CRILIN: a semi-homogeneous crystal calorimeter for the Muon Collider

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Summary. — A muon collider is being proposed as a next generation facility. The incredible physics potential comes at the cost of technological challenges due to the short muon lifetime. From the detector side, the beam-induced background, produced by the muon decays in the beams and subsequent interactions, may potentially limit the physics performance. As an example, a diffused flux of photons and neutrons passes through the calorimeter system, which thus requires a design to avoid this substantial background. The Crilin calorimeter is being studied as a valuable option for the muon collider electromagnetic calorimeter: it is a semi-homogeneous calorimetric system with Lead Fluoride (PbF2) crystals interfaced with Silicon Photomultipliers (SiPMs). In this talk the simulation studies towards the Crilin design are presented. The experimental tests on a prototype, consisting of two layers of 3x3 PbF2 crystals each, performed using 40-150 GeV electrons at CERN H2, are also presented. These tests are fundamental to demonstrate that the requirements established with the muon collider simulation are achieved by the Crilin technology.

1. – The Muon Collider project

The Muon Collider is one of the most promising proposals for future accelerators, where beams of muons and antimuons collide at multi-TeV center-of-mass energies. Such high energies can be reached since muons have a mass approximately 200 times that of electrons, making the energy loss due to synchrotron radiation and beamstrahlung negligible. Additionally, since muons are elementary particles, the entire beam energy is available for interactions, leading to cleaner collisions compared to those in hadronic colliders. These characteristics enable the Muon Collider to function both as a precision machine, similar to electron-positron colliders, and as a discovery machine, like hadronic colliders [1].

The main challenge in constructing a Muon Collider is related to the unstable nature of the muons that form the beams. Their decay in flight produces an intense flux of particles known as Beam-Induced Background (BIB) [2]. Specifically, electrons, positrons, and neutrinos generated from muon decay can interact with the machine's materials, producing a high flux of secondary and tertiary particles. These particles can enter the detector region and affect its performance. A characterization of the BIB particles was conducted through detailed simulations at a center-of-mass energy of 1.5 TeV, based on the machine design developed by the Muon Accelerator Program (MAP) [3]. Despite the presence of a pair of cone-shaped tungsten absorbers in the forward region of the detector, each with an angular aperture of approximately 10°, a significant quantity of BIB particles still reach the detector region. The background inside the detector mainly consists of photons, neutrons, and electrons/positrons, characterized by low momentum and asynchronous arrival time with respect to the bunch crossing.

The proposed detector for the Muon Collider features a typical multi-purpose design, with a cylindrical configuration and a hermetic geometry [1]. Starting from the interior, the detector consists of a tracking system surrounding the interaction point, followed by a calorimeter system that includes an electromagnetic calorimeter (ECAL) and a hadronic calorimeter (HCAL). At the outermost region is placed a superconducting solenoid that provides a magnetic field of 3.57 T, and finally, the muon system.

2. – Requirements for the electromagnetic calorimeter at Muon Collider

In a multi-TeV Muon Collider, the calorimeter system faces the challenge of operating with a dense flux of low-energy particles generated by the BIB. On the inner face of the electromagnetic calorimeter the particle flux is approximately 300 particles per cm^{-2}, predominantly consisting of photons (96%) with an average energy of 1.7 MeV, along with neutrons (4%). The choice about the technology and the design for the ECAL must be carefully considered to minimize the impact of BIB, while achieving optimal physics performance. This necessitates meeting several key requirements:

- **Longitudinal segmentation** helps to distinguish the electromagnetic showers generated by BIB particles from those produced by signal particles. As shown in Figure 1 (right), the longitudinal development of signal particle showers differs from that of BIB showers;

- **Fine granularity** reduces the hit density per individual cell. Due to high density, multiple particles may overlap within a single cell, leading to a combined hit where their energies sum up. This overlap can result in hits with energies similar to those from the signal, making it challenging to distinguish from BIB contributions;

- **Excellent timing** is crucial for reducing the out-of-time component of the BIB. As shown in Figure 1 (left), applying a time window of approximately 300 ps can filter out part of the BIB (in red) while preserving the signal (in blu). A timing resolution better than 100 ps ($\Delta t = 3\sigma_t$) is required.

- **Good energy resolution** is essential for accurately measuring the energy of particles in interaction events. A resolution better than $10\%/\sqrt{E}$ is required.
- **Radiation hardness** is crucial to maintain adequate performance over time. The ECAL is expected to recive approximately 100 krad/year of total ionizing dose and 10^{13-14} cm^{-2} 1-MeV-neq fluence [1].

3. – CRILIN: a new proposal of calorimeter technology

The Crilin (Crystal Calorimeter with Longitudinal Information) design has been proposed as a candidate solution to meet the requirements of the Muon Collider ECAL detector [4]. The Crilin calorimeter is a novel proposal of semi-homogeneous calorimeter based on Lead Fluoride (PbF2) crystals read out by surface mounted UV extended Silicon Photomultipliers (SiPMs). This proposal features a modular architecture based on stackable submodules composed of crystal matrices. Each crystal is read out individually by a 2x2 matrix of SiPMs, which are paired to create two separate readout channels. Crystal dimensions are 10×10×40 mm^3 and the surface area of each SiPM is 3×3 mm^2. The fine granularity, scaling with the size of the SiPMs, combined with excellent timing resolution ensured by the use of Cherenkov crystals, good pileup capability, and high radiation resistance of both the crystals and SiPMs, allows it to meet the primary requirements for the Muon Collider detector. In particular, the proposed layout consists of 5 layers of crystals totaling 22 radiation lengths (X_0).

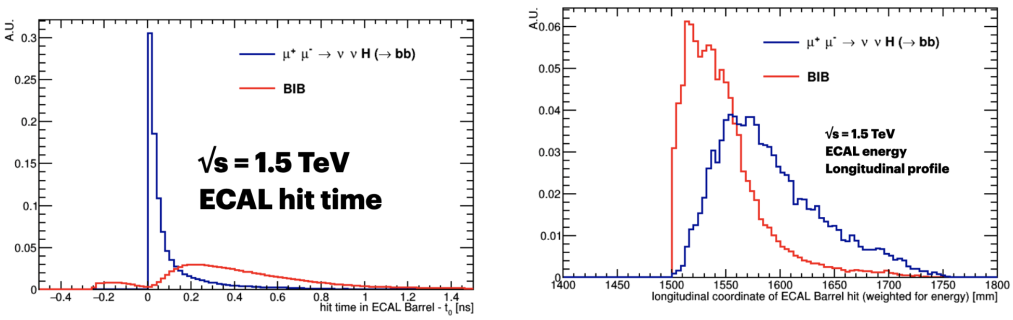

Fig. 1.: Left: Timing of ECAL barrel hits relative to the bunch crossing time for BIB (Red) and $H \to b\bar{b}$ signal (Blue). Right: Distribution of the energy of the ECAL barrel hits respect the distance from the beam axis, for BIB (Red) and $H \to b\bar{b}$ (Blue).

4. – Performance characterization studies from simulations

The CRILIN technology was implemented into the detector at simulation level and the performance benchmarks was evaluated using a Monte Carlo sample of 15000 single event photons originating from the interaction point, with a uniform energy distribution between 1 GeV and 1000 GeV and a uniform polar angle distribution between 70° and 110° degrees, relative to the beam axis. This angular region focuses on the central part of the barrel, chosen to avoid the transitional regions between the barrel and endcap where

the detector is not full optimized. The simulation of particle interactions with detector materials was performed using the Geant4 toolkit within the ILCsoft software package and the simulated response of the detector was carried out using the Marlin framework. Particle reconstruction was based on the PandoraPFA package, which employs the particle flow method to combine information from the sub-detectors [5].
The matching between Monte Carlo and reconstructed photons was achieved by selecting, within a cone of opening radius $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.1$ centered around the Monte Carlo photon's direction, a reconstructed particle identified as a photon, where ϕ represents the azimuthal angle and η the pseudorapidity. Figure 2 (left) illustrates the high reconstruction efficiency as a function of Monte Carlo energy, comparing the cases without (blue) and with the contribution of BIB (red). To study the energy resolution, a correction factor (k) was applied to the reconstructed photon energy to normalize the detector response across different photon energies. This correction factor was determined by the ratio of the Monte Carlo photon energy (E_{MC}) to the reconstructed photon energy (E_{RC}). The energy resolution was determined by dividing the energy range into bins of constant width and studying the distribution of the relative difference between the Monte Carlo energy and the reconstructed energy, incorporating the correction factor:

$$\frac{\Delta E}{E_{MC}} = \frac{(E_{MC} - E_{RC} \cdot k)}{E_{MC}} \tag{1a}$$

A Gaussian fit was applied to the distributions obtained for each energy bin, and the sigma value was extracted. Figure 2 (right) displays the energy resolution as a function of Monte Carlo energy, with (in red) and without (in blue) the BIB contributions. The resolution is fitted using the typical function for homogeneous electromagnetic calorimeters. These preliminary results indicate a degradation in performance due to the presence of the BIB, with the stochastic term increasing from $4.8\%/\sqrt{E}$ to $15\%/\sqrt{E}$. Currently, optimization studies of the clustering algorithm are ongoing. In particular, by introducing specific acquisition time windows for each layer of CRILIN, it will be possible to filter out the out-of-time BIB component, thereby improving overall performance and meeting the required specifications.

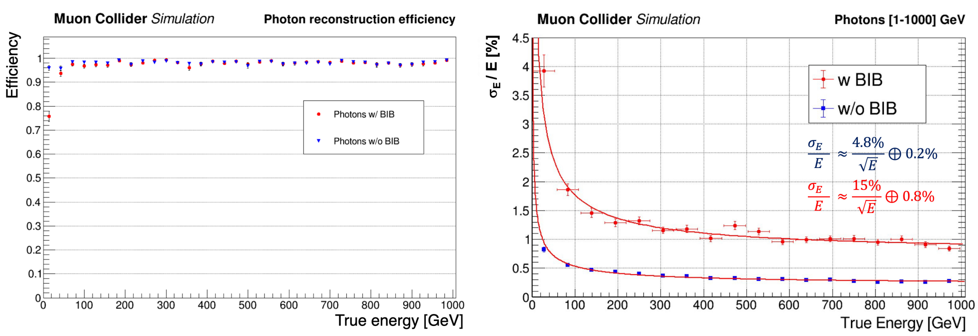

Fig. 2.: Left: Photon reconstruction efficiency as a function of Monte Carlo energy. Right: Energy resolution as a function of Monte Carlo energy. Red with BIB contribution, blue without.

5. – Experimental test results

The selection of PbF_2 crystals and SiPMs as photodetectors is motivated by their high resistance to radiation damage. To evaluate the radiation tolerance of these components, dedicated testing campaigns have been conducted. Regarding the PbF_2 crystals, a Total Ionizing Dose (TID) irradiation campaign was conducted at the ENEA-Calliope facility using a ^{60}Co sources to product 1.25 MeV photons. Transmittance measurements were taken longitudinally along the crystal axis, and the resulting transmittance spectra after some irradiation steps are presented in Figure 3 (top left). In particular, after a total ionizing dose above 350 kGy, only a slight decrease in transmittance was observed.

Regarding the SiPMs, neutron exposure causes an increase in dark current. A dedicated irradiation campaign was conducted at the Frascati Neutron Generator (FNG-ENEA) facility using 14 MeV neutrons with a fluence of up to $10^{14} n_{1MeV}/cm^2$ and two models of SiPMs were tested with different pixel size: 15 μm and 10 μm. By measuring the dark current after irradiation at different temperatures, it was found that the SiPM model with 10 μm pixel size exhibits a smaller increase in dark current and is thus optimal for withstanding the radiation environment of the Muon Collider [6].

To assess the time resolution and overall functionality of the CRILIN technology, a dedicated test beam experiment was conducted at CERN-H2 using electron beams with energies ranging from 40 GeV to 150 GeV impinging on a prototype. As shown in Figure 3 (top right), the Proto-1 prototype consists of two layers of 3x3 crystal matrices. In this setup, the electron beam first impinged upon the first layer, where the SiPMs in each cell were connected in series pairs, while in the second layer, they were connected in parallel. The time resolution estimation was based on measuring the time difference (ΔT) between the two readout channels of the central crystal in the 3x3 matrix. Figure 3 shows the Gaussian fit of the ΔT distribution for the first layer (bottom left) and the second layer (bottom right) for 120 GeV electrons, from which the sigma value $\sigma_{\Delta T}$ was extracted. The time resolution, determined as $\sigma_T = \sigma_{\Delta T}/2$, was found to be on the order of 20 ps, meeting the required specifications.

6. – Conclusions and future prospects

The Muon Collider project represents a promising proposal of future collider and despite the challenges posed by BIB due to the decay of muons, advanced detector technologies and designs, such as the CRILIN calorimeter, show significant potential in mitigating these effects. The CRILIN design with its fine granularity, radiation hardness and good timing and energy resolution, represents a very promising proposal to meet the stringent requirements for the electromagnetic calorimeter at a multi-TeV Muon Collider. Simulation studies and test beam experiments have demonstrated that this technology can achieve excellent temporal resolution, surpassing the 100 ps requirement, and provide good energy resolution, thereby confirming its suitability for the Muon Collider detector. Future plans involve more detailed simulation studies to optimize the mitigation of the BIB, alongside executing more extensive experimental tests with larger and complete prototypes.

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This work was developed within the framework of the International Muon Collider Collaboration (`https://muoncollider.web.cern.ch`), where the Physics and Detector

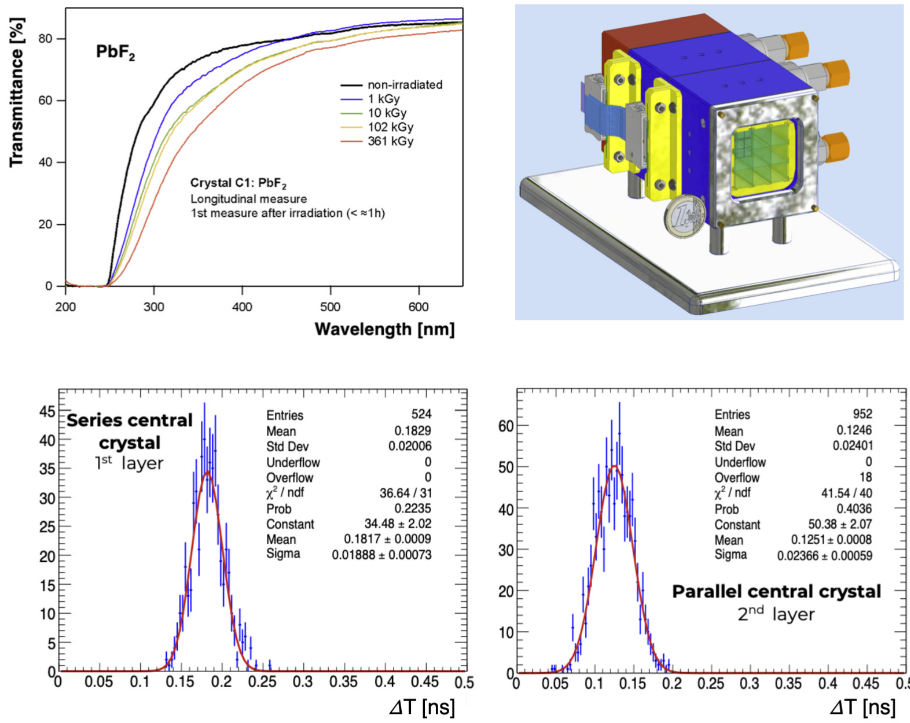

Fig. 3.: Top left: Transmission spectra obtained at various irradiation stages. Top right: 3D proto-1 overview. Bottom: Gaussian fit of ΔT distributions for the central crystal of first layer (left) and second layer (right).

Group aims to evaluate potential detector R&D to optimize experiment design in the multi-TeV energy regime. This work was supported by the EU Horizon 2020 Research and Innovation Programme under Grant Agreements No. 101006726 and No. 101004761. The authors thank the LNF Division Research and ENEA NUC-IRAD-GAM Laboratory (Casaccia R.C.) for their technical and logistic support. They also thank the BTF staff for providing the beam time and helping them get a smooth running period.

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