Optimizing an ECAL barrel for a Muon Collider: The CRILIN design

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International MUON Collider Collaboration

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**.

Muon Collider pros:
- **$m_\mu >> m_e$** (negligible synchrotron radiation)
- **point-like particle:** all energy is available in collisions
- perfect for **direct search of heavy states and Higgs studies**

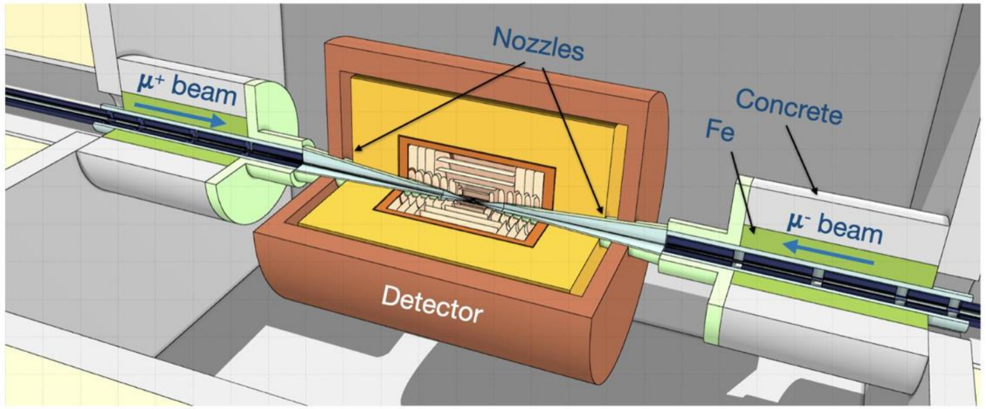
Muon Collider cons:
- **τ_0= 2.2μs :** very fast cooling and fast-ramping magnet system needed
- **μ** decay + interaction with machine: **beam-induced background (BIB)**, partially shielded by nozzles

→ detectors must be able to cope with the BIB while keeping good physics performances

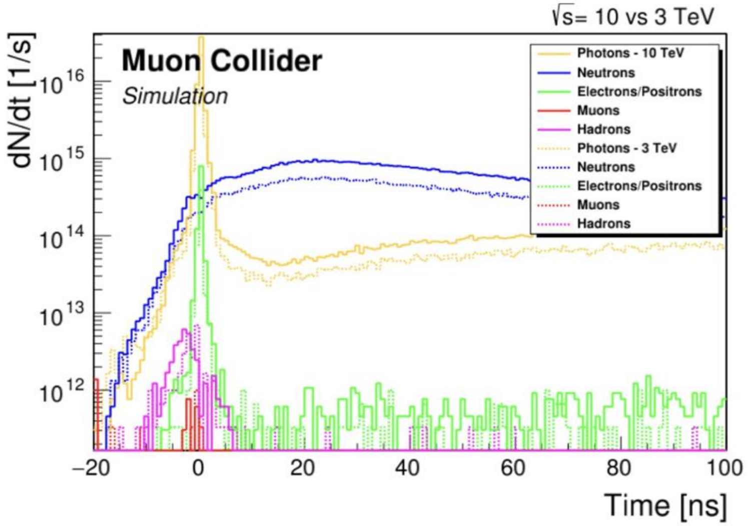
Beam Induced Background

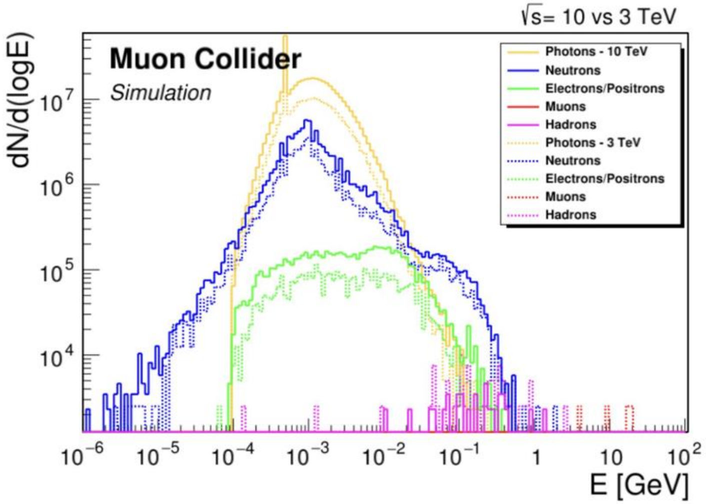
The decay of muons in flight along the accelerator ring produces high-momentum secondary particles, which interact with the machine's materials, and generate an **intense flux of tertiary particles** entering the detector region→ Beam-Induced Background (BIB)

- 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.



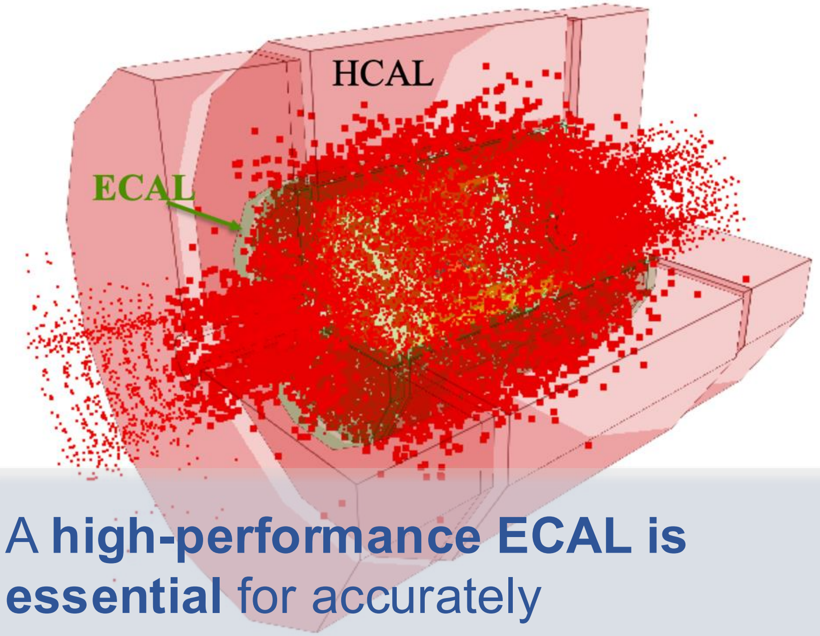


Muon Collider requirements

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

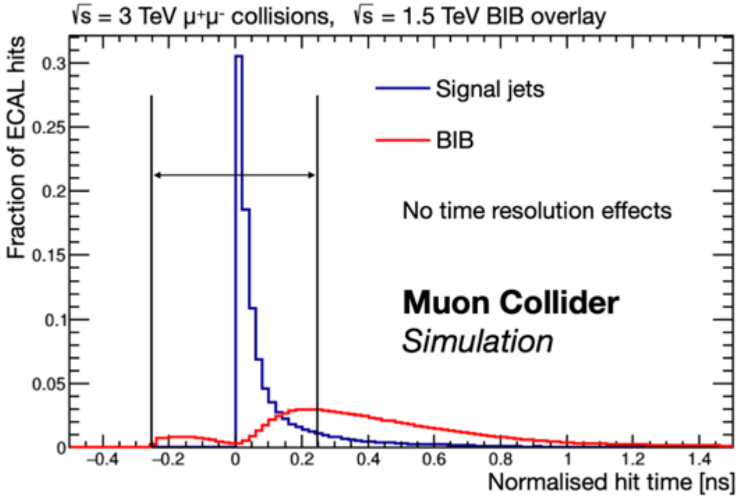
- Flux of 300 particles per cm^2 through the ECAL surface mainly γ (96%) and n (4%), average photon energy 1.7 MeV
- **Time of arrival flatter** throughout the bunch crossing → can exclude most of BIB with an acquisition window of ~240 ps
- Different **hit longitudinal profile** wrt signal
- **Total Ionising Dose**: ~1 kGy/year
- **Neutron fluence**: 10^{14} $n_{1MeVneq}/cm^2$ / year

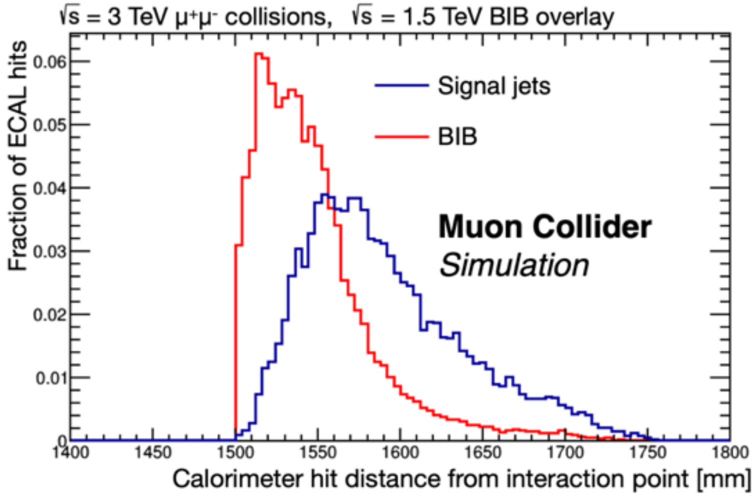
BIB hits in the calorimeters



A **high-performance ECAL is essential** for accurately reconstructing physics objects at the Muon Collider hence it should have:

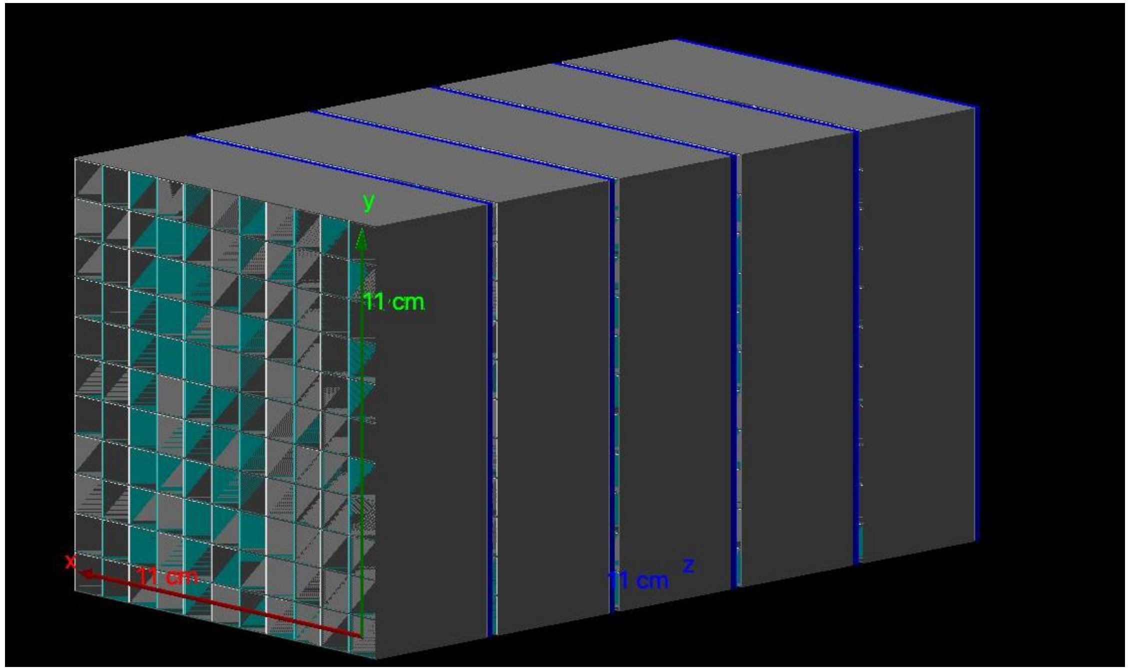
- σ_t ~ 80 ps
- longitudinal segmentation
- fine granularity to distinguish BIB and signal
- radiation resistance
- σ_E/E ~ $10\%/\sqrt{E}$





The CRILIN calorimeter

- ECAL design optimized for a Muon Collider → need to cope with the Beam Induced Background (BIB)
- **Semi-homogeneous, compact** and **flexible** ECAL made of **Cherenkov (PbF_2) crystal matrices** interspaced and readout by **SiPMs**



Key Features:

Excellent timing: (< 50 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.

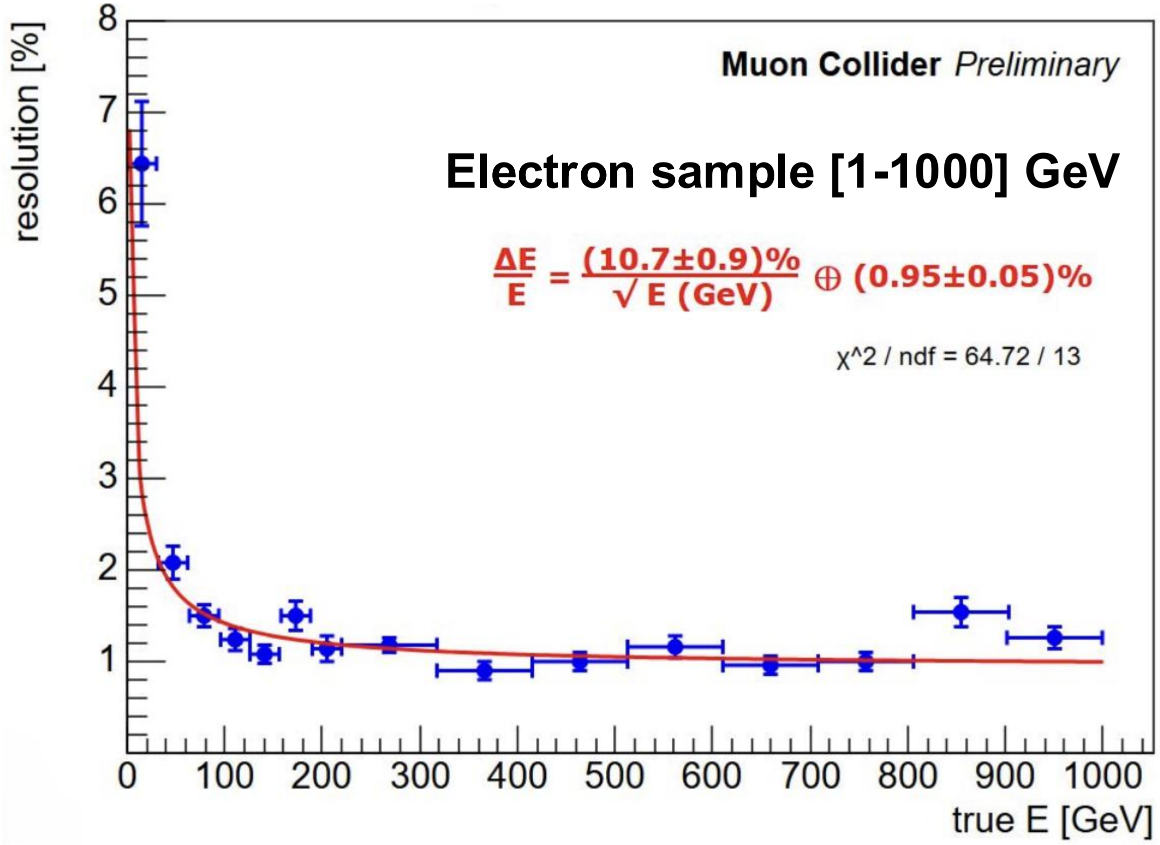
Good resistance to radiation: good reliability during the experiment

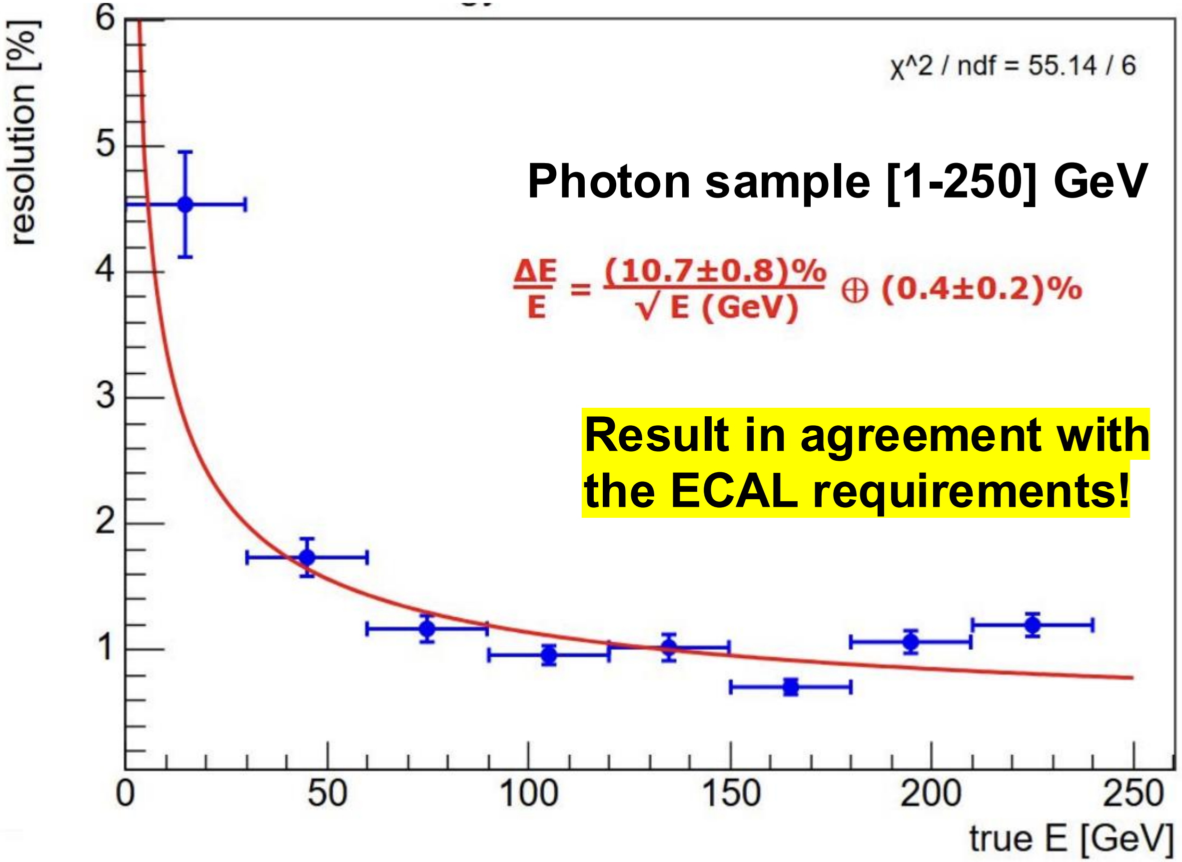
Energy resolution: targeting a level of $\sigma_E/E \sim 10\%/\sqrt{E}$, MC confirmed

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

Simulated performances

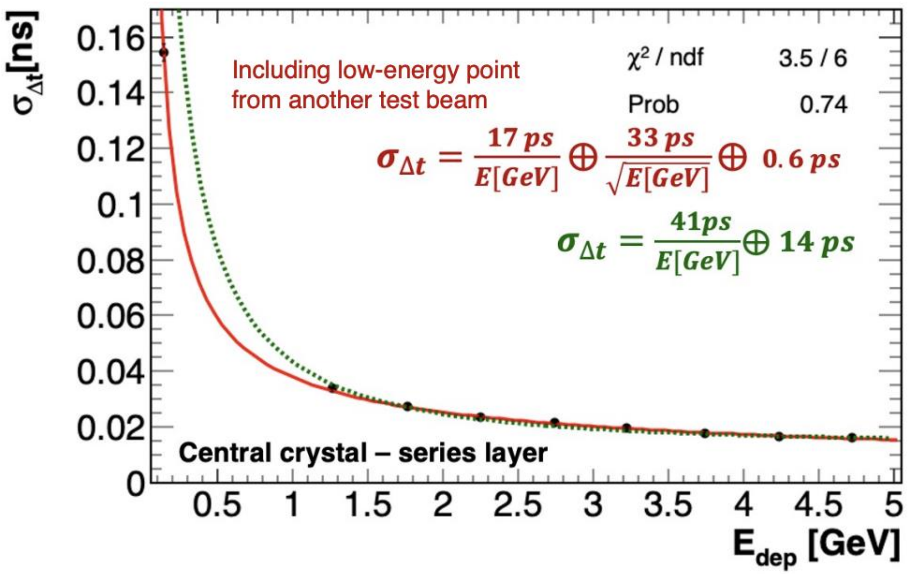
- The CRILIN calorimeter was implemented in the Muon Collider detector **MUSIC** (MUon System for Interesting Collisions) geometry.
- Performance studies based on the Muon Collider simulation framework using MC **particle gun samples** of **photons** and **electrons,** including the **beam induced background contribution**.





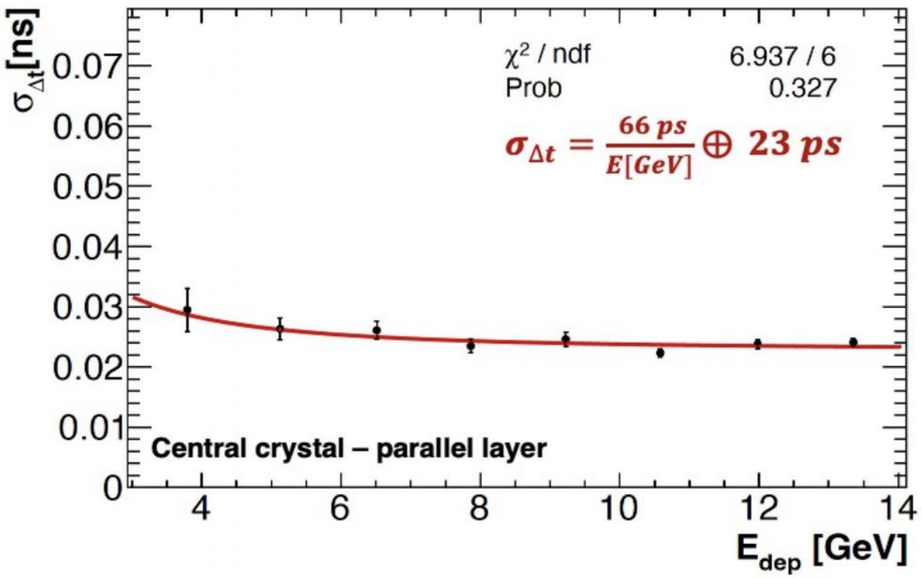
Result in agreement with the ECAL requirements!

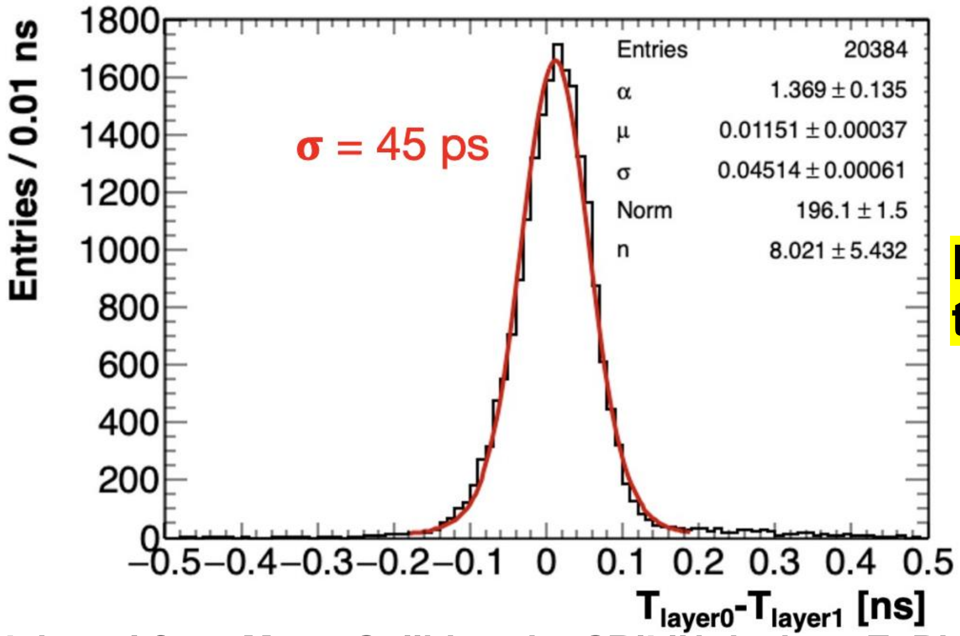
Timing results



Dedicated test beam at SPS-H2 (e^- 120 GeV) for time resolution evaluation on the **3x3x2 prototype (Proto-1)**.

- **Outstanding time resolution** of **O(20 ps)** for E_{dep} > 1 GeV was achieved in both the case of the **both layers**.
- **Excellent results** using central crystals of **different layers** with $\boldsymbol{\sigma_t}$**=45 ps**. Time resolution dominated by the 2 SiPM board **synchronization jitter O(32ps)**.





Result in agreement with the ECAL requirements!

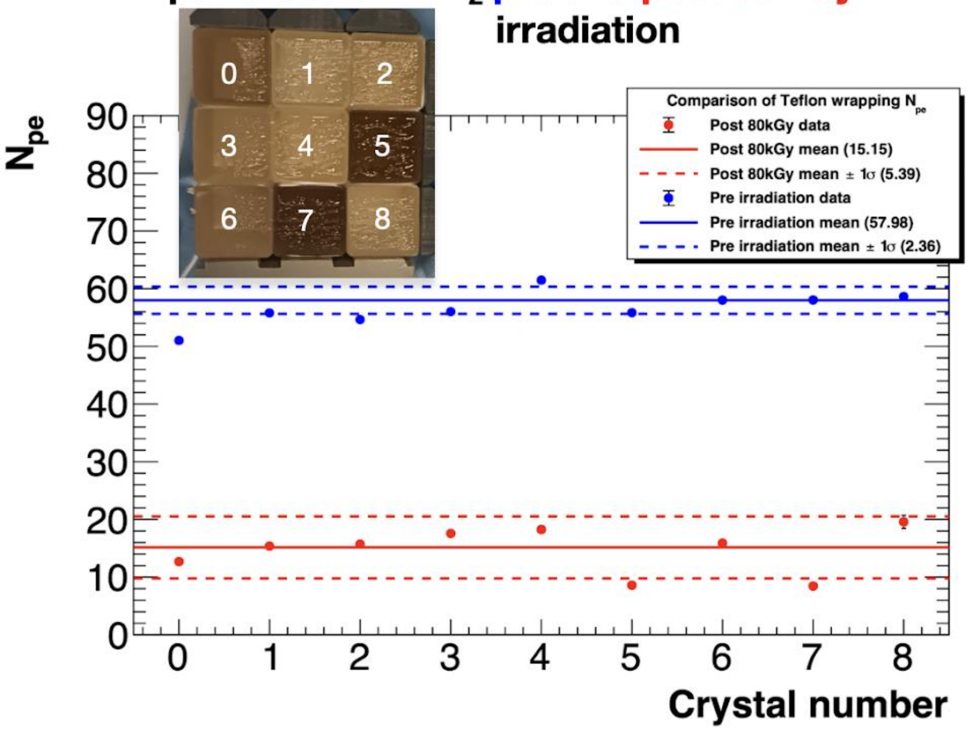
Radiation hardness

Dedicated Test Beam at BTF (e^- 450 MeV) in single particle mode to test the **LY loss due to TID**

- Different wrapping tested → **Teflon sensibly damaged**
- Crystals evident loss of transparency → **still good amount of light detectable**
- **SiPM dark counts increases significantly** with the absorbed dose
- New tests planned to evaluate SiPMs PDE loss and optical grease degradation

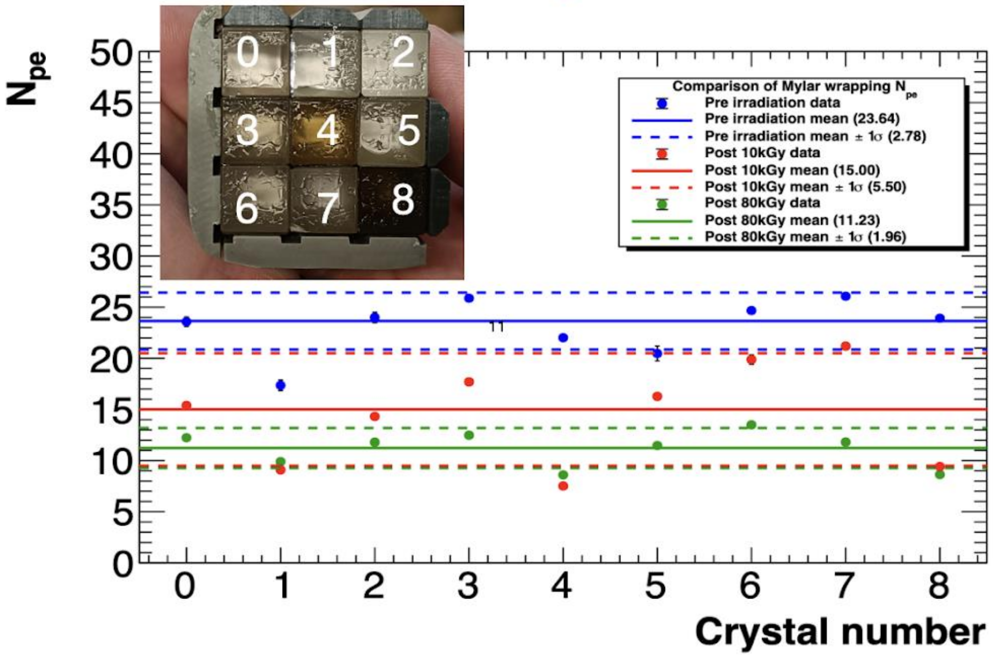
Telfon wrapping

Npe values of PbF_2 pre and post 80 kGy irradiation



Mylar wrapping

Npe values of PbF_2 pre, after 10 kGy and after 80 kGy irradiation



Summary

- **Simulated energy resolution** perfectly in line with the Muon Collider requirments
- **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

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

DRD6-WP3 2025

- Expanding prototype to a 7x7x5(layers) configuration, with a target of 2 M_R – 22 X_0.
  - Beam test week approved for September 2025 to test the new FEE and DAQ options
  - Final test beam scheduled for 2026