SAPIENZA
UNIVERSITÀ DI ROMA

International
MUON Collider
Collaboration

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

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16 - 20 May 2022 University of Sussex, Brighton, UK

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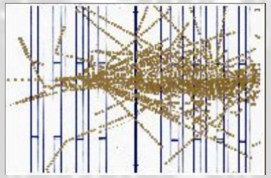
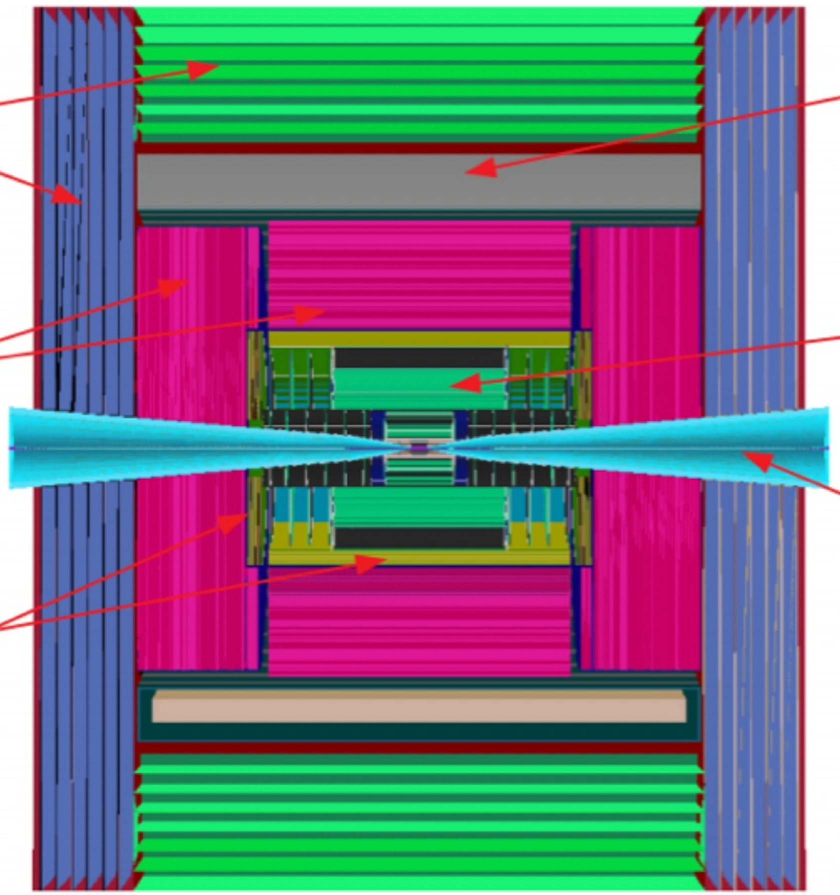


Calor 2022

Introduction

- **Muon colliders (MC)** have great potential for high energy physics especially in the TeV range. However, the jet reconstruction is affected by the **Beam Induced Background (BIB)** due to $\mu \rightarrow e\nu_e\nu_\mu$ decay and following interactions;
- The present MC ECAL barrel is based on W and Si pad layers. This choice can be very expensive. Moreover, this type of calorimeter would need a huge number of channels and would be characterized by low time resolution.
- **Time of arrival and high-granularity are key factors**. This means that a finely segmented calorimeter that can implement timing reconstruction should be favored for this type of collider.

Muon Collider



- Based on CLIC detector, with modification for BIB suppression.
- Dedicated shielding (nozzle) to protect magnets/detector near interaction region.

Beam Induced Background

- The interaction of the beam muons decay products with the machine elements (mainly with nozzles) produces a pervasive flux of secondary and tertiary particles that eventually may reach the detector.

Photons
Neutrons
Electrons/Positrons
Charged Hadrons
Muons

→

They are produced within few tens m from the interaction point by muons primary decays.
Secondary muons are also produced up to 200 m from the interaction point.

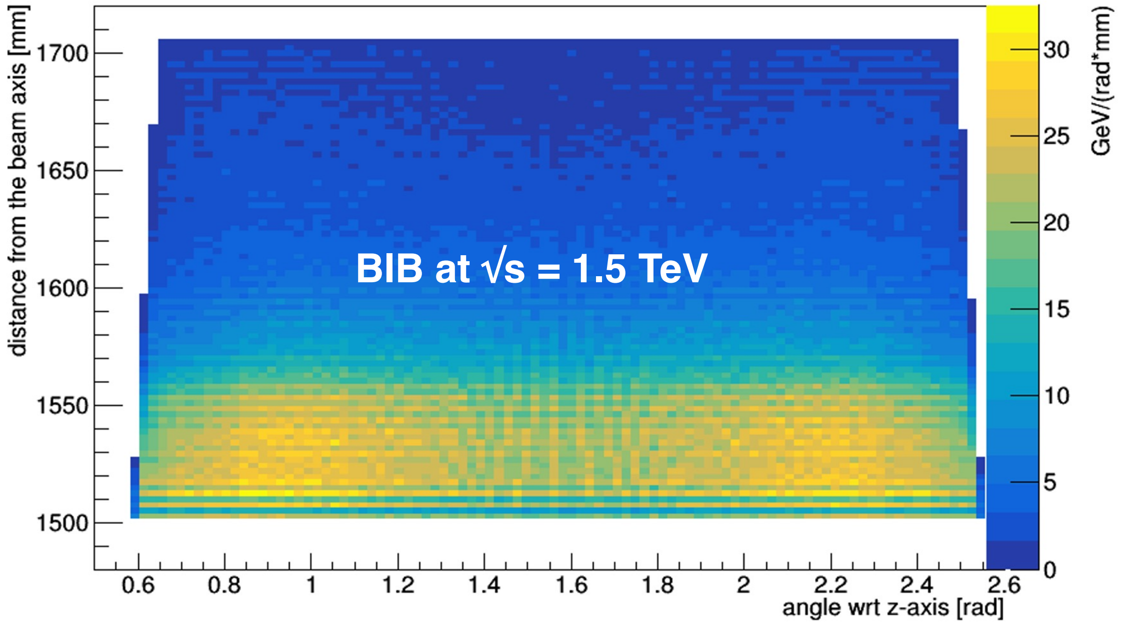
- BIB strongly depends on Center of Mass (CM) energy and machine design;
- Expected BIB on the ECAL barrel ~300 γ/cm^2 /events.

Muon Identification with the calorimeter

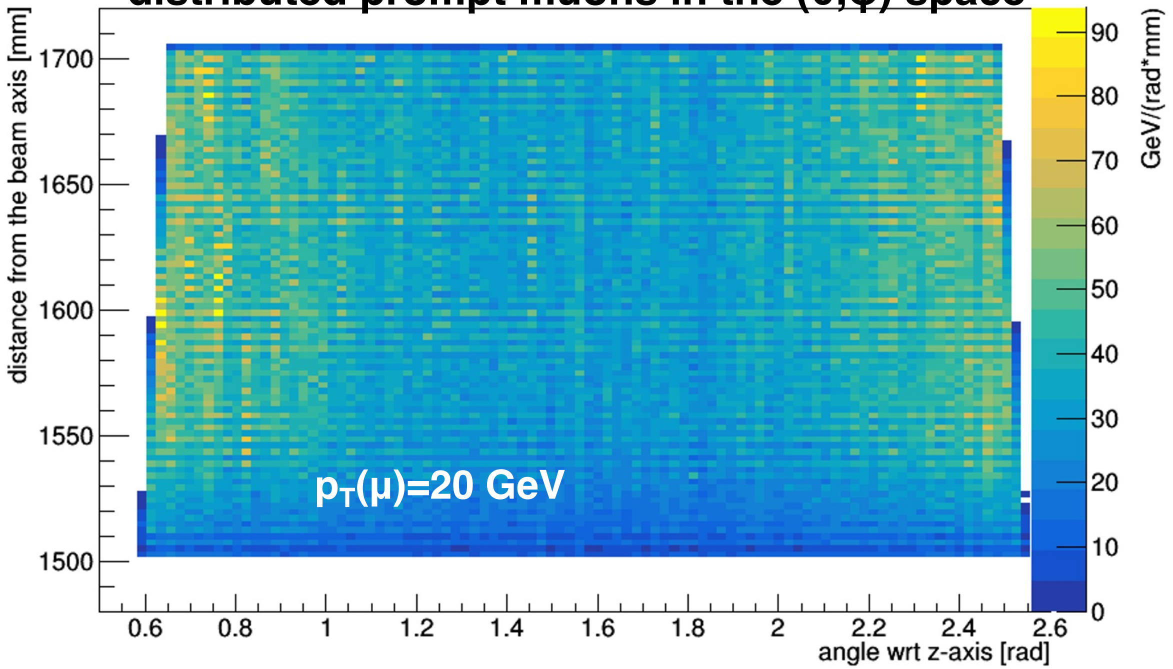
Calorimeter longitudinal segmentation improves the high p_T muons track reconstruction obtained from muon detector.

- BIB can be subtracted using information from energy releases.
- Muons and BIB have a very different behavior in the longitudinal energy release.

Energy released in ECAL barrel by one BIB bunch crossing



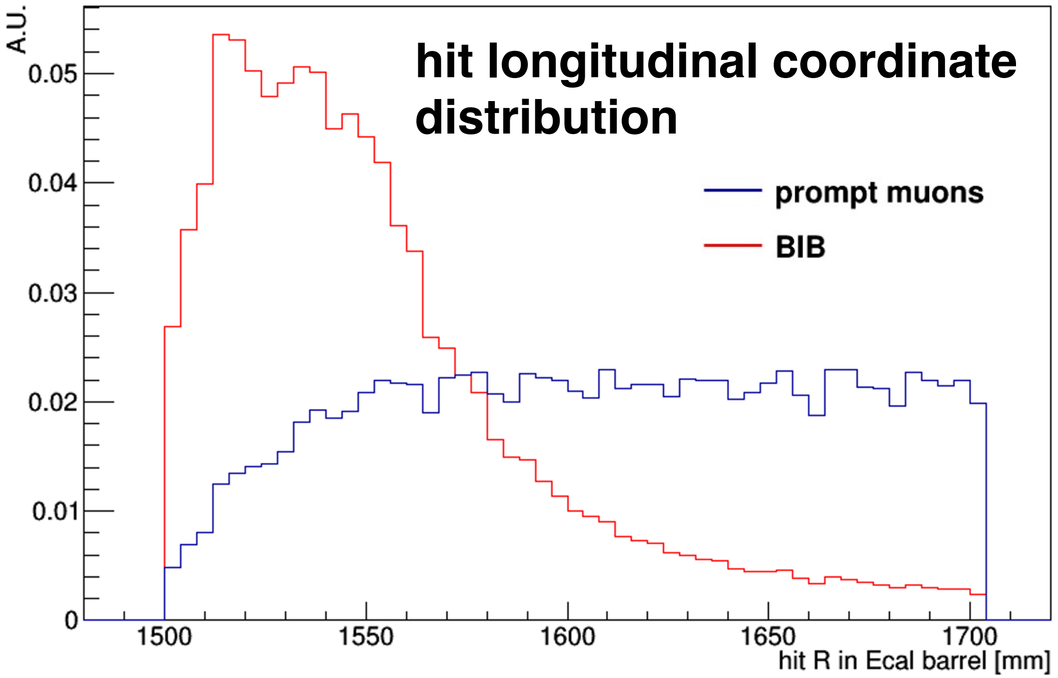
Energy released in ECAL barrel by uniformly distributed prompt muons in the (θ,ϕ) space



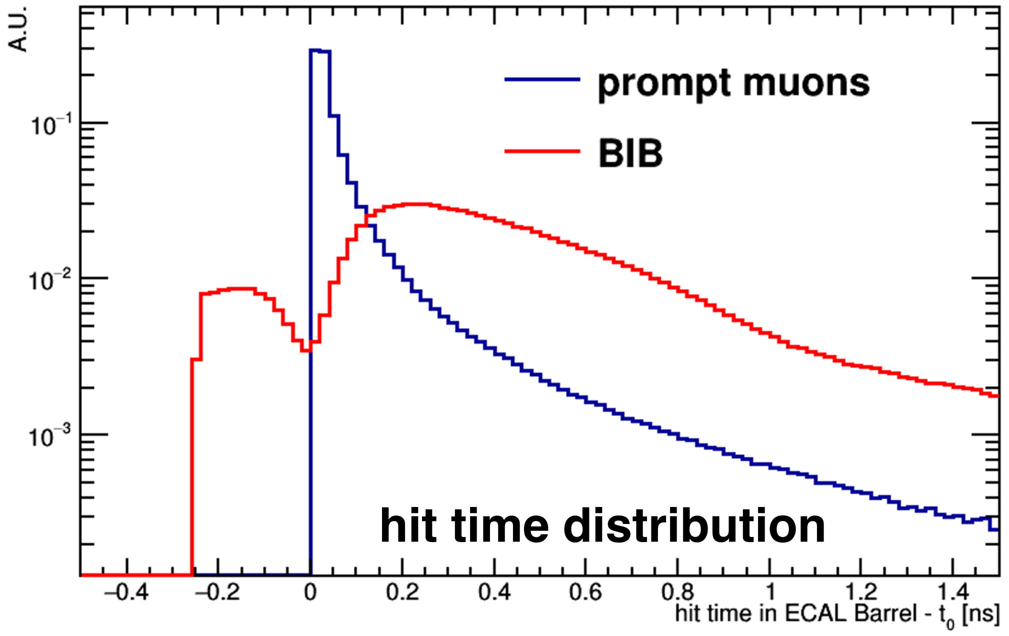
Muon Identification with the calorimeter-2

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.

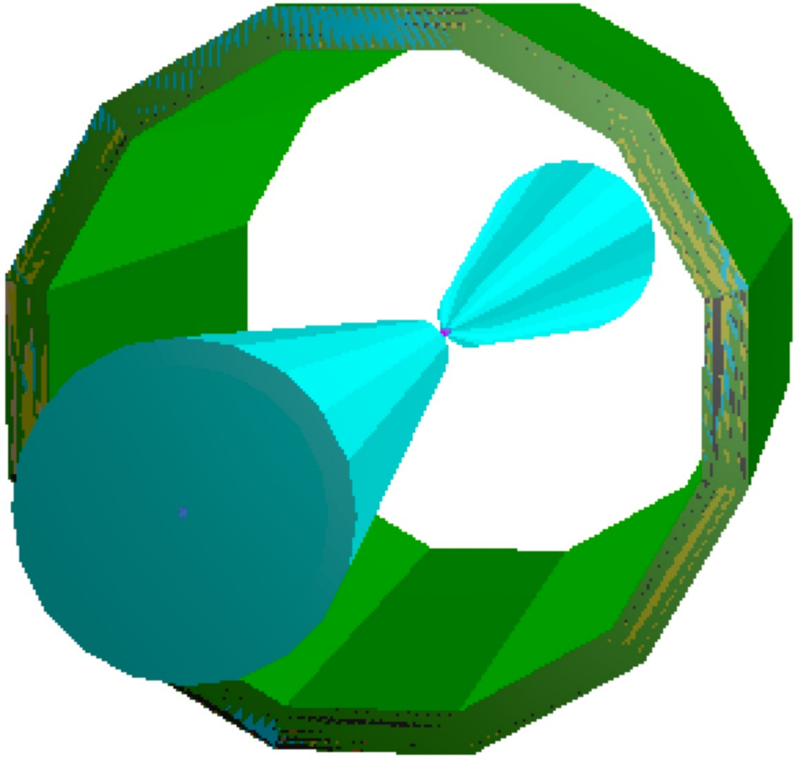


- Since the BIB hits are out-of-time wrt the bunch crossing, a **measurement of the hit time performed cell-by-cell** can be used to **remove most of the BIB.**



The Crilin Calorimeter

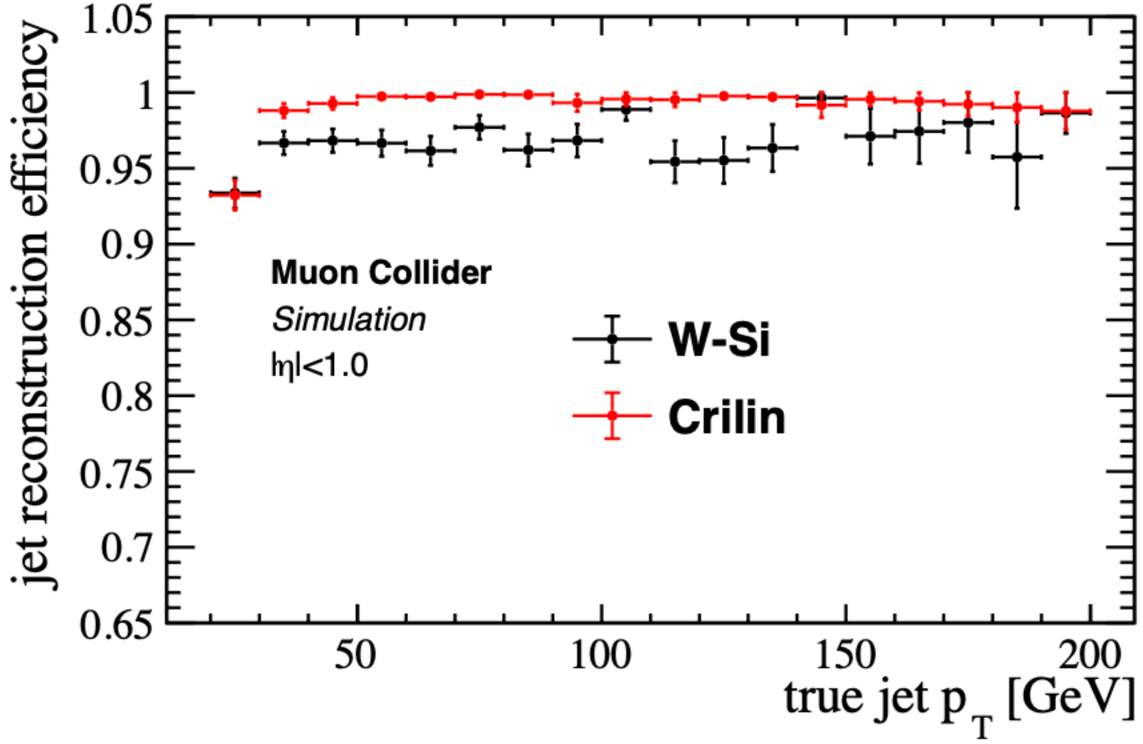
- The goal is to build a crystals calorimeter, fast, relative cheap, and with high granularity (both transversal and longitudinal) optimized for muon collider.
- Our proposed design, **Crilin**, is a **semi-homogeneous** electromagnetic calorimeter made of **Lead Fluoride Crystals** (PbF_2) matrices where each crystal is readout by 2 series of 2 UV-extended surface mount **SiPMs.**
- **It represents a valid and cheaper alternative to the W-Si Muon Collider ECAL**.

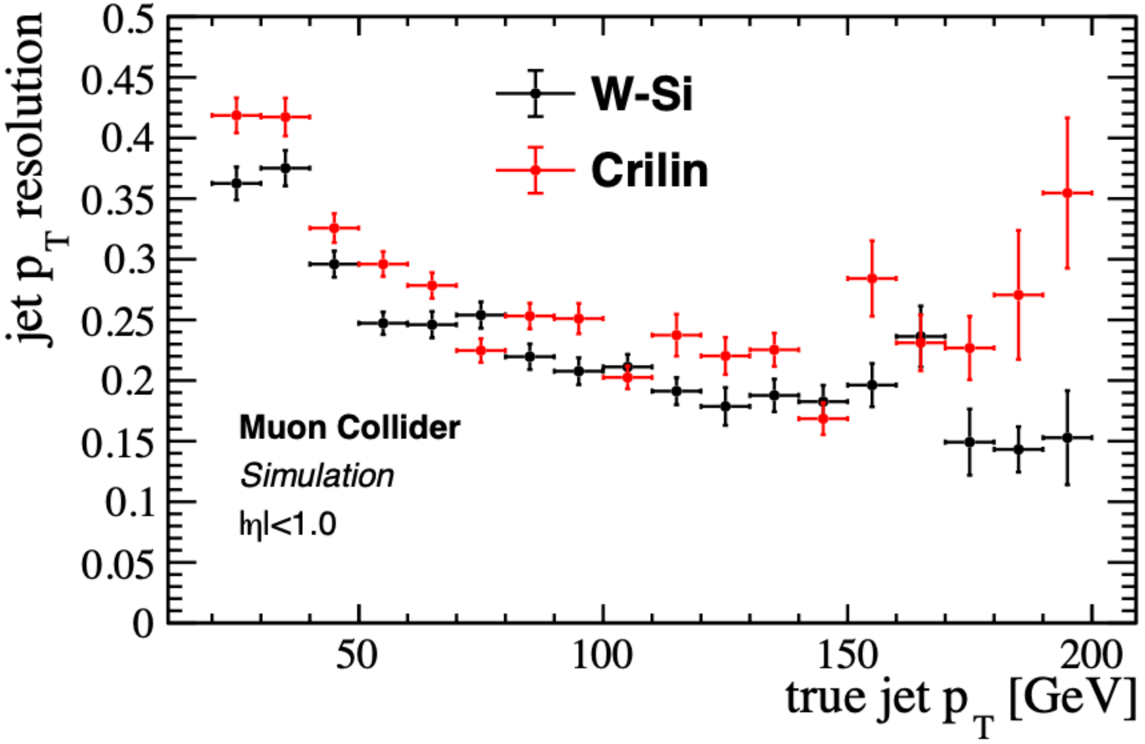


Geant4 realization of Crilin

Simulation and performance in the MC

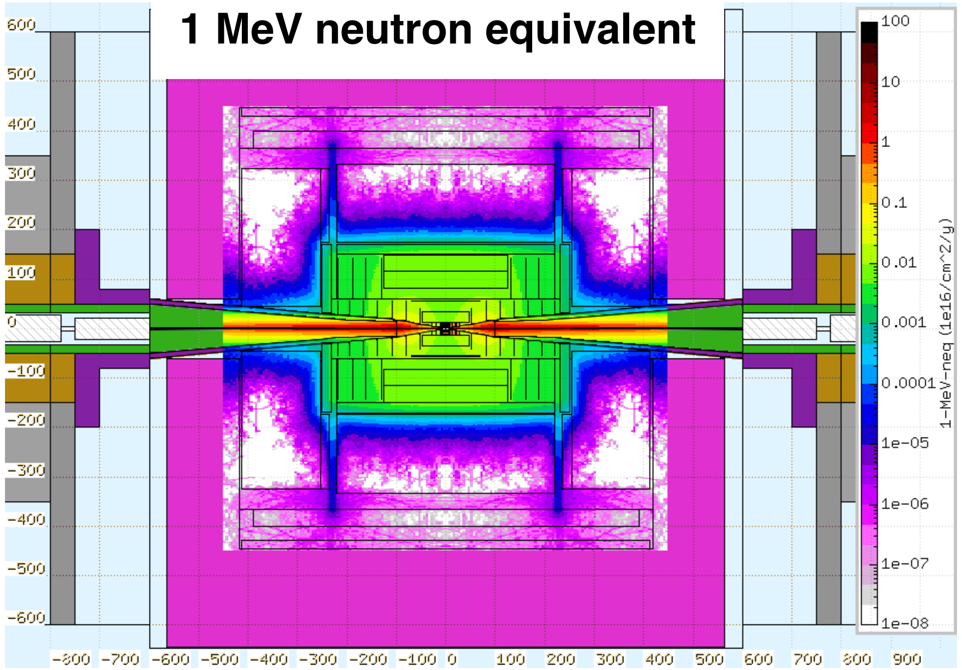
b-jet reconstruction and resolution simulation on a 40 mm thick and 10 x 10 mm^2 of cell area of Crilin ECAL compared to the W-Si one. The performance are quite similar.

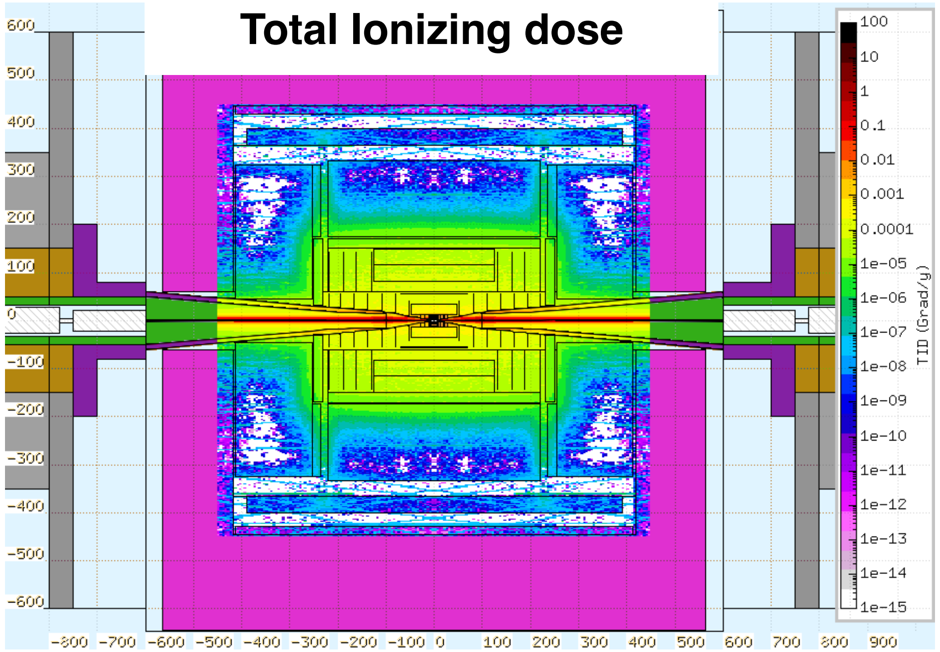




Radiation hardness

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** $\sim$ **100 krad/year** on ECAL.

Crystals Characterisation

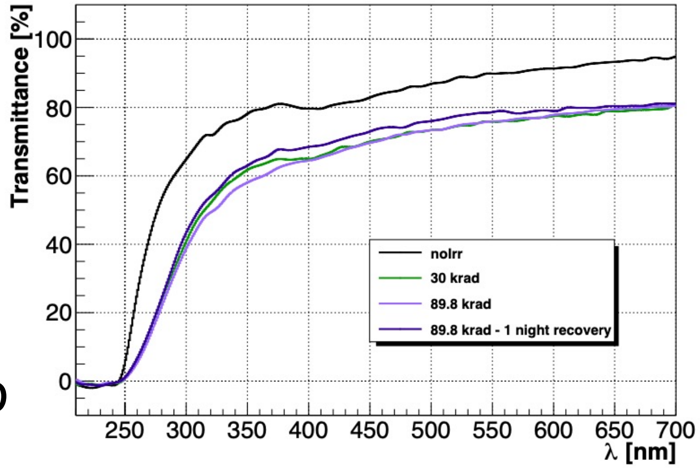
Two crystals were used to evaluate **PbF_2 radiation hardness**, by comparing their **transmittance** before and after irradiation, with or without Mylar wrapping**.**

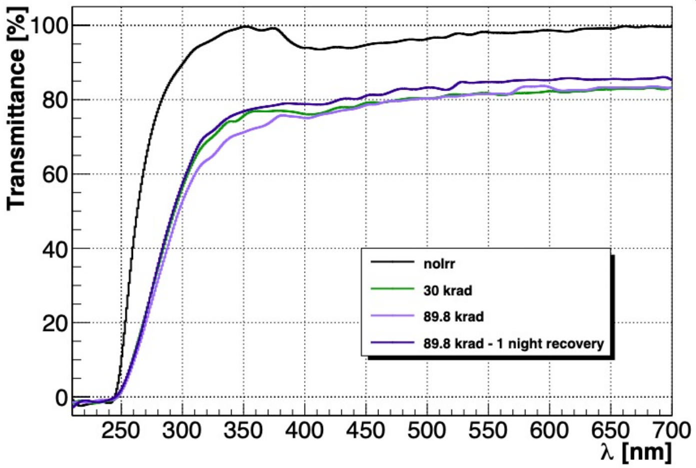
Photons: Exposed to ^{60}Co source up to 4.4 Mrad.

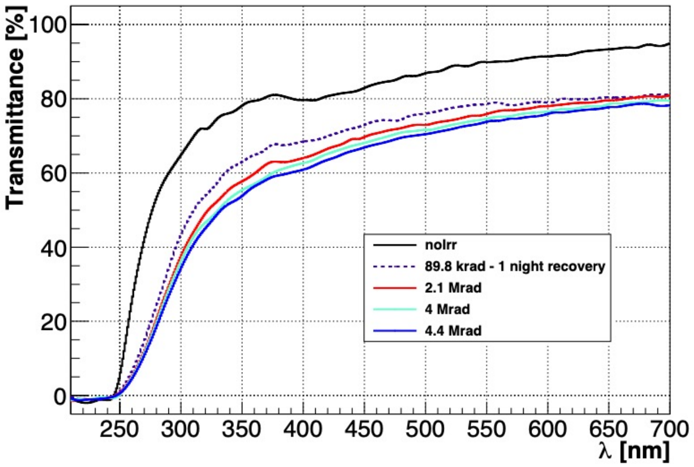
After a TID ~ 80 krad no significant decrease in transmittance observed suggesting a saturation effect caused by the damage mechanism.

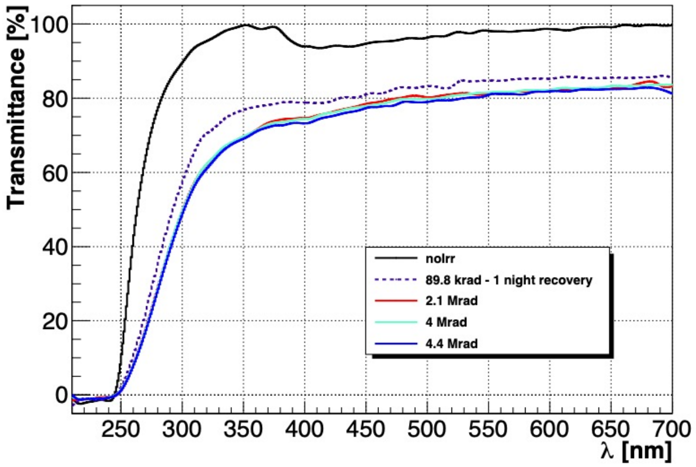
Naked Crystal

Mylar wrapping





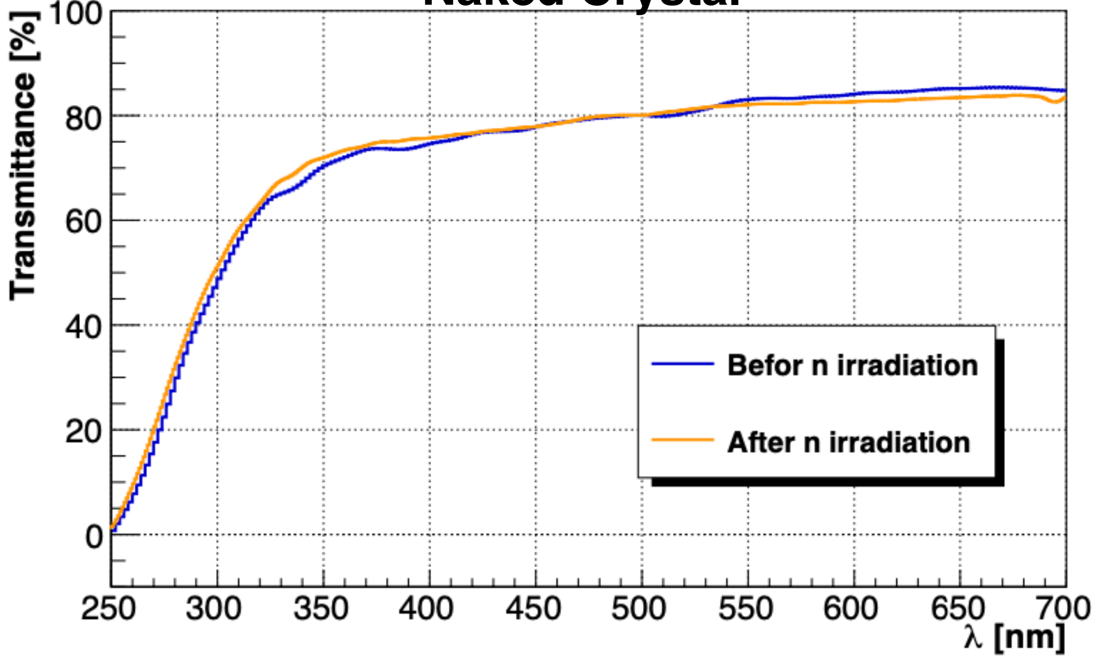




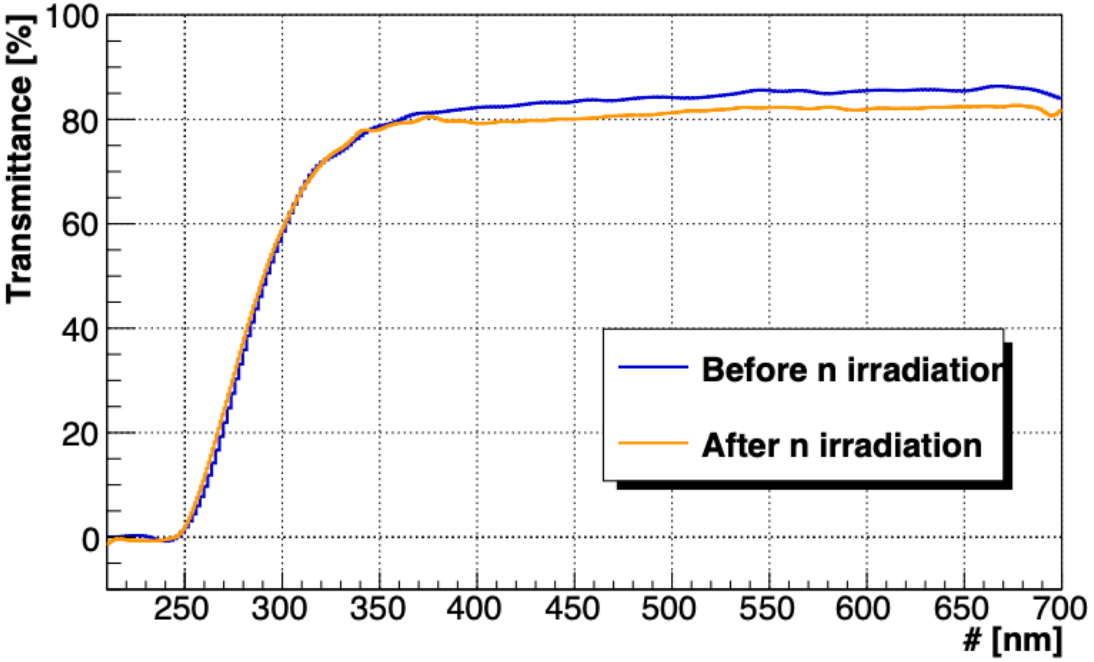
Crystals Characterisation-2

Neutrons: 14 MeV neutrons with a total fluence of 10^{13} n/cm^2 on for 1 hour and 30 minutes. Results, evaluated 14 days after the irradiation, show that there is **no alteration in the transmittance spectrum**.

Naked Crystal

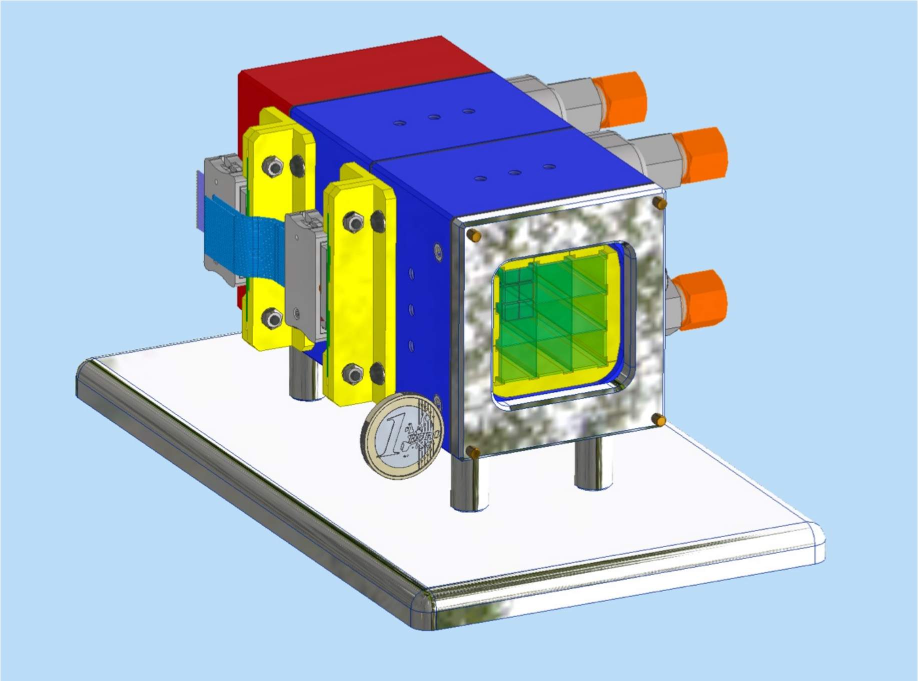


Mylar wrapping



Crilin Prototype

- Four layers of 5×5 PbF_2 crystals each readout by thin SMD SiPMs by Hamamatsu.
- The operational temperature will be 0/-10°C.
- **Proto-0:** one layer with 2 crystals, it showed promising results in 2021 Cern Test Beam.
- **Proto-1**: two sub-modules, each composed of a 3×3 crystals matrix.
- New 15 μm SiPMs already tested with the new front-end electronics.

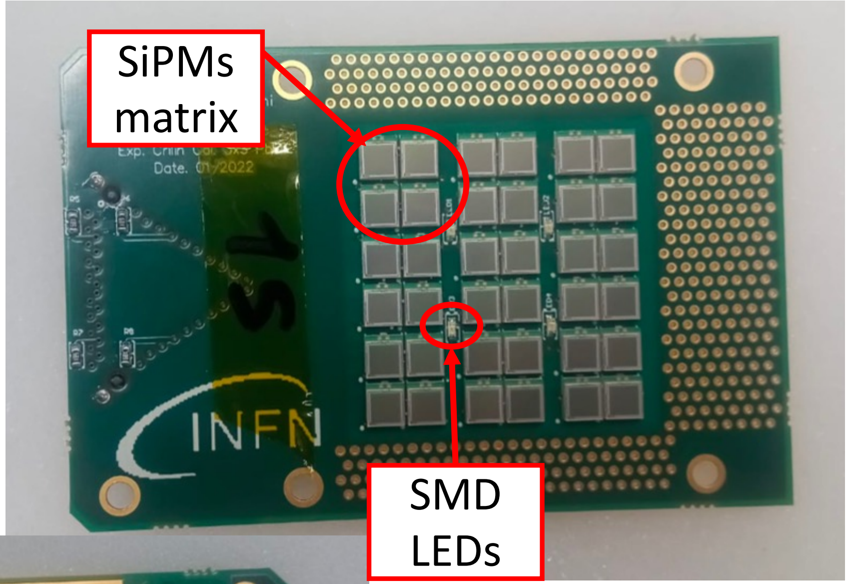


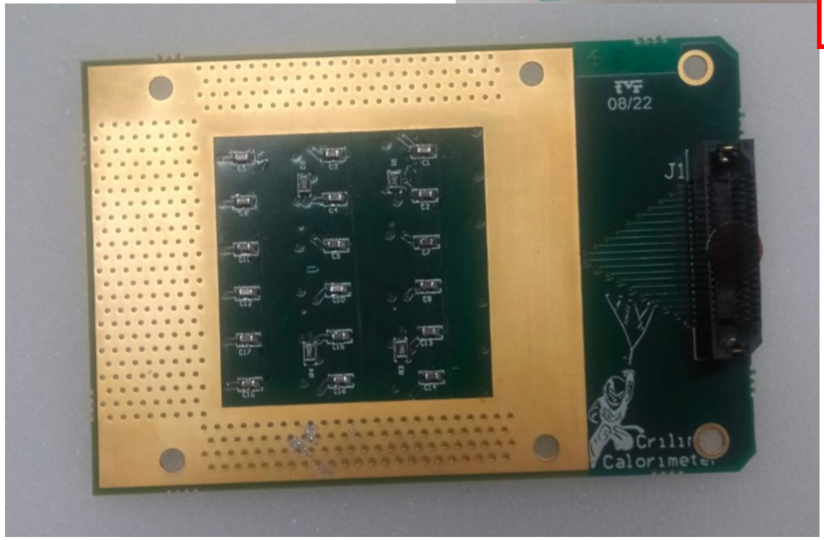
Electronics – SiPMs Board

The SiPMs board is made of:

- 36 **15 μm Hamamatsu SiPMs** →each crystal has **two separate readout channels connected in series**.

- Four SMD blue LEDs nested between the photosensor packages.

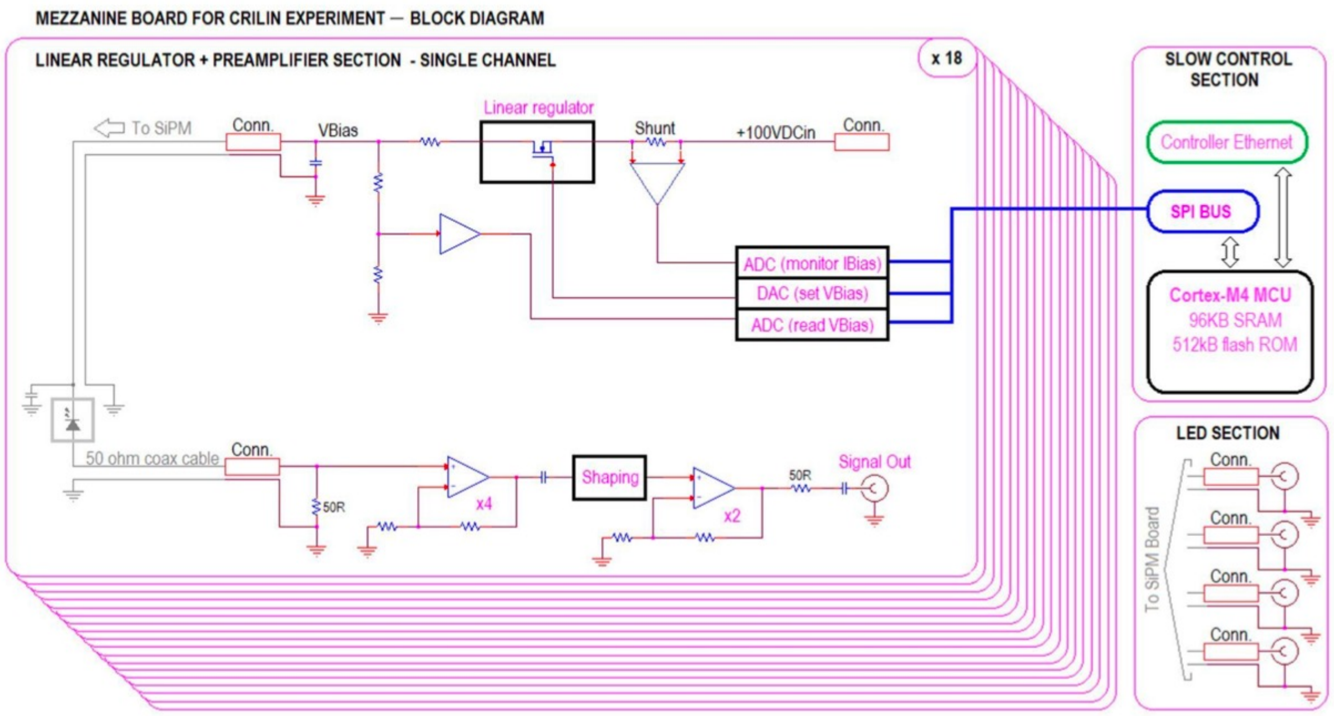




Electronics – Mezzanine Board

The Mezzanine Board for 18 readout channels:

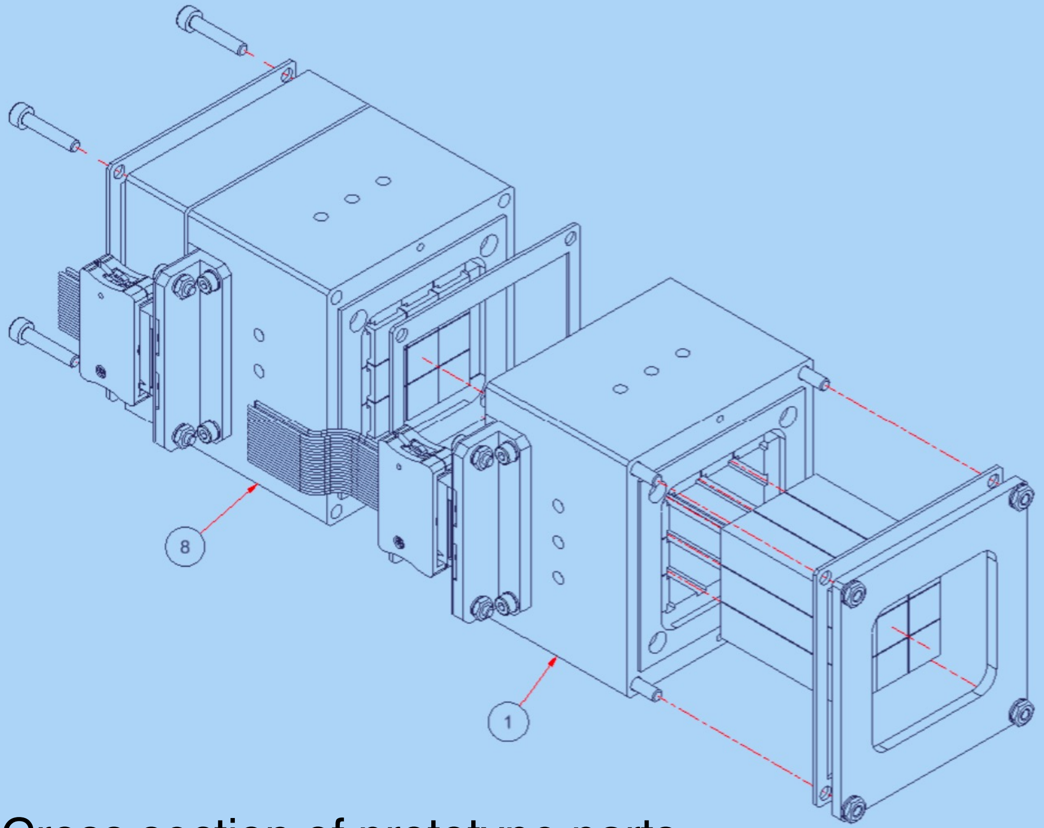
1. Pole-zero compensator and high speed non-inverting stages;
2. 12-bit DACs controlling HV linear regulators for SiPMs biasing.
3. 12-bit ADC channels;
4. Cortex M4 Processors.



Mezzanine board CAD

Mechanics

- Crystal matrix cases made of ABS plastic;
- Locking plates;
- Hydraulic connectors that transport dry gas in each module;
- Seals in between the modules.
- Tedlar windows at the endcaps.



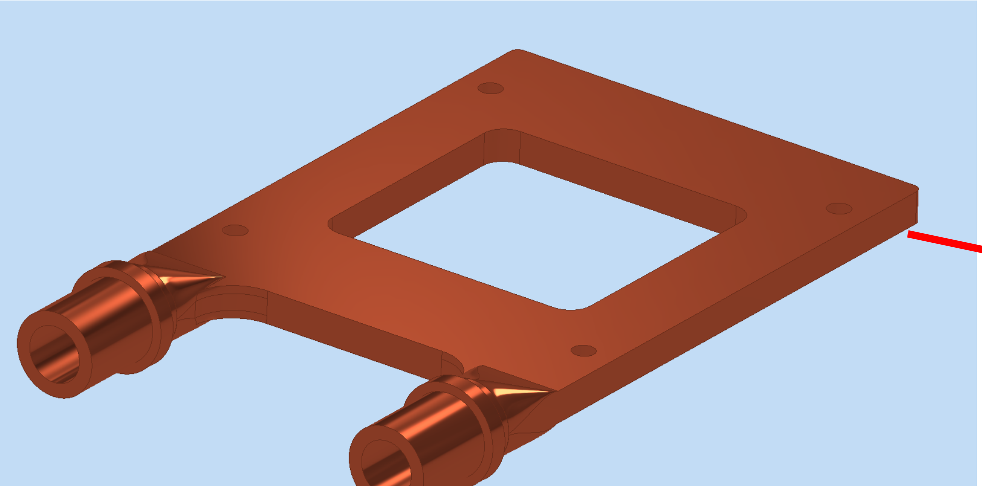
Cross section of prototype parts

See A. Saputi's poster: "**Mechanical Design for an Electromagnetic Calorimeter for Muon Collider**"

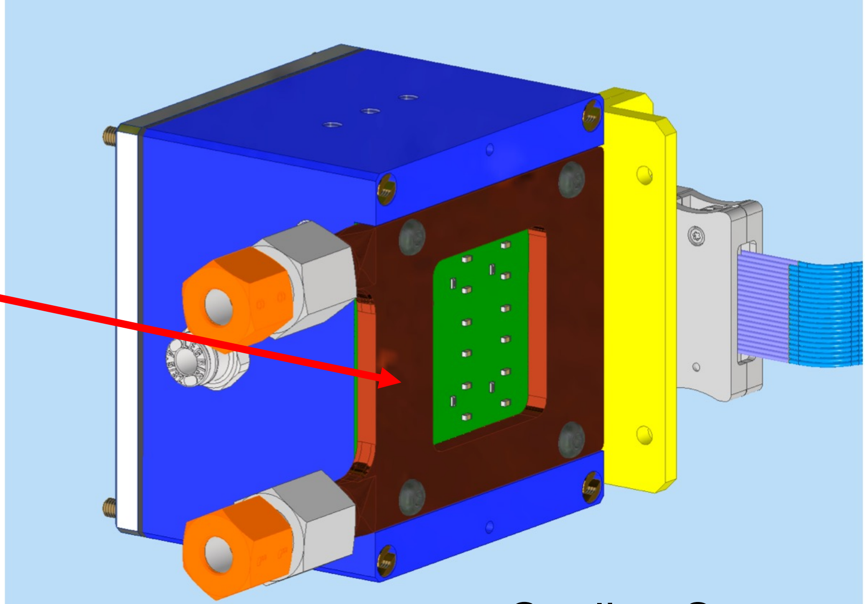
Cooling System

Total heat load estimated: **350 mW per crystal.**

- Cold plate heat **exchanger** made of copper mounted over the electronic board.
- **Glycol based water solution** passing through the deep drilled channels.



Copper exchanger



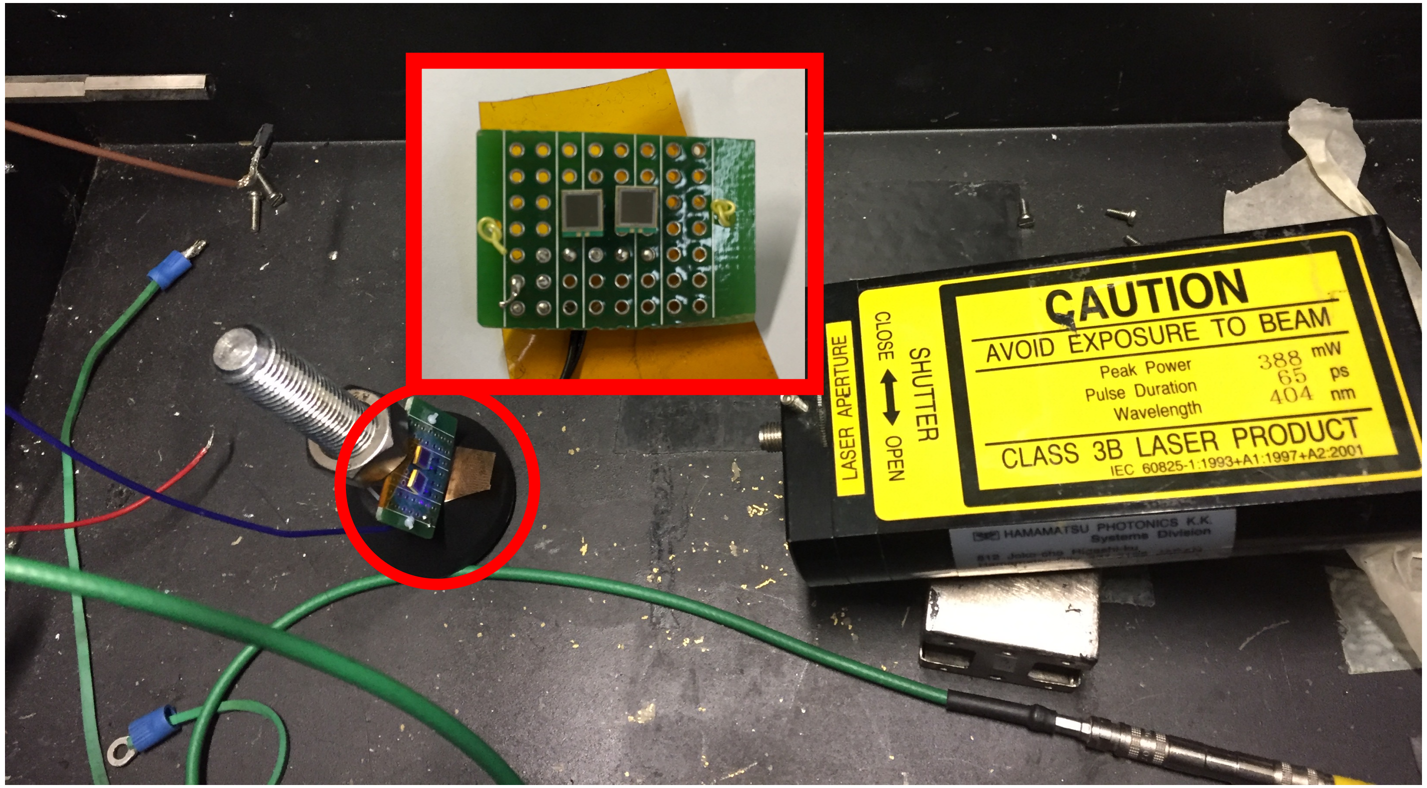
Cooling System

FEE and SiPMs test

- Two 15 µm SiPM in series;
- Front End Electronics;
- Picosecond UV laser source by Hamamatsu.
- 40GS/s oscilloscope for data taking.

Three sets of measurement performed changing:

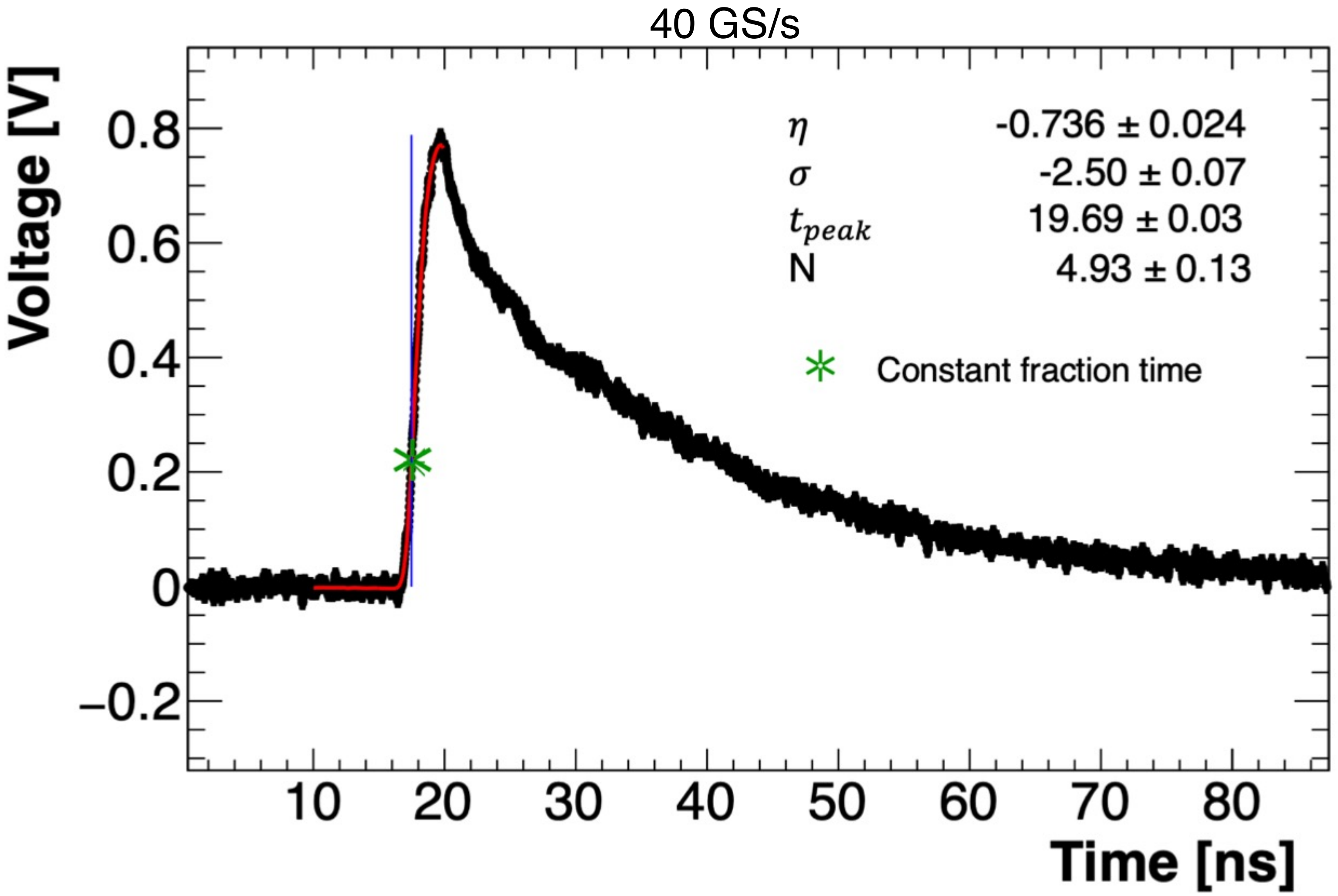
1. The oscilloscope sample rate;
2. The laser repetition rate;
3. The peak amplitude of the waveform.



FEE and SiPMs test-2

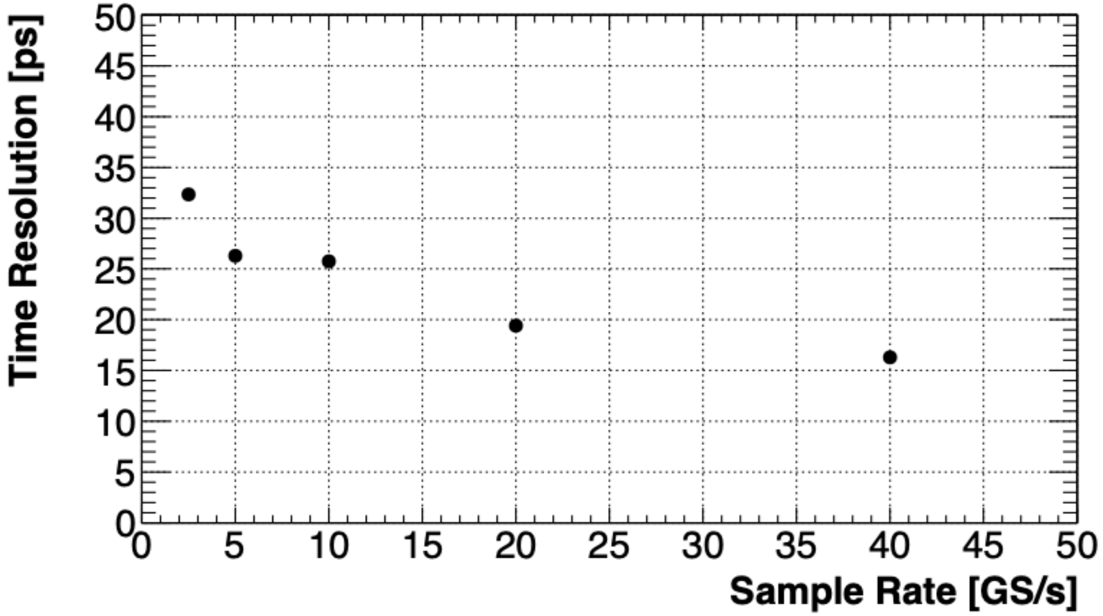
Digitized signals (40 GS/s)

- dynamic range: 0-2 V;
- Fast rising edge ~ 2 ns;
- Full width of ~ 70 ns;
- Timing reconstruction performed using **Constant Fraction method** on a **lognormal fit.**
- Impressive **time resolution** (≪**100 ps**).

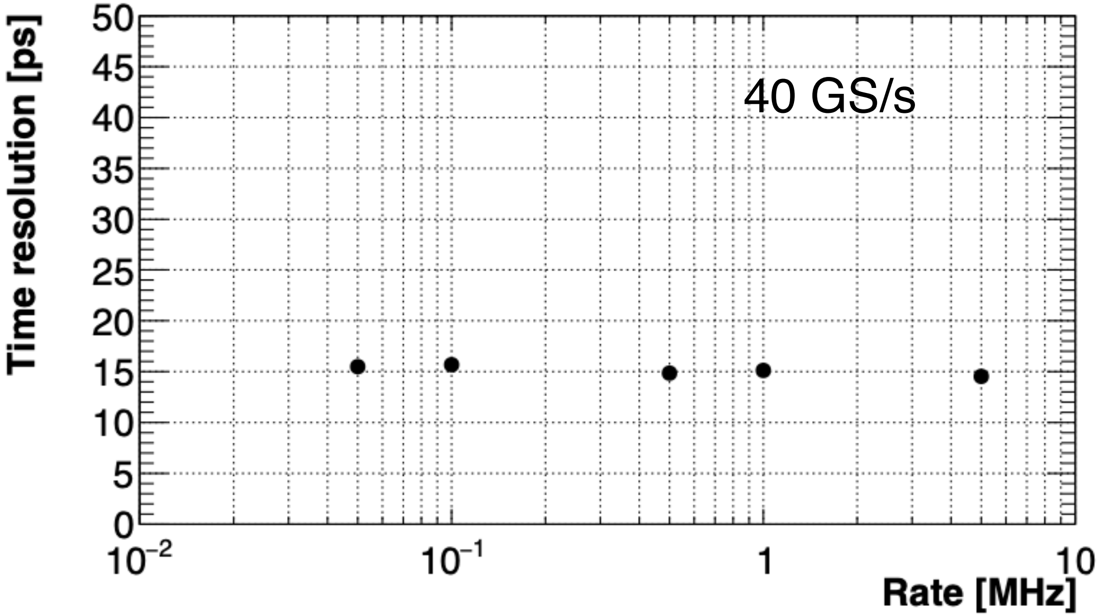


FEE and SiPMs test-3

1. **Timing vs oscilloscope sample rate**



2. **Timing vs laser repetition rate**

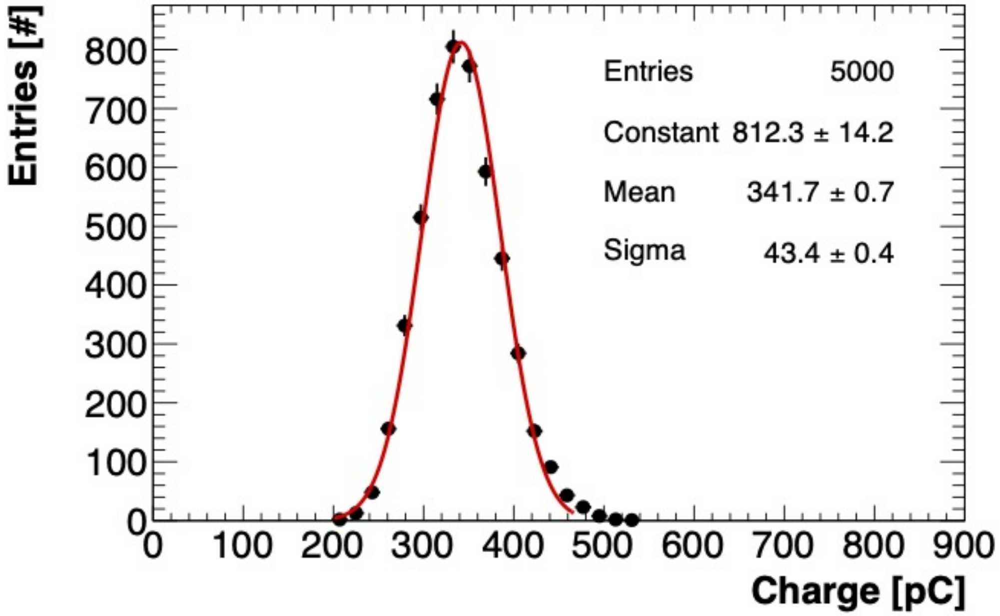


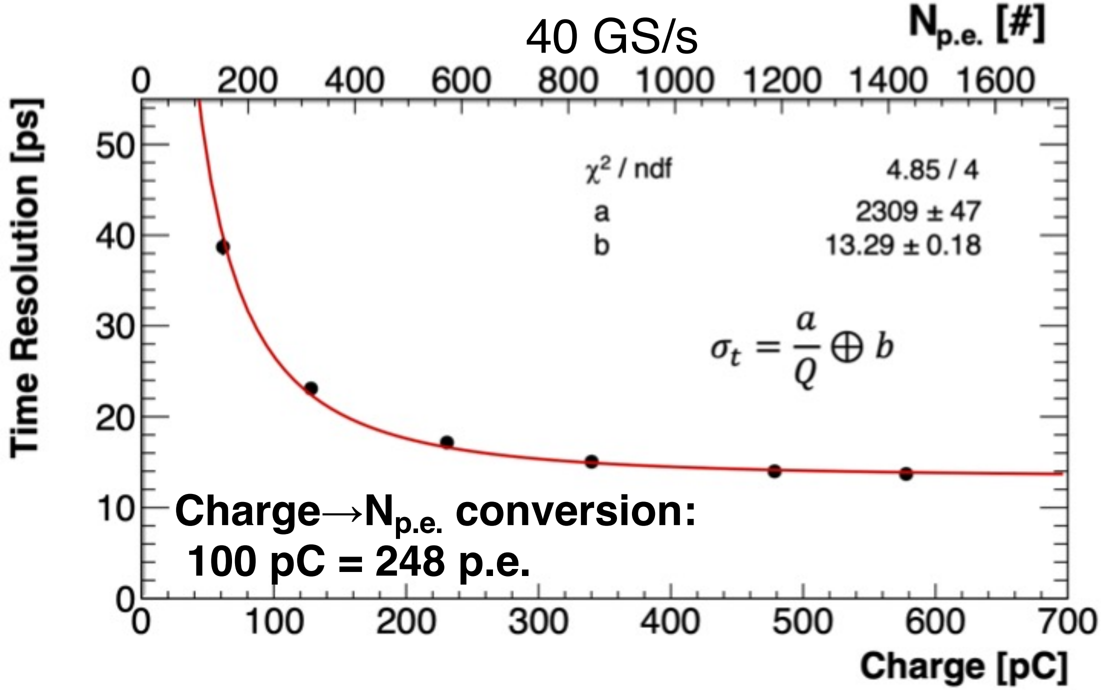
- Strong dependence from the sample rate since the **time resolution at 2.5 GS/s is twice the one at 40 GS/s.**
- The laser repetition rate scan shows a constant behaviour meaning that the **waveform stays unchanged in the 50 kHz-5MHz range.**

FEE and SiPMs test-4

3. **Timing vs mean charge and number of photo-electrons.**

Six different waveform peak amplitude values. For each of this runs we looked at charge and reconstructed time distribution extrapolating respectively the mean value and the RMS.





Time resolution is already **less than 40 ps even at low charges** (50 pC - 124 p.e) and an impressive **constant term b of ~ 13 ps**.

Conclusions

Crilin is a semi-homogenous calorimeter with **longitudinal segmentation** and **excellent timing resolution.** Before the construction of the prototype the single components were evaluated. In particular:

- Irradiation studies of crystals indicated no significant damages up to 80 krad TID and 10^{13} n/cm^2 fluence*;
- Preliminary two-crystals test beam at BTF with 500 MeV in July 2021 and at Cern in August 2021
  - **promising results in terms of time resolution: <100 ps, ~1p.e. / MeV (expected energy resolution < 10%/√E)**

Next steps:

- Irradiation studies on SiPMs up to $\sim 10^{14}$ n_{1MeVeq}/cm^2;
- Test Proto-1 performances with 500 MeV electrons at BTF and with a high energy beam (>100 GeV) at CERN (before the end of 2022).

* arxiv:2107.12307v3

Backup slides

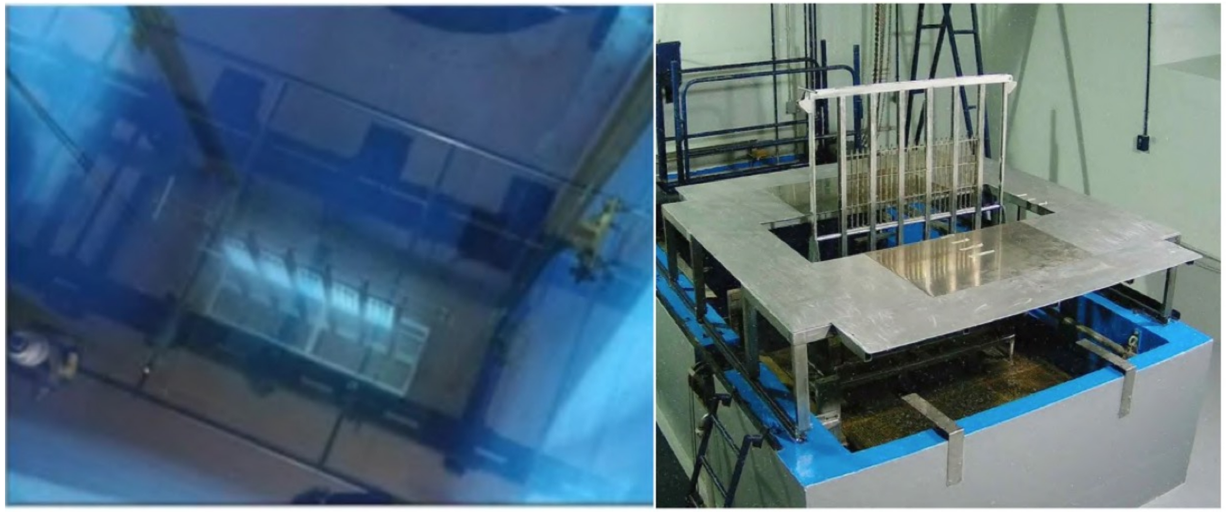
Irradiation sources

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

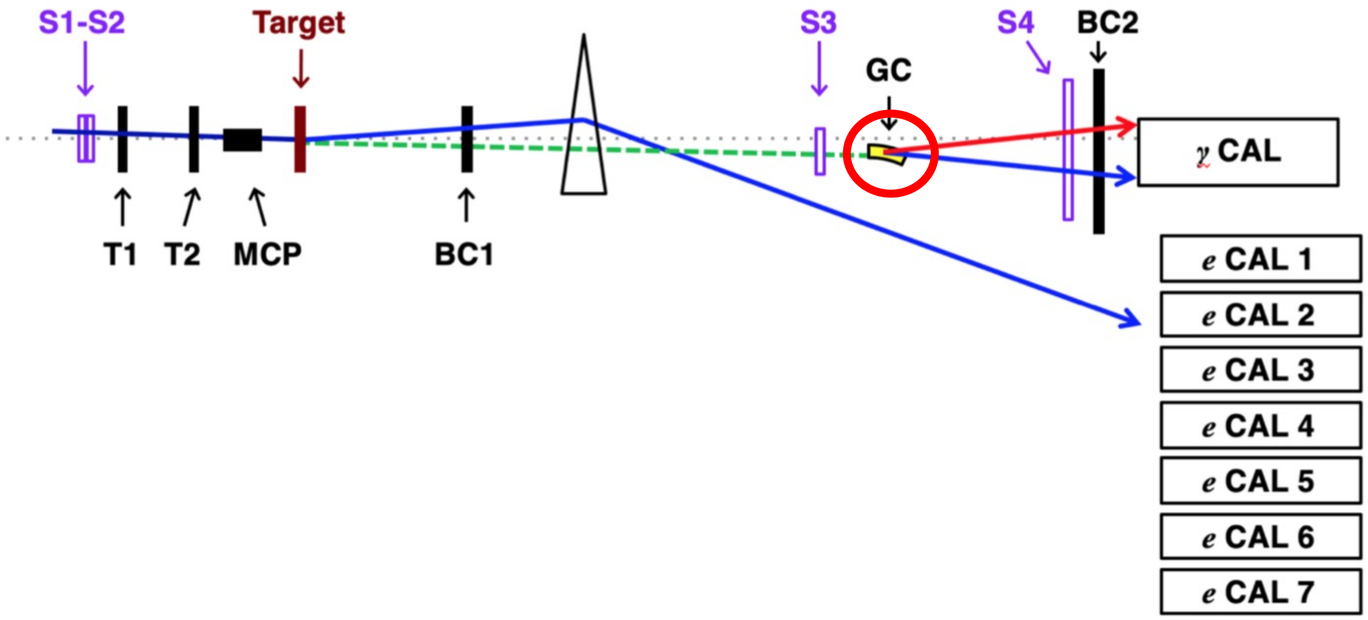


FNG facility:

- 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.

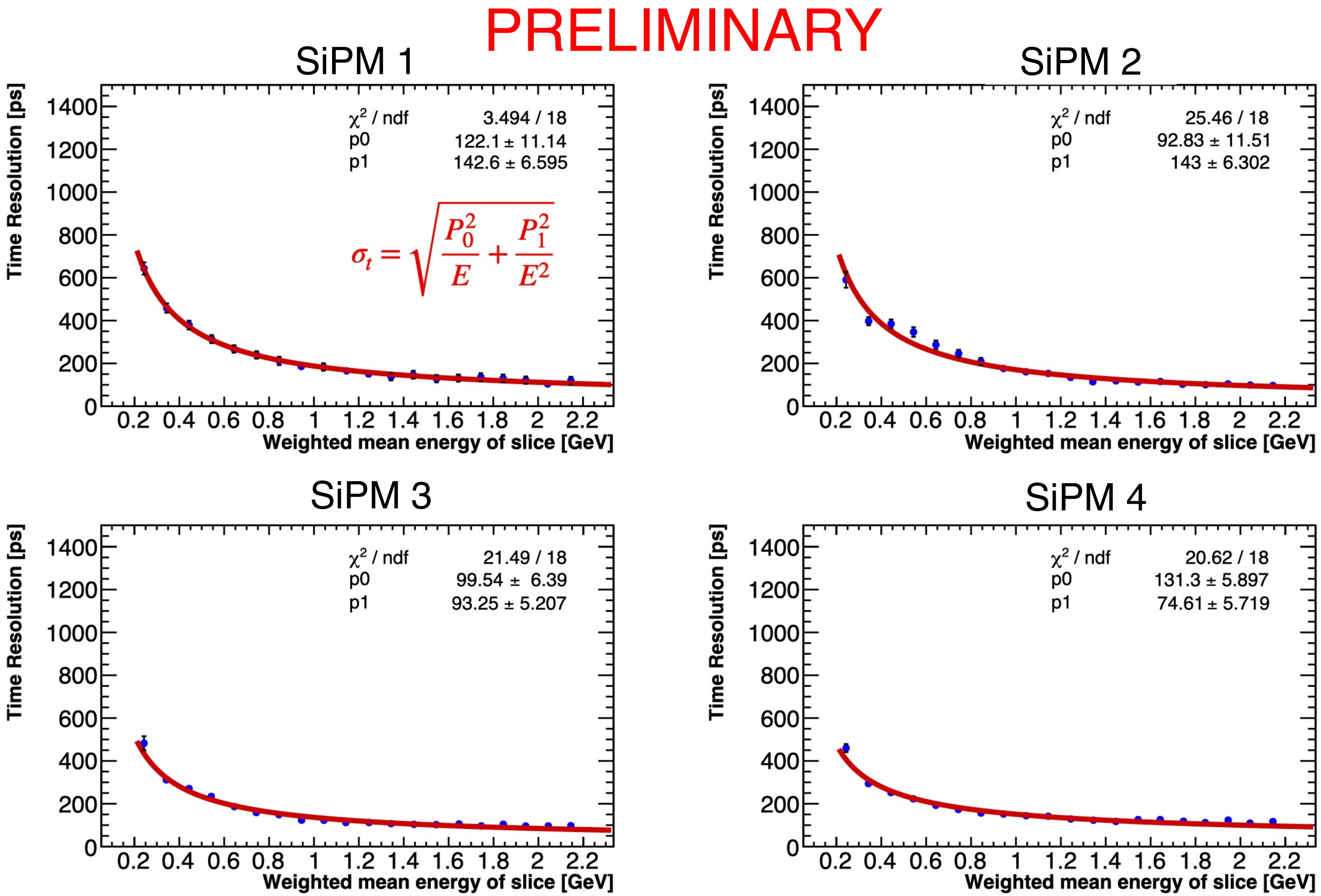
Test Beam

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



Test Beam-2

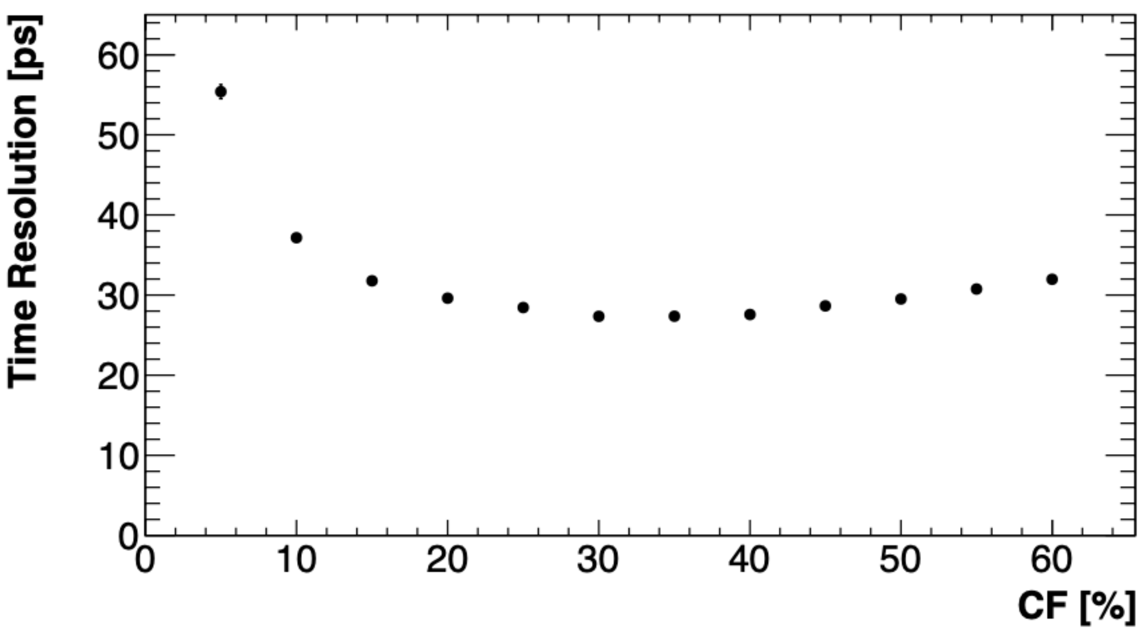
Time resolution results for Crilin SiPMs regarding 120 GeV electrons.



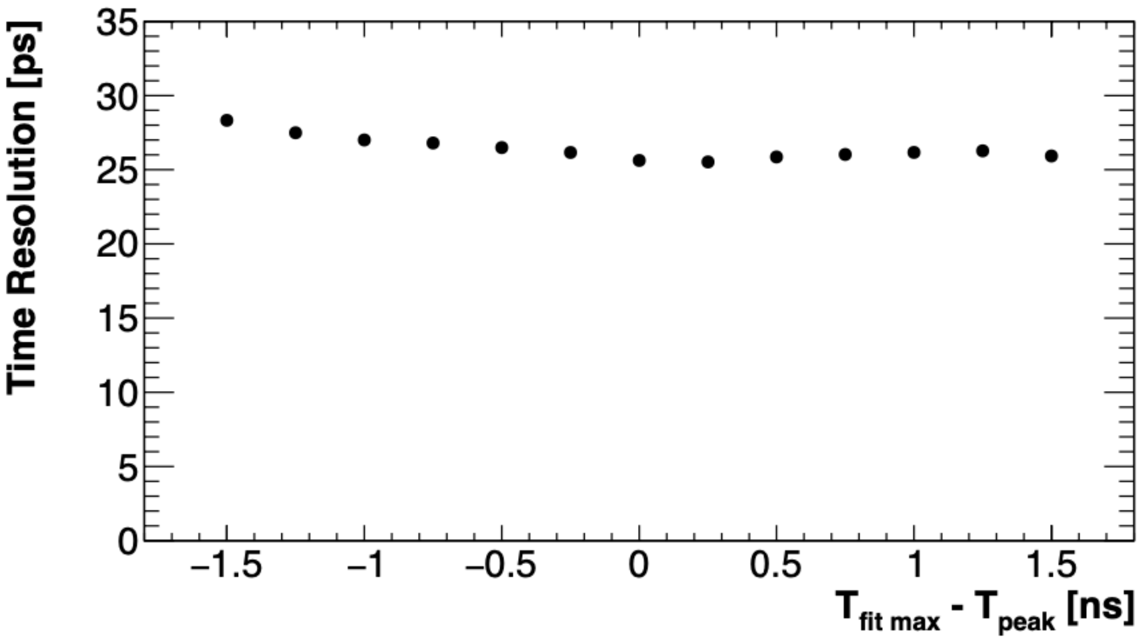
Constant fraction and fit window optimization

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