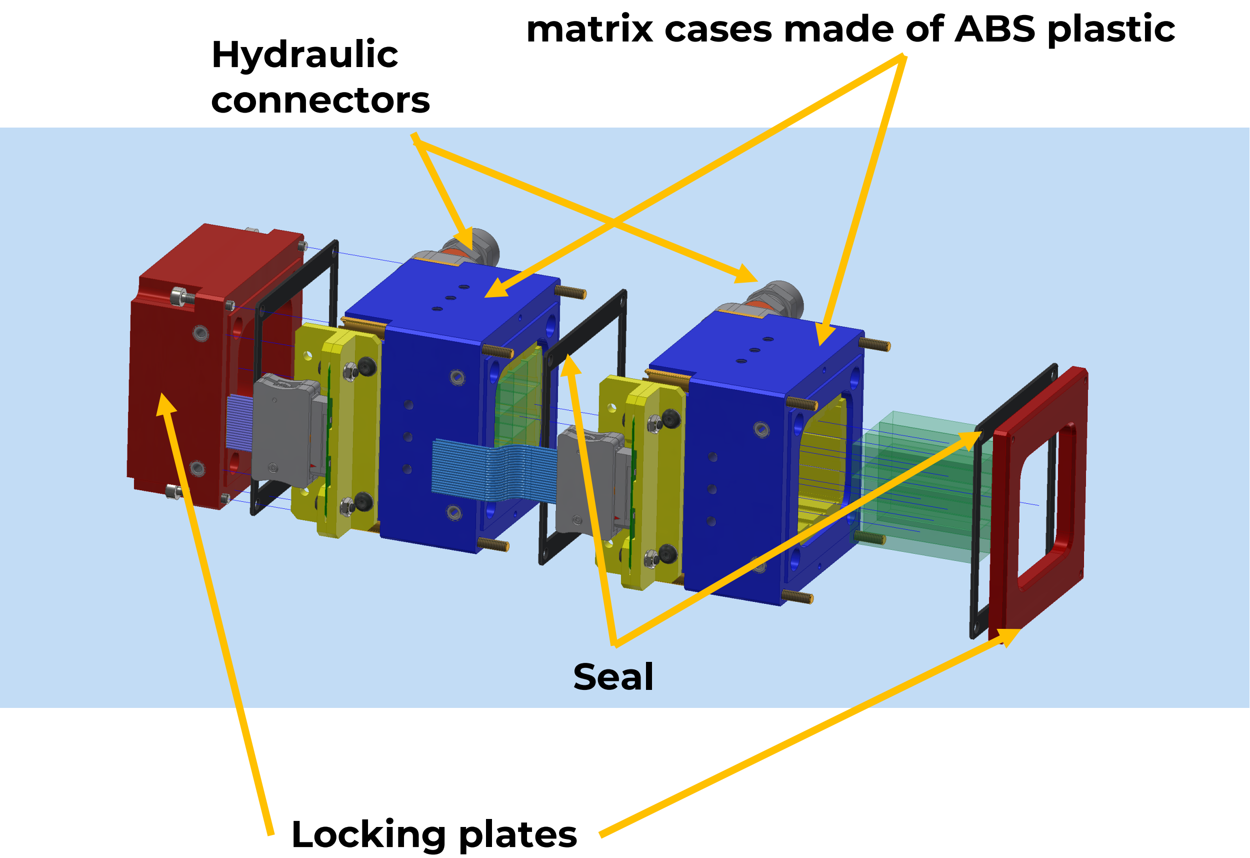
- **Proto-0**: 1 module composed of 2 crystals readout by 4 SiPMs
  - validate the design choices characterizing in detail the response of crystals and photosensors,
  - Good results from a Test Beam @H2 facility,CERN, in 2021



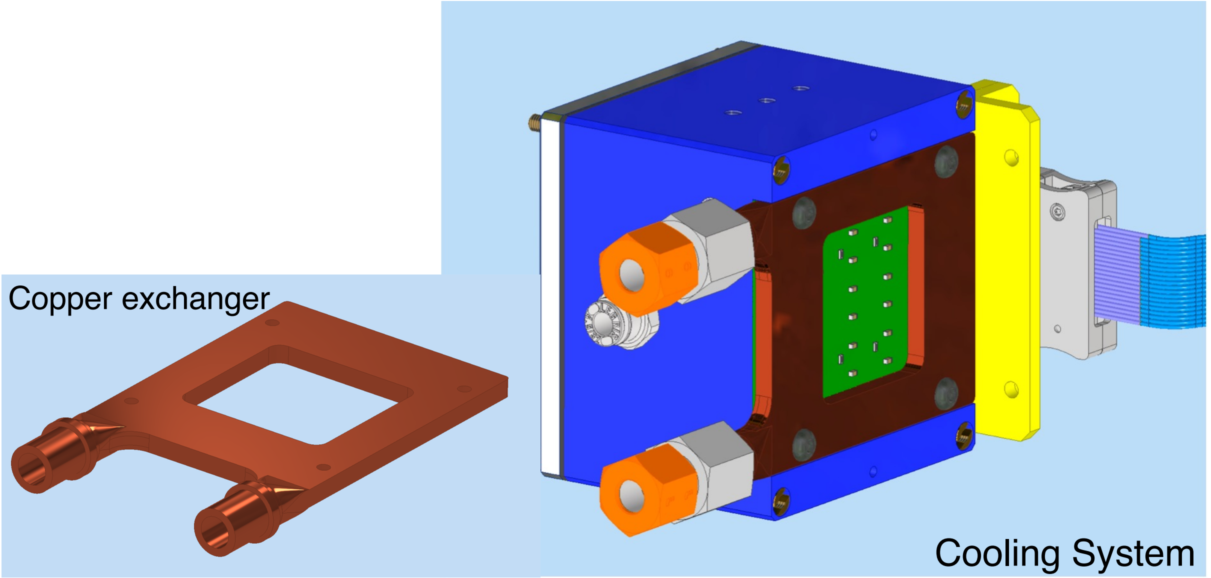
- **Proto-1:** 2 submodules assembled by bolting, each composed **of 3x3 crystals+36 SiPMS** (2 channel per crystal)
  - light-tight case which also embeds the front-end electronic boards and the heat exchanger needed to cool down the SiPMs.
  - SiPMs are connected via 50-ohm micro-coaxial transmission lines to a microprocessor-controlled Mezzanine Board which provides signal amplification and shaping, along with all slow control



Mechanics and cooling system

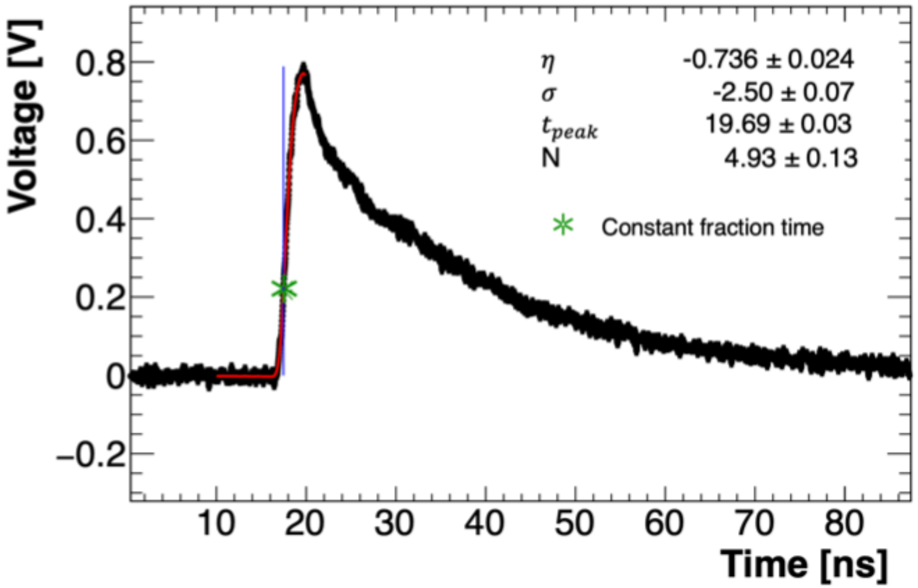


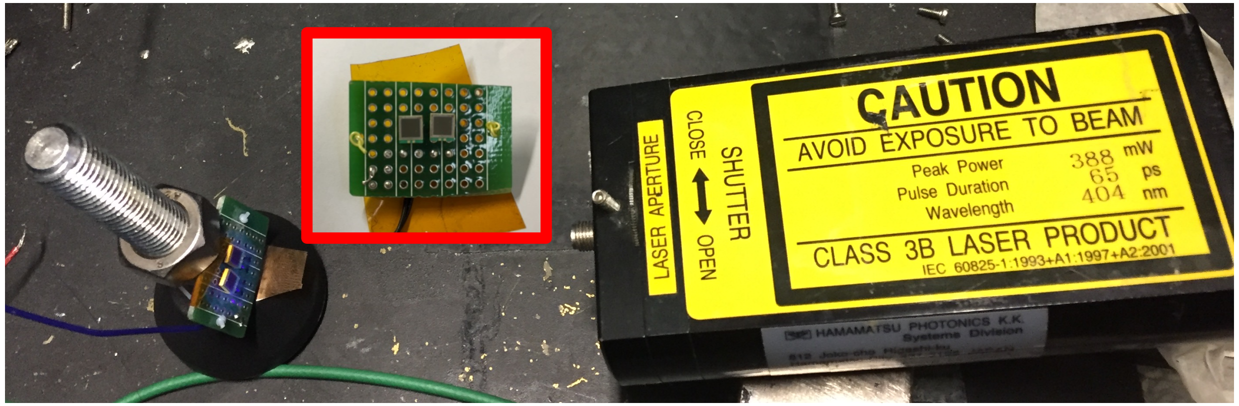
- Total heat load estimated: **350 mW per crystal** (two readout channels)
- Cold plate heat **exchanger** made of copper mounted over the electronic board.
- **Glycol based water solution** passing through the deep drilled channels.



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 V),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

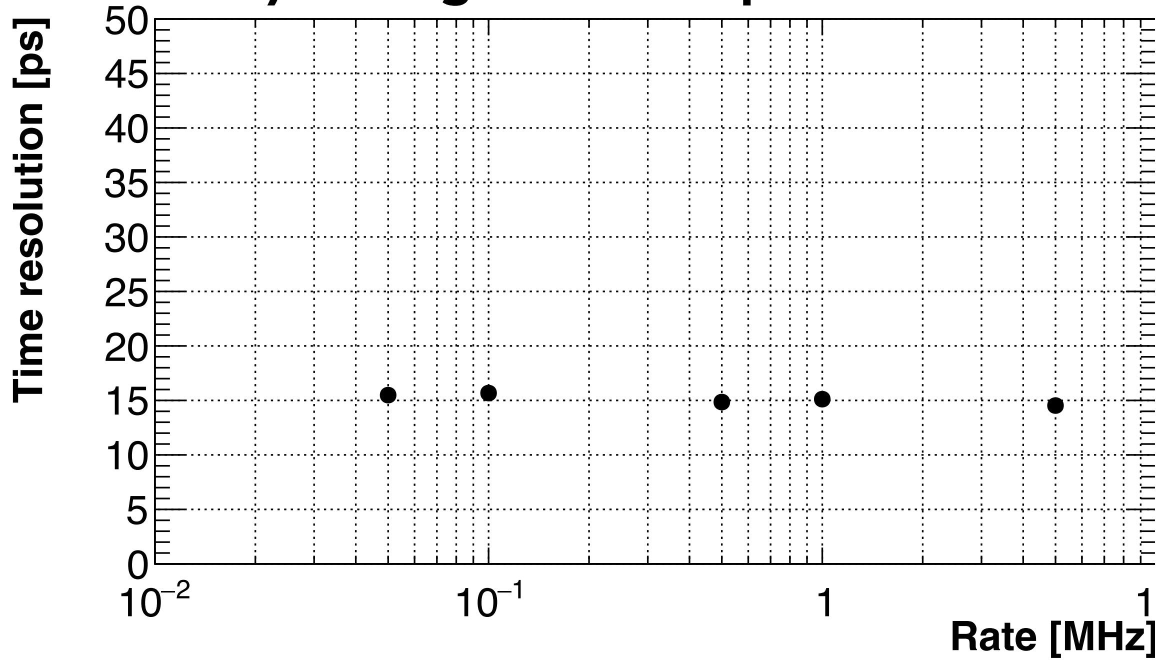




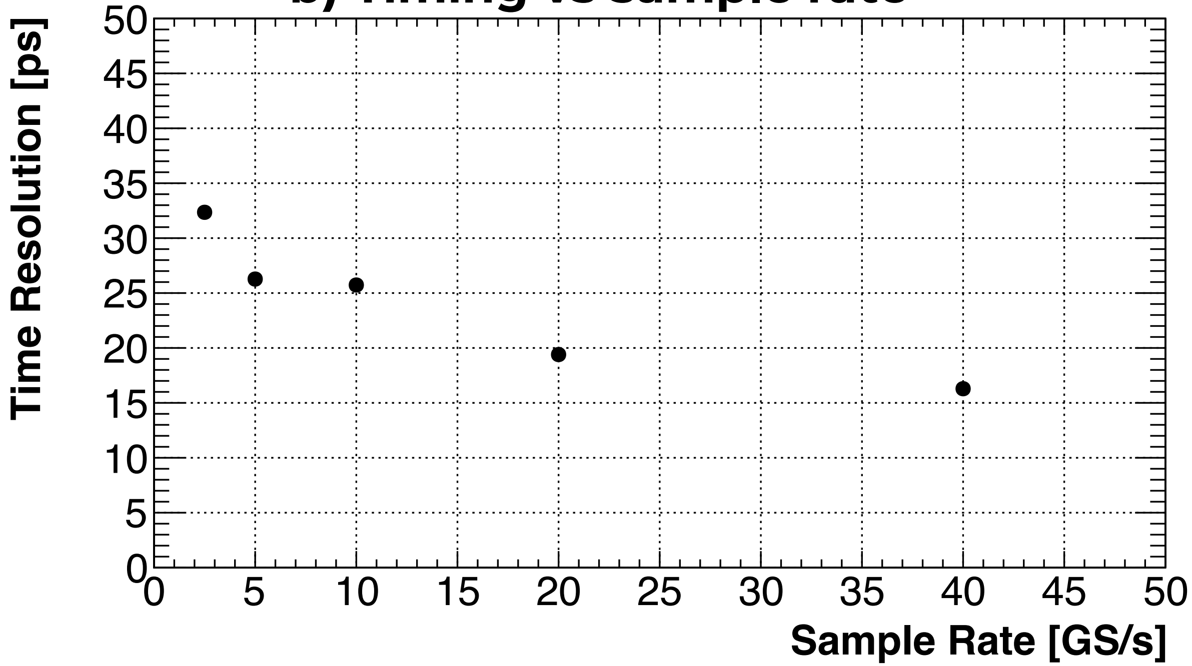
- Dynamic range: (0-2)V
- Fast rising edge ~ 2 ns;
- Full width of ~ 70 ns;
- Timing reconstruction performed **using Constant Fraction method** (~30% of Peak amplitude) on a lognormal fit.

Time resolution studies: first results (1)

a) Timing vs laser repetition rate



b) Timing vs sample rate

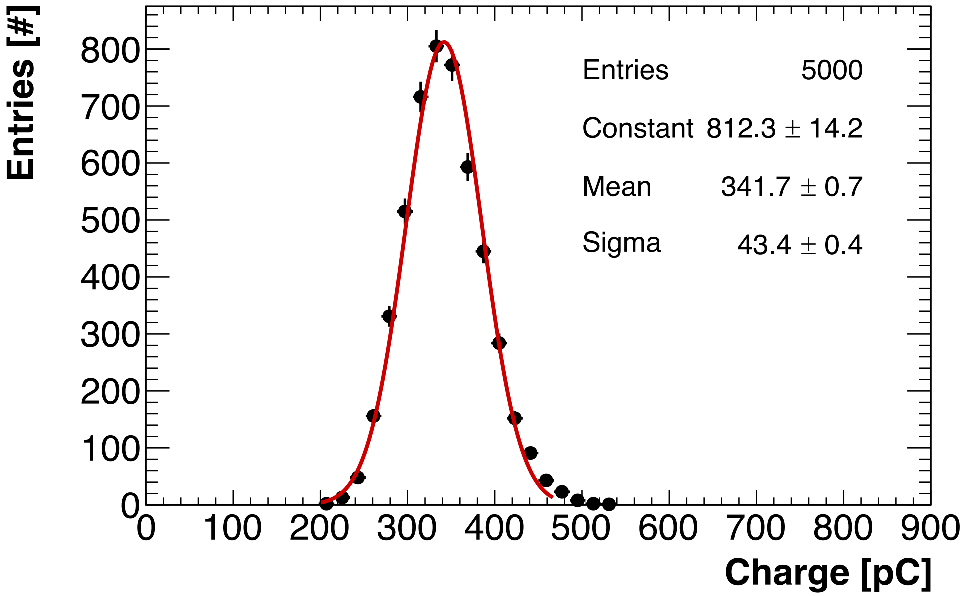


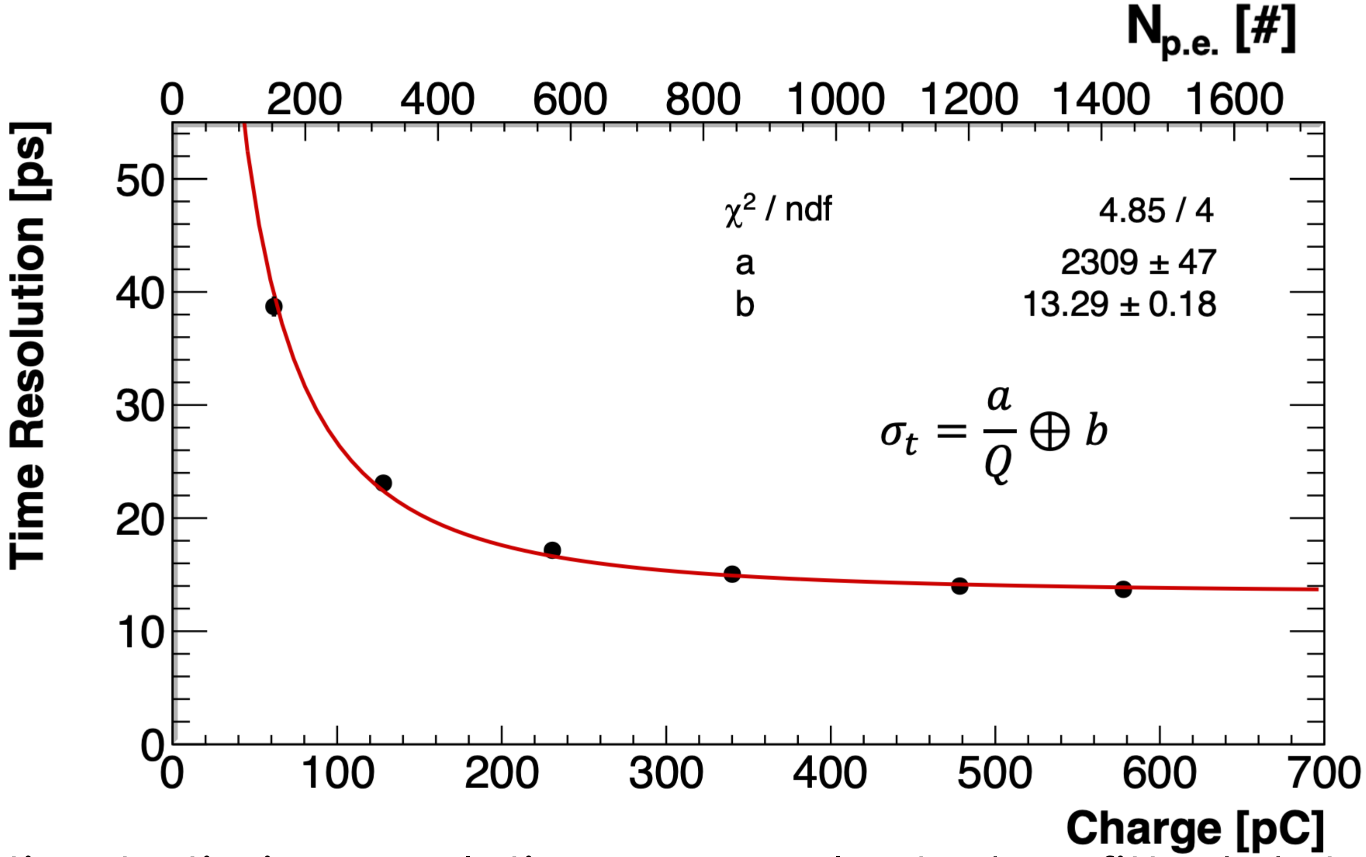
Constant behaviour meaning that the **waveform stays unchanged in the 50 kHz-5MHz range**.

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

Time resolution studies: first results (2)

c) 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

Conclusions

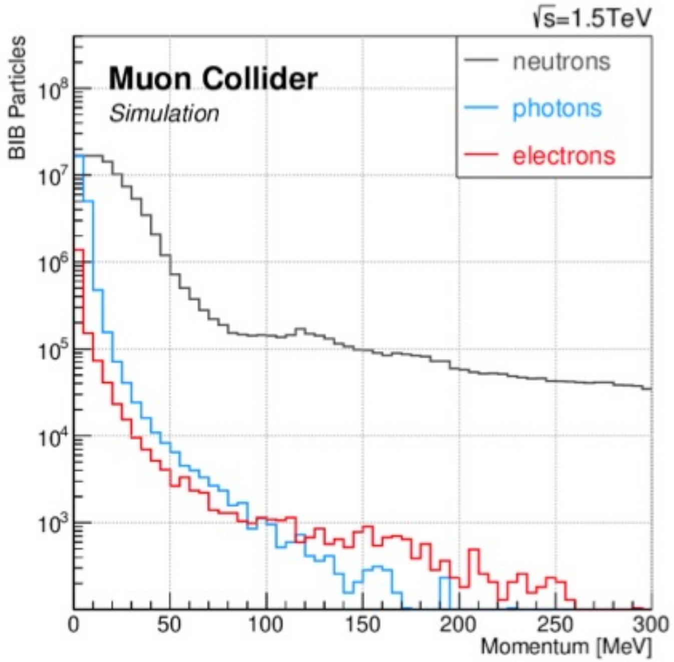
- Crilin[a] is a semi-homogeneous calorimeter with longitudinal segmentation and excellent timing resolution;
- It represents a good compromise between homogeneous and sampling calorimeter and is well quoted as alternative solution to W-Si ECAL for future MC
- Before the construction of the Proto-1 (3x3 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*;
  - Neutron irradiation up to 10^{14} n/cm^2 on SiPMs
- 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

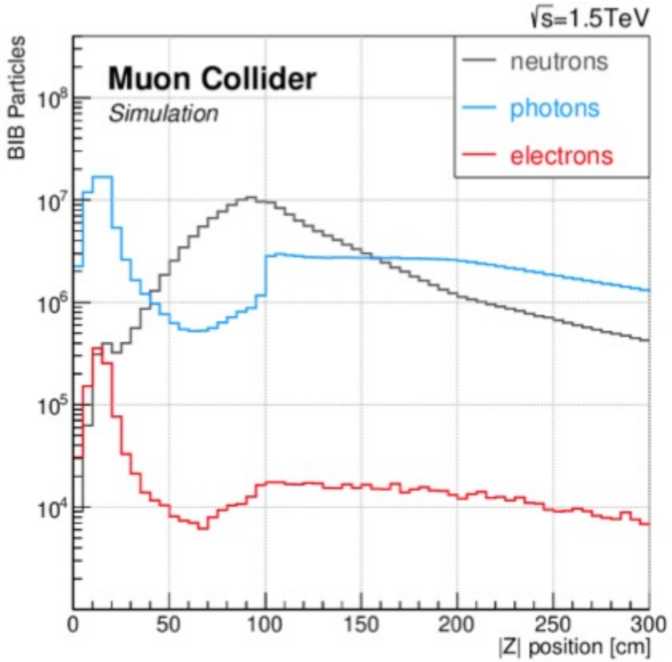
Thank you!

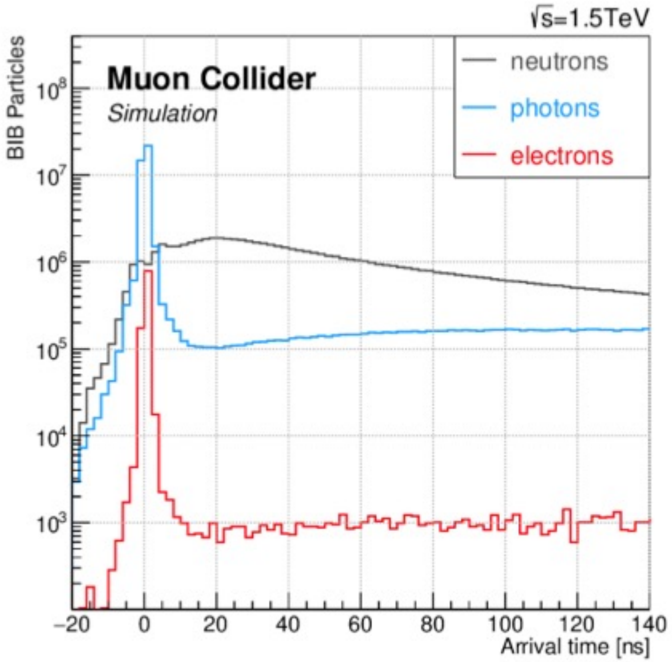
(a) Ceravolo, S et al., "Crilin: A CRystal calorImeter with Longitudinal InformatioN for a future Muon Collider" – Submitted to Jinst
(b) Cemmi, A., et al. "Radiation study of Lead Fluoride crystals." Journal of Instrumentation 17.05 (2022): T05015.

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;





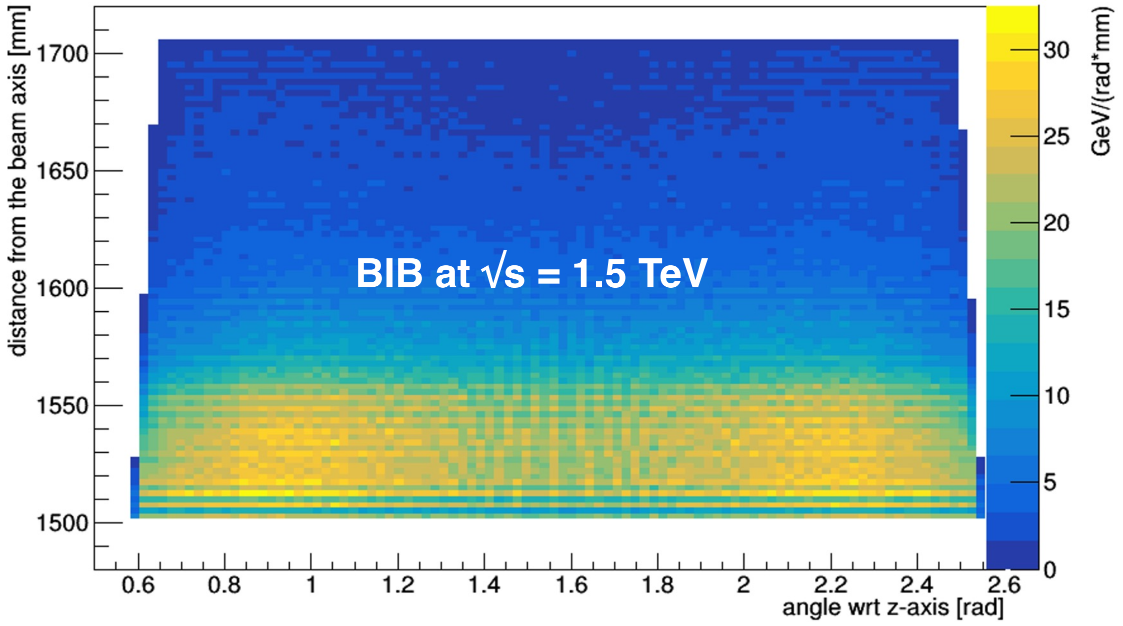


BIB in ECAL

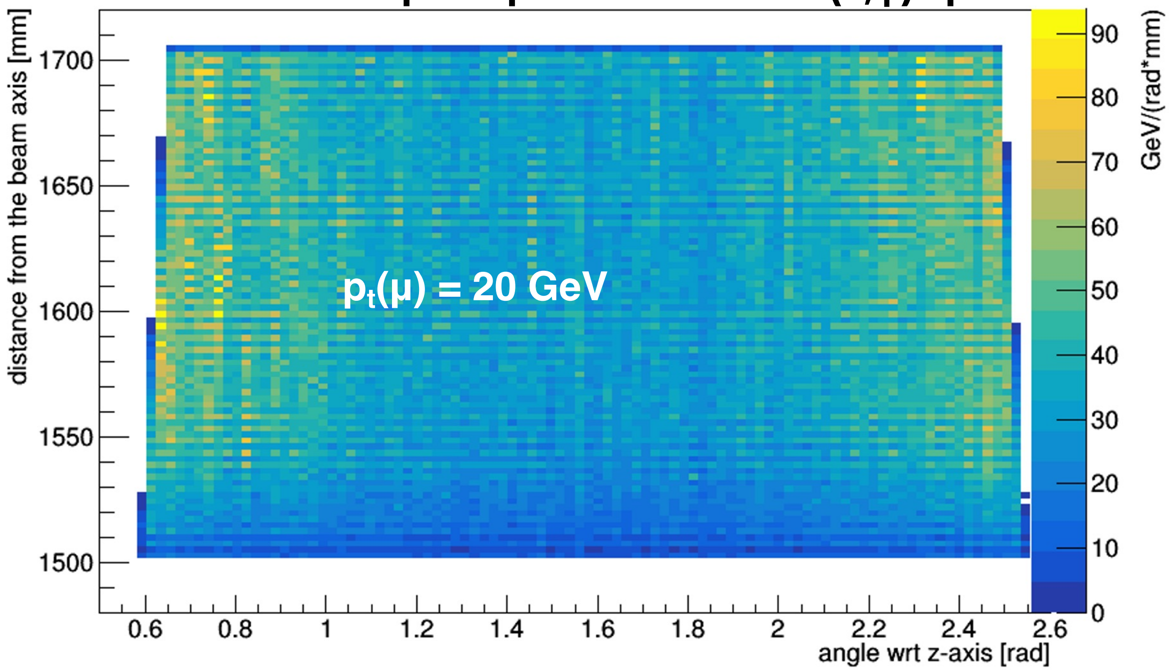
Timing and longitudinal segmentation play a key role in BIB suppression

- 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

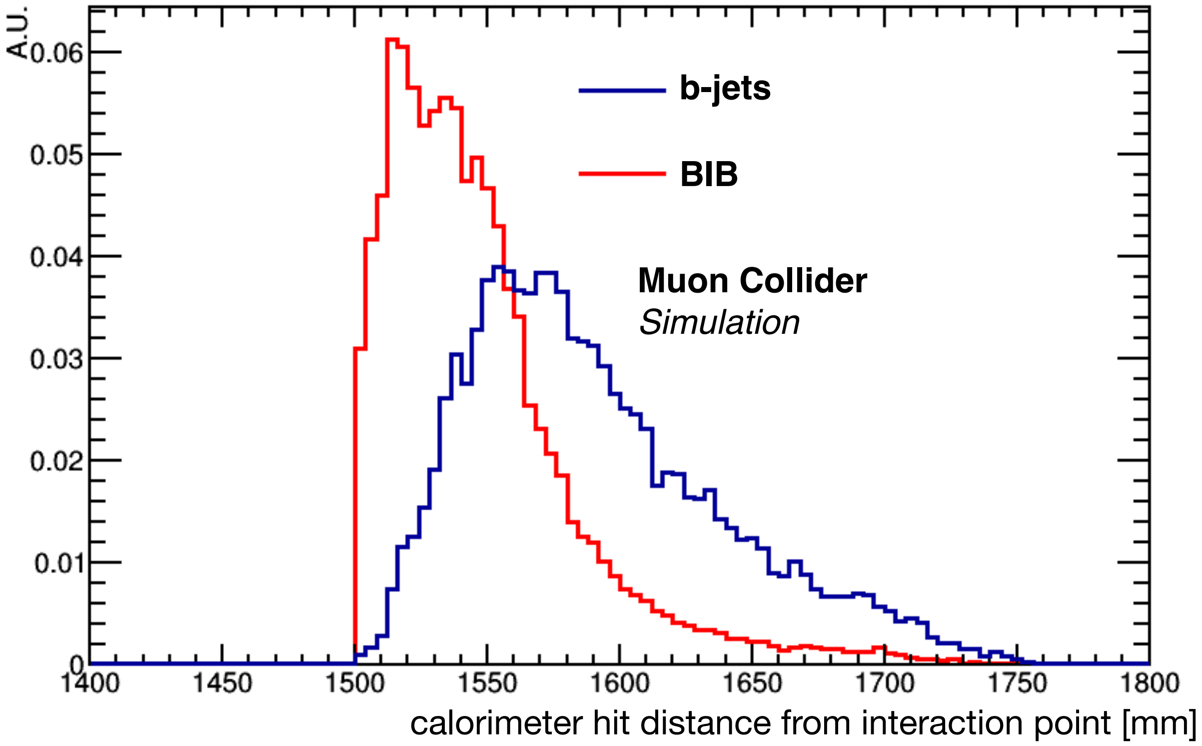


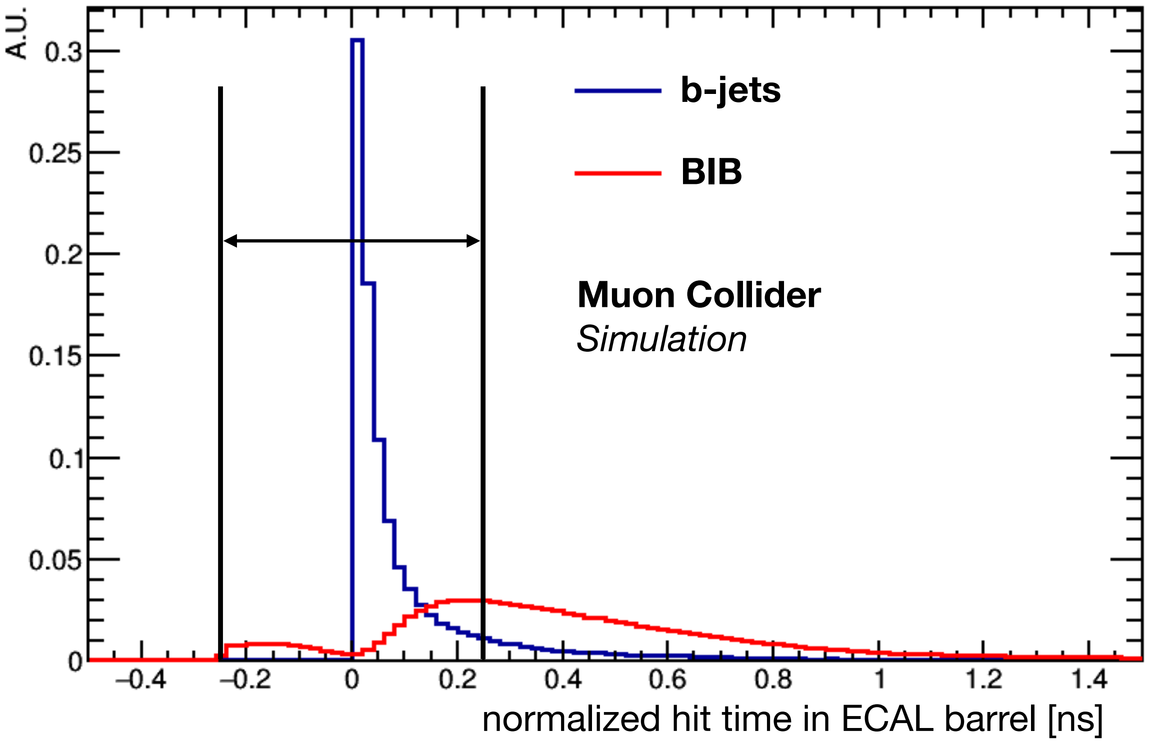
Energy released in ECAL barrel by uniformly distributed prompt muons in the (θ,φ) space



Muon identification

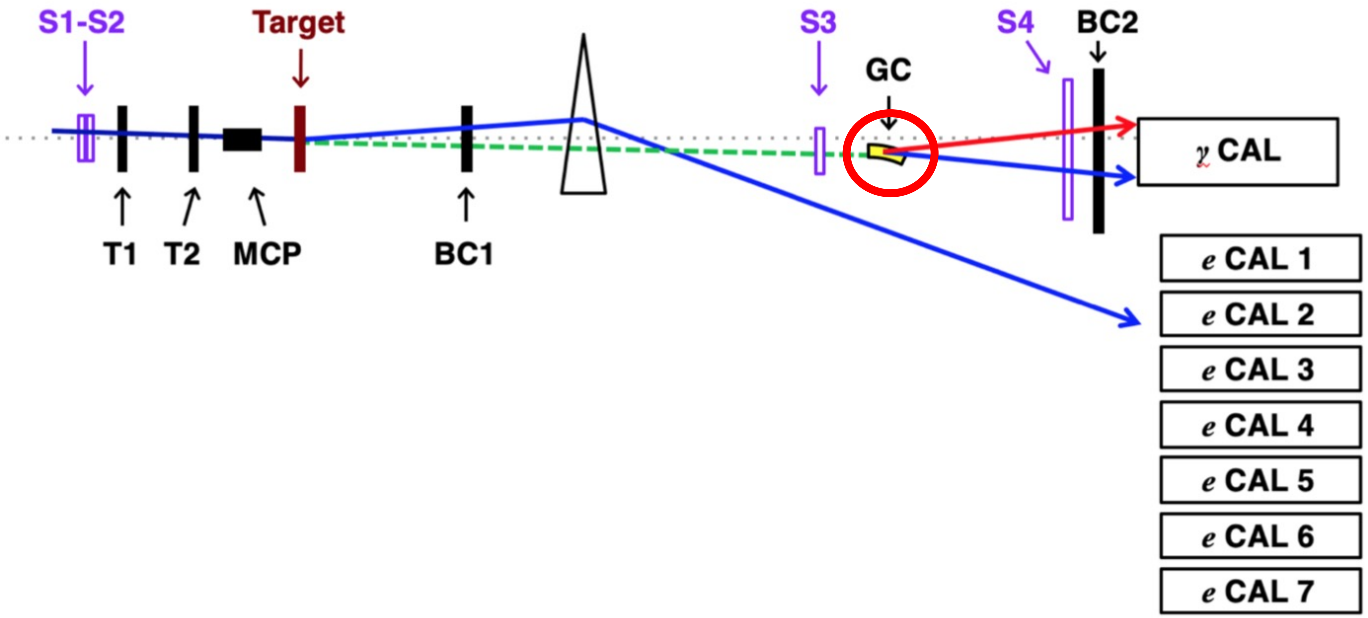
- Muons and BIB leave two different signatures in the ECAL barrel:
  - The BIB produces most of the hits in the first layers of the calorimeter while muons produce a constant density of hits after the first calorimeter layers.
  - Since the BIB hits are out-of-time w.r.t. the bunch crossing, a **measurement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





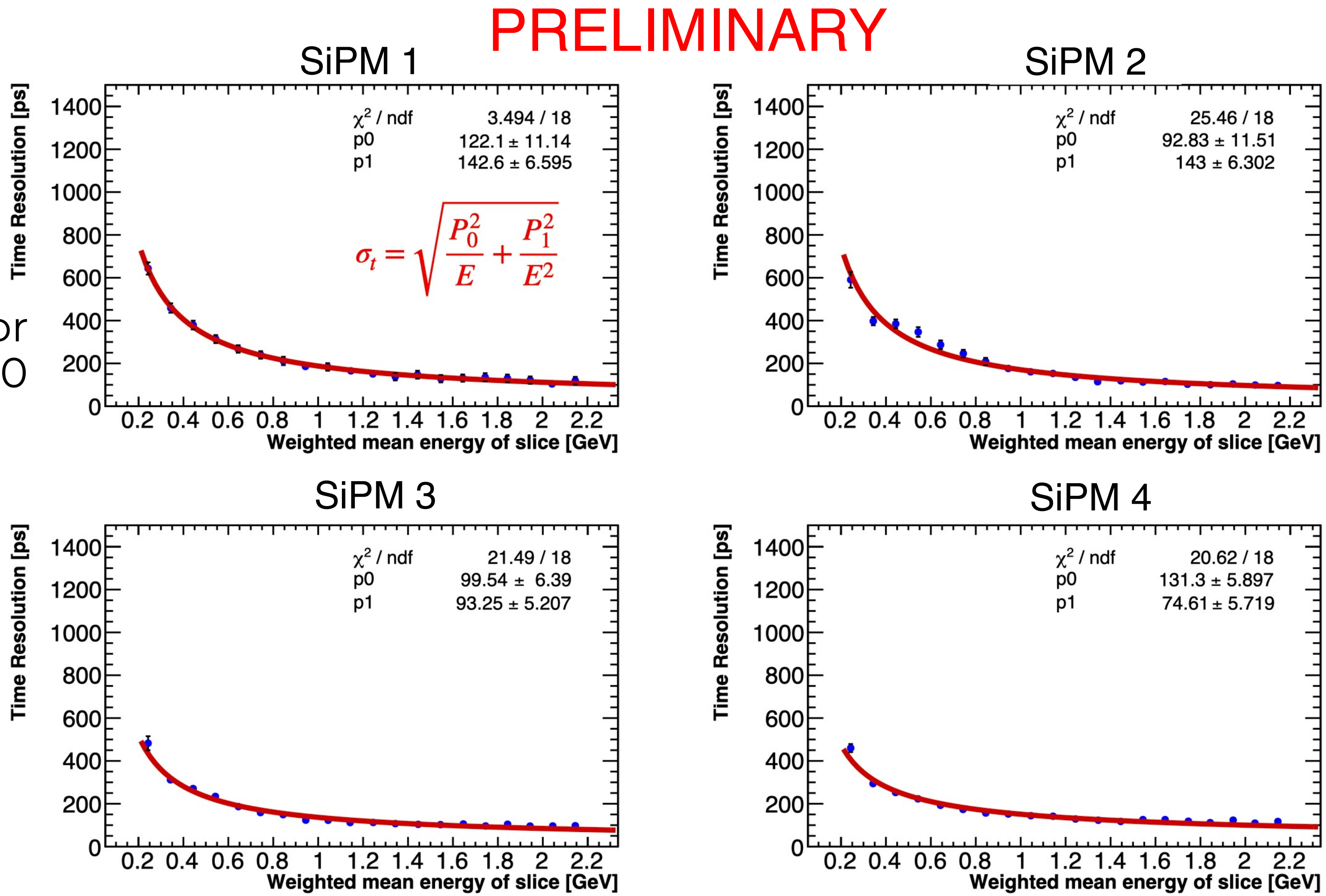
Test Beam

- CERN H2 beamline;
- Setup designed to allow measurements with 20-120 GeV electrons and tagged photons produced with 120 GeV electron beams



TestBeam-2

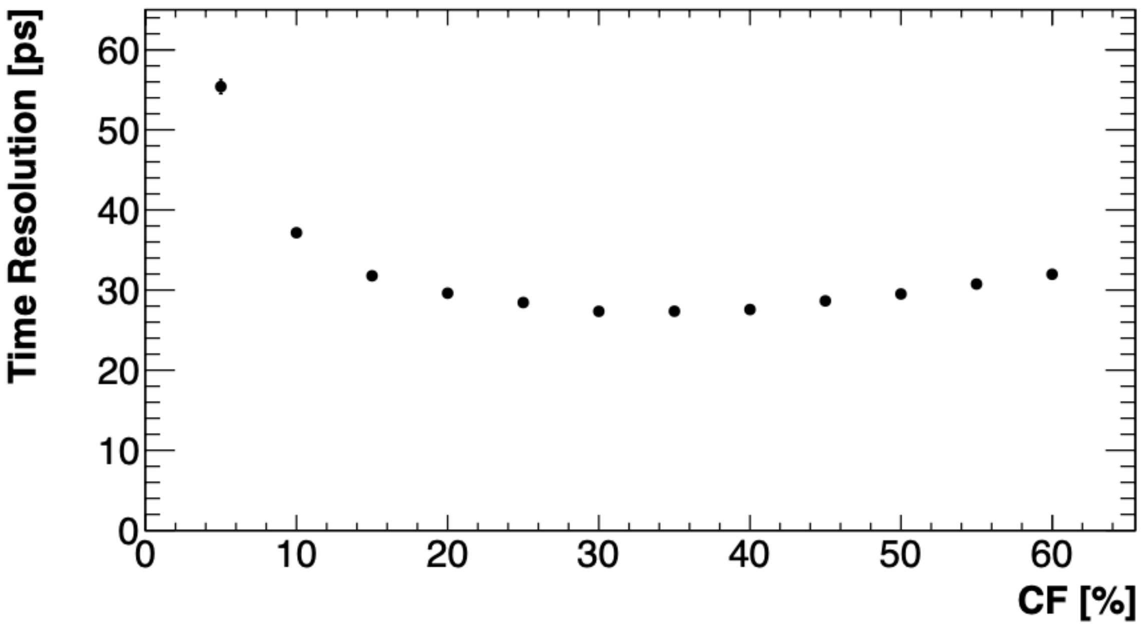
Time resolution results for Crilin SiPMs regarding 120 GeV electrons.



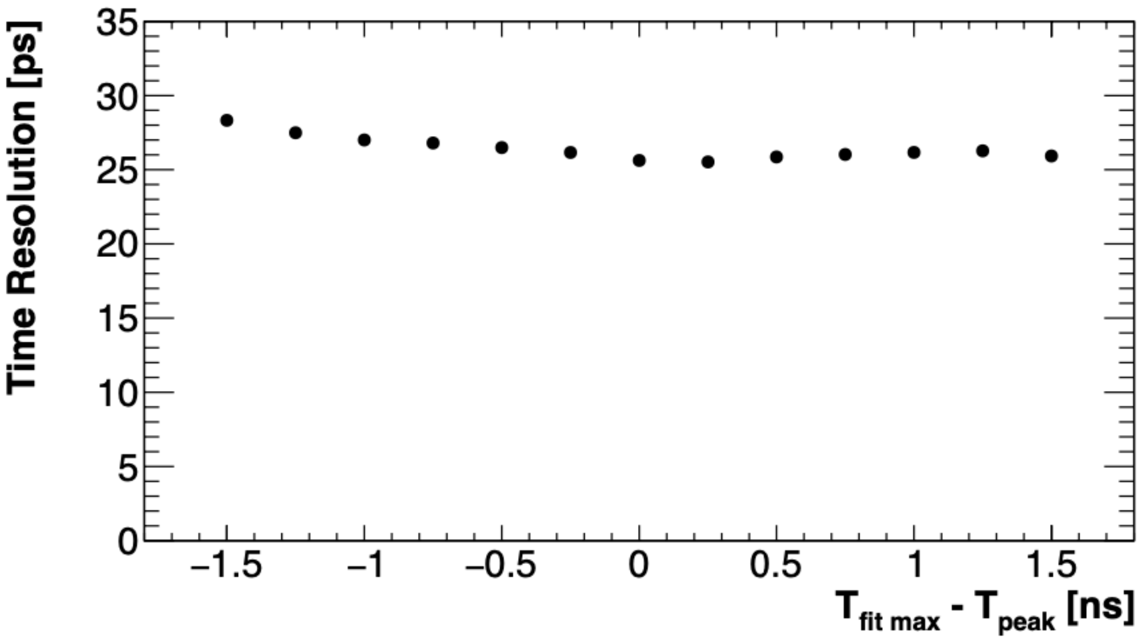
Constant fraction and fit window

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

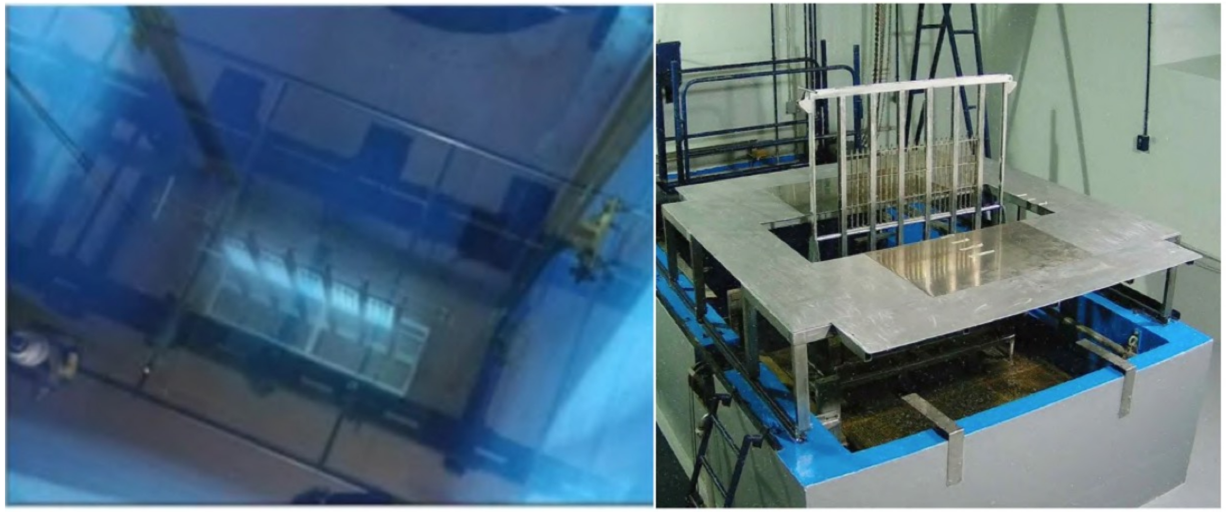
Irradiation sources

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



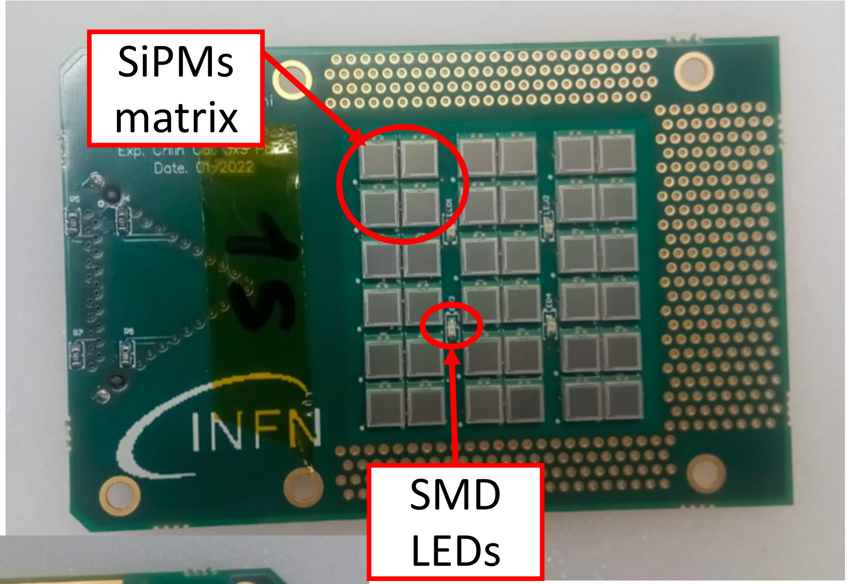
FNG facility:

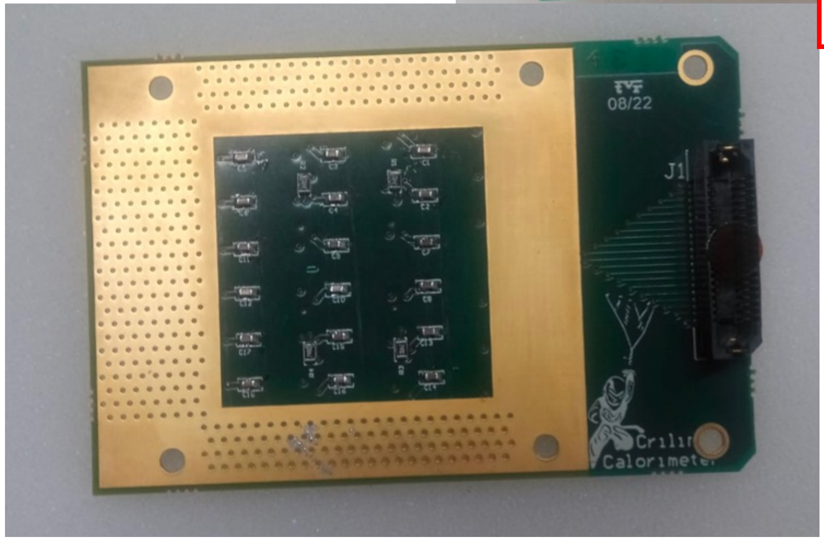
- Neutron source based on T(d,n)α fusion reaction;
- 14 MeV neutrons with a flux up to 10^{12} neutrons/s in steady state or pulsed mode.

Electronics – SiPMs Board

The SiPMs board is made of:

- 36 **15 μm Hamamatsu SiPMs** $\longrightarrow$each crystal has **two separate readout channels connected in series**.
- Four SMD blue LEDs nested between the photosensor packages.

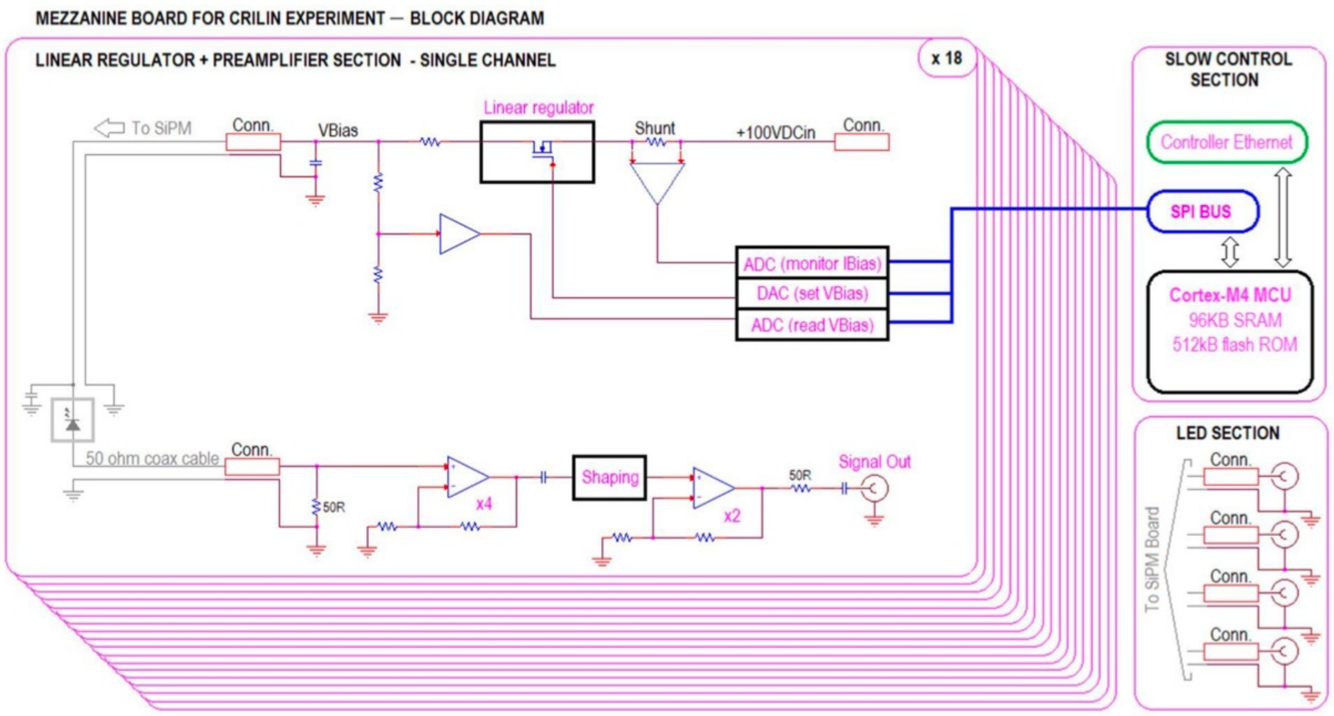




Electronics – Mezzanine Board

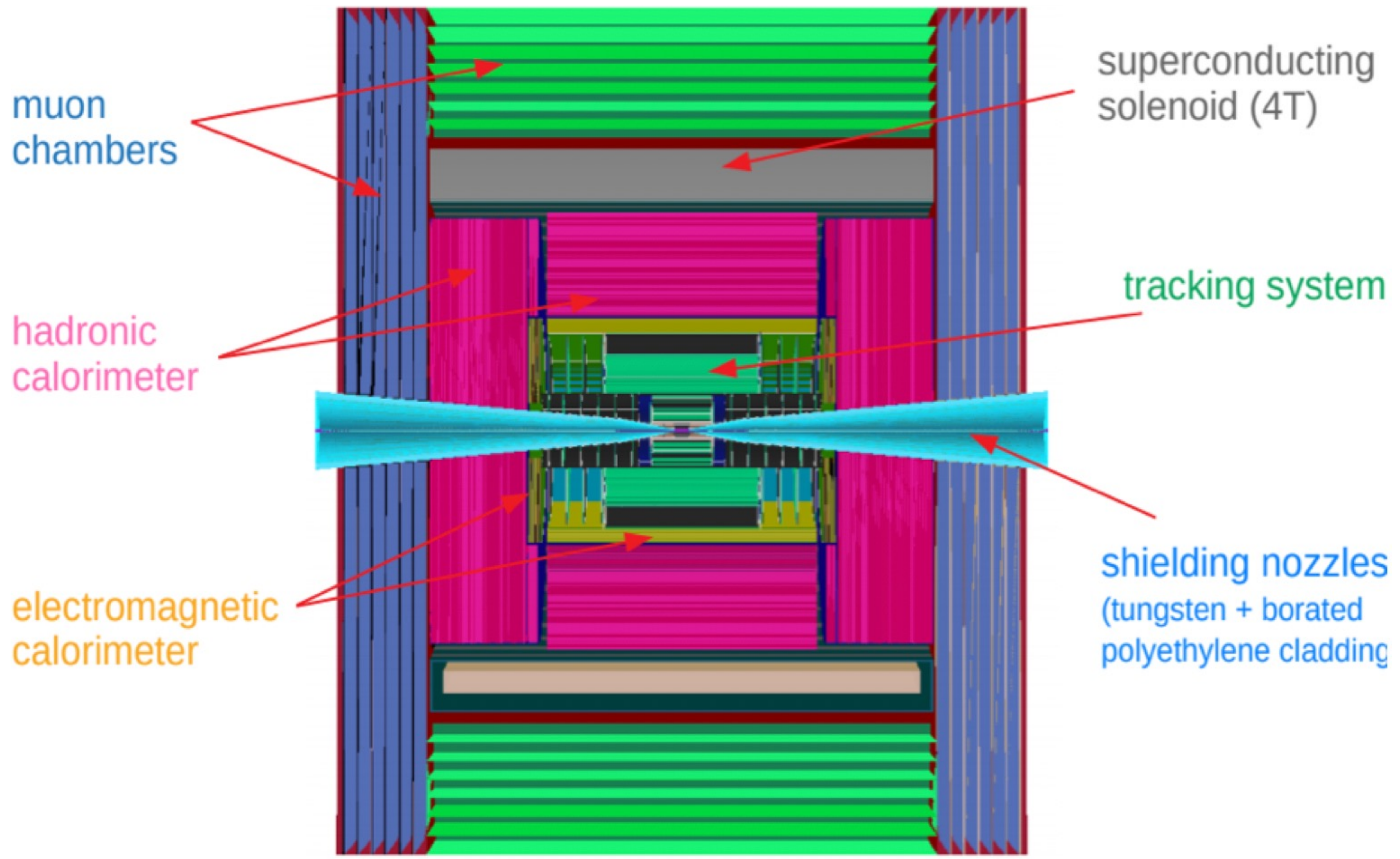
The Mezzanine Board for 18 readout channels:

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

Muon Collider



- Based on Compact Linear Collider (CLIC) detector with modification for BIB suppression
- Dedicated shielding (nozzle) to protect magnets/detector near the interaction region