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BEAMTEST CHARACTERIZATION OF ORIENTED CRYSTALS FOR THE KLEVER SMALL ANGLE CALORIMETER

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CONTENTS

INTRODUCTION	1
1 THE HIKE/KLEVER PROJECT	5
1.1 Physics Beyond the Standard Model	6
1.1.1 A theory of everything	6
1.1.2 Extensions of the Standard Model	7
1.1.3 Experimental strategies	8
1.2 The HIKE project	11
1.2.1 Physics opportunities in standard mode	12
1.2.2 Physics opportunities in beam dump mode	16
1.2.3 Kaon beamline layout	17
1.2.4 Particle detectors	20
1.3 The Small Angle Calorimeter	24
2 THE PHYSICS OF ORIENTED CRYSTALS	29
2.1 Crystalline lattices	29
2.2 Motion of a charged particle in a crystal lattice	31
2.2.1 Axial channeling	31
2.2.2 Planar channeling	36
2.2.3 Dechanneling	38
2.2.4 Positive and negative charged particles	38
2.3 Radiative processes	39
2.3.1 Standard Bremsstrahlung	40
2.3.2 Channeling Radiation	42
2.3.3 Coherent Bremsstrahlung	45
2.3.4 Strong Field regime	46
2.4 Electron-positron pair production	48
2.5 Applications	52
3 THE KLEVER 2021 BEAMTEST AT THE CERN SPS	57
3.1 Beamtest goals	57
3.1.1 The crystal samples	58
3.1.2 The photodetectors	62
3.2 The experimental setup	67
3.2.1 General overview	68
3.2.2 The Plastic Scintillator Trigger	68
3.2.3 The tracking system	70

3.2.4	The Micro-Channel Plate	71
3.2.5	The bending magnet	72
3.2.6	The goniometer	72
3.2.7	The Multiplicity Counter	73
3.2.8	The photon calorimeter	74
3.2.9	The electron spectrometer	75
3.2.10	The Data AcQuisition system	76
3.3	Preliminary analysis	79
3.3.1	Alignment of the silicon trackers	79
3.3.2	Characterization of the electron beam	81
3.3.3	Calibration of the calorimeters	82
4	CHARACTERIZATION OF THE ORIENTED CRYSTALS	89
4.1	Crystal alignment	89
4.2	PbF ₂ characterization	92
4.2.1	The events selection criteria	93
4.2.2	The preliminary measurements	93
4.2.3	The SiPM calibration	98
4.2.4	The enhancement of the pair production cross-section	102
4.2.5	The radiation length reduction	105
4.3	PbWO ₄ characterization	107
4.3.1	The preliminary measurements	108
4.3.2	The enhancement of the pair production cross-section	112
4.3.3	The radiation length reduction	114
5	TIME RESOLUTION MEASUREMENTS	117
5.1	The zero-crossing algorithm	117
5.2	The Micro-Channel Plate time resolution	119
5.3	The CRILIN photodetection system	121
5.3.1	Measurements with the non oriented PbF ₂ crystals	121
5.3.2	Measurements with the oriented PbF ₂ crystal	126
5.4	The STORM photodetection system	128
	CONCLUSIONS	131
A	EXPERIMENTAL METHODS	135
A.1	Reconstruction of the Pulse Height of the Multiplicity Counter	135
A.2	Geant4 simulation of the experimental setup	137
A.3	Analysis of the CRILIN waveforms	138
	Acronyms	143
	List of Figures	147
	List of Tables	153

Bibliography	154
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INTRODUCTION

The Standard Model of particle physics (SM) is the quantum field theory which describes the nature and the properties of the elementary particles and their interactions. This theory is based on a limited number of assumptions and parameters and it has been capable of describing most of the visible Universe, with an outstanding level of accuracy. After the discovery of the Higgs boson, announced by the ATLAS and CMS collaborations in 2012, the Model appeared to be complete. However, this is only partially true, since it leaves unanswered a number of fundamental questions: for instance, it does not explain the observed neutrino oscillations and the nature of the dark matter and the dark energy, which account for more than 95% of the known Universe.

Currently, the particle physics community is making a large effort in the search of signs of a new physics “Beyond” the Standard Model (BSM). An intriguing possibility is represented by the study of the ultra-rare kaon decays, since their branching ratios are well determined by the SM: the observation of a statistically significant difference between their predicted and measured values would be a clear sign of BSM physics. A particularly interesting process is the $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay: it has never been observed before, due to its incredibly small branching ratio ($\mathcal{B} \sim 10^{-11}$) and to its signature (two photons with a large missing momentum, and nothing else). Its observation could represent a fundamental step in the quest for new physics and is the main goal of the KLEVER experiment, which has been recently proposed as a part of the HIKE project, the multi-decade evolution plan of NA62. The KLEVER experimental setup is quite complex and it requires the use of high performance particle detectors, in order to achieve its ambitious goals.

A key element of the KLEVER experimental setup is the Small Angle Calorimeter (SAC), which will be located directly in the neutral beamline and has to detect the photons produced at a small angle ($\lesssim 2$ mrad) in the π^0 decays. The SAC must satisfy a number of requirements, in order to comply with the harsh environment of the KLEVER beamline and the HIKE physics programme. In particular, the SAC must achieve a photon detection efficiency as large as possible, while remaining essentially blind to the intense neutral hadron background. The SAC current design foresees an electromagnetic calorimeter composed of four layers of Cherenkov (or scintillating) high-Z crystals, with a total length of $\sim 17 X_0$, coupled to small and fast photodetectors.

An intriguing possibility is represented by the use of oriented crystals. In fact, it has already been demonstrated that the pair production cross-section of a photon impinging on the axis of an oriented single crystal may increase of a factor as large as 100, with respect to the Bethe-Heitler prediction. However, this phenomenon is observed only if the Strong Field condition is satisfied, namely if the impinging particle features an energy lar-

ger than ~ 10 GeV and an incidence angle smaller than ~ 1 mrad. A similar effect has also been observed for high energy electrons and positrons incident on a crystalline lattice. Unfortunately, such effects have been studied experimentally with crystals limited in number, composition and length. This means that there is not yet the possibility to properly account for the Strong Field effects in the design of a particle detector based on oriented crystals. For this reason, the STORM collaboration has performed in the last few years an extensive characterization of the Strong Field effects occurring in several materials of interest for the particle physics applications (such as tungsten and PbWO_4).

In August 2021, the STORM and KLEVER collaborations performed a joint beamtest on the H2 beamline at the CERN SPS. The main goal of this beamtest was to study the enhancement of the pair production cross-section which occurs when an oriented scintillating crystal (or Cherenkov radiator) is exposed to a beam of high energy photons. In particular, this effect was evaluated by directly measuring the increase of the intensity of the light emitted inside the crystal due to the interactions of the incident beam. The results of such an experiment have never been reported before in literature: for this reason, the KLEVER 2021 beamtest represents a fundamental step towards the development of a fully oriented Small Angle Calorimeter. Moreover, this study allowed the evaluation of the time resolution of the photodetection systems under development for the SAC readout, which are based on the Silicon PhotoMultiplier (SiPM) technology.

The first chapter of this work presents the HIKE project: after a brief introduction on the limits of the Standard Model, the project and its multi-phase structure will be described. For each phase, both the physics goals and the experimental layout will be discussed, with a particular attention for the KLEVER experiment (i.e., the third phase), which is the focus of this thesis work. The final part of the chapter presents the currently considered SAC design.

Chapter 2 is focused on the physics of oriented crystals. After a general introduction on the motion of a charged particle in an oriented lattice (i.e., the channeling phenomenon), the effect of the crystalline structure on the bremsstrahlung and pair production processes will be described, considering high energy particles moving along a crystallographic axis or plane. The last part of the chapter presents the features of the Strong Field regime and discusses how the latter could be exploited for a particle physics detector.

Chapter 3 discusses the experimental setup of the KLEVER 2021 beamtest, performed on the H2 line at the CERN SPS. The first part of the chapter presents the crystal samples and the photodetectors which are the subject of this work. The second part describes the particle detectors and equipment composing the experimental setup, which were used to produce and tag the secondary photon beam employed in the measurements. The last part of the chapter presents the results of the preliminary measurements which were performed before the physics runs.

Chapter 4 is dedicated to the characterization of the Strong Field effects occurring in the studied crystals. The initial part of the chapter provides an introduction on the proced-

ure used to align the crystals with the impinging beam. The central part of the chapter describes the method used to estimate the variation of the energy deposit in the crystals and the multiplicity of the charged particles exiting from the samples, as a function of the energy and incidence angle of the tagged photons.

The final chapter of this work is dedicated to the measurement of the time resolution of the tested photodetection systems. The first part of the chapter describes the “zero-crossing” method, which was used to measure the time corresponding to the trigger of the detectors under test. The central part of the chapter presents the measurement of the time resolution of the Micro-Channel Plate detector, which was used to provide a stable reference in time for the other measurements. The final part of the chapter compares the time resolution curves of the tested photodetection systems, which were measured as a function of the energy deposited in the crystals.

THE HIKE / KLEVER PROJECT

The Standard Model (SM) of particle physics is the quantum field theory that describes the essential components of the ordinary matter, namely the elementary particles and their interactions. This theory was capable to predict with high precision a variety of physical phenomena and it was completed in 2012 with the observation of the Higgs boson at the Large Hadron Collider (LHC) [1, 2]. While this theory has not been confuted yet, it leaves a number of fundamental questions unanswered. Examples of the latter include a complete quantum description of the gravitational force and an explanation of the matter-antimatter asymmetry. Thus, it is an urgent priority for the particle physics community to define where and how to search for signs of new physics.

Currently, there are two leading approaches in the search of the so-called Beyond the Standard Model (BSM) physics: the first is to perform structural upgrades to the LHC, while simultaneously building one or more next-generation particle accelerators, to reach unprecedented levels of energy and luminosity [3]. The second approach is to search for evidences of new physics with the tools that are currently available, both with and without particle accelerators [4]. A particularly intriguing possibility is given by the study of rare kaon decays, since they offer a clear access to physical observables which both constrain the validity of the SM and are highly sensitive to a variety of its theorized extensions. One of such decays is:

$$K_L \rightarrow \pi^0 \nu \bar{\nu} \quad (1.1)$$

The study of this process is the main focus of the KLEVER experiment, which has been proposed as the third phase of the HIKE project [5], the long-term evolution plan of the NA62 experiment. Due to the technical challenges it offers and the ambitiousness of its goal, this phase may be the most critical and the most rewarding of the entire program and thus it will require detectors with unprecedented performances. This chapter aims at describing the physics motivations of the HIKE program, focusing on its foreseen timeline, the experimental challenges that will be faced and the reasons to develop an innovative generation of electromagnetic calorimeters, based on oriented crystals.

Fermions ($\frac{1}{2}$ spin)	Quarks			Leptons		
	u Up	c Charm	t Top	e Electron	μ Muon	τ Tau
	d Down	s Strange	b Bottom	ν_e Neutrino	ν_μ Neutrino	ν_τ Neutrino
Hadrons	Baryons Fermionic Hadrons (Three Quarks)		Mesons Bosonic Hadrons (Quark & Anti-Quark)			
Force		Electromagnetic	Strong	Weak		Gravity
Vector Boson (integer spin)		γ Photon	g Gluon	$W^\pm$ Boson	Z^0 Boson	Graviton (hypothetical)
Scalar Boson	Higgs					

Figure 1.1: Table of the Standard Model fundamental forces and particles [8]. The gravity and graviton are reported here for completeness, while not being technically part of the Model.

1.1 PHYSICS BEYOND THE STANDARD MODEL

1.1.1 A THEORY OF EVERYTHING

The Standard Model is the theory that describes the nature and properties of the elementary particles and their mutual interactions (figure 1.1). This theory is remarkably simple and at the same time general: it is based on a relatively limited number of assumptions and parameters and it is capable of describing most of the known Universe. The assumptions behind the Model concern the Lagrangian density function [6], which must respect: (i) the global Poincaré symmetry, in order to be compatible with special relativity, and (ii), a local $SU(3) \otimes SU(2) \otimes U(1)$ gauge symmetry, to give rise to the three fundamental forces (i.e., electromagnetism and the strong and weak nuclear forces). The parameters of the Standard Model are the constants whose values are not defined inside the theory itself, but rather must be measured experimentally. These parameters include, among the others, the quark and lepton masses and the four parameters appearing in the Cabibbo-Kobayashi-Maskawa (CKM) matrix. Using these assumptions and constants, it has been possible to both predict and describe a variety of physical phenomena and physical observables, sometimes with a spectacular agreement between theory and measurements. For instance, this is the case of the electron gyromagnetic ratio ($g - 2$): the relative discrepancy between its predicted and measured value is $\mathcal{O}(10^{-10})$ [7].

After the discovery of the Higgs boson, announced by the ATLAS and CMS collaborations in 2012 [1, 2], the Standard Model appeared to be complete. While no contradiction between the Model and an experiment has been found so far, a variety of phenomena still remain unexplained [4, 9]:

- **Gravity.** This force, while being completely described on a macroscopical scale by the General Relativity, does not seem to be compatible with a renormalizable quantum field theory.
- **The neutrino oscillations.** The observation of this phenomenon implies two facts: (i) neutrinos have mass and (ii) there exist two different bases for their representation, connected by a non-diagonal matrix. The Standard Model includes neither of these properties, but their existence is not strictly forbidden; however, accepting them opens up more questions, such as which among the three neutrinos is the lightest and which is the heaviest (hierarchy problem).
- **The matter-antimatter asymmetry in the observable Universe,** which is not compatible with the Standard Model laws, if we assume a symmetrical primordial Universe.
- **The existence of dark matter,** which is composed of particles interacting only through the gravitational force. Its existence is suggested by a variety of experimental measurements and theoretical considerations, ranging from a precise analysis of the cosmic microwave background to the observation of the stability and rotation curves of the galaxies.
- **Cosmological inflation,** meaning that the Universe is currently in an accelerated expansion phase, which can be explained only assuming that there is a form of unknown energy permeating it (i.e., the dark energy).

Beyond these fundamental questions, there is a number of other minor issues with the assumptions of the Model, which are not problems by themselves, but rather they suggest that the SM may be an approximation of a wider theory [9]. Finally, there are few disagreements between the Model and some experimental data which have not yet reached a significance large enough (i.e., 5σ). Some of these have been solved through in-depth measurements, such as the difference between the τ and μ couplings of the W boson [10]. Others, such as the magnetic dipole moment of the muon [11], are still unsolved. However, there is currently no sign of where a hypothetical new BSM physics may be found. Thus, the current challenge is double-fold: first, to develop extensions of the SM capable of solving all of its problems, while retaining all of its strengths; secondly, to define a set of measurable quantities that may be used to prove or disprove the latter.

1.1.2 EXTENSIONS OF THE STANDARD MODEL

In the last few decades, there has been an extensive drive in the field of theoretical physics, in particular in the development of theories broader than the Standard Model [4]. They can be divided as follows:

1. **Theories based on new physics at the TeV scale or beyond.** Examples of these theories are the Grand Unified Theories (GUTs), which describe the three fundamental symmetries of the Standard Model as part of a larger symmetry, such as $SU(5)$ or

SO(10) [6]. This hypothesis would imply the existence of new particles and processes never observed before, such as the proton decay. Other theories have been formulated, based on the existence of a supersymmetry, a new symmetry operator which would transform bosons into fermions and vice versa. To allow this, a family of new particles would be required, one for each SM particle (e.g., the “selectron” for the electron, the “smuon” for the muon and so on). No compelling evidence for GUTs or supersymmetry have been observed at the LHC yet.

2. **Theories based on neutrinos.** This group includes all the theories that postulate the existence of either more than three neutrinos, or properties not strictly required by the SM (i.e., their right-handedness, or whether they are Dirac or Majorana particles). An interesting and viable theory in this field is the Neutrino Minimal Standard Model, which is able to account for dark matter, matter-antimatter asymmetry, neutrino oscillations and their masses, by adding a triplet of sterile, right-handed neutrinos [4, 12]. This theory may be confirmed if at least one sterile neutrino is found with a mass in the keV range.
3. **Theories based on weakly interacting dark matter.** This group includes all the theories that describe dark matter as composed of thermal relics of the early Universe and acting as Feebly Interacting Particles (FIPs). Essentially, these models assume that the dark matter particles should be very heavy ($\mathcal{O}(100 \text{ GeV})$) and should have only very feeble interactions with the other SM particles. Several theories also allow these particles to interact with SM-particles through new boson mediators, whose mass should lie in the sub-GeV range.
4. **Theories based on axion dark matter.** These models describe dark matter as composed of incredibly light particles, possibly well below the eV scale: this would both solve the dark matter problem and explain the absence of CP violation in the strong interaction. Extensions to these models theorize also the existence of Axion-Like Particles (ALPs), similar to the axions but with masses anywhere from the sub-eV scale up to the GeV scale.

In conclusion, each of these models postulate the existence of new particles, while having to explain why none of them have been observed yet. The reasons attributed to such absences are essentially two: either the particles have masses outside the currently reachable energy scales (i.e., $\lesssim 1 \text{ eV}$ or $\sim 1 \text{ TeV}$), or they have exceptionally weak coupling strengths. This means that their discovery relies entirely on either reaching new energy scales, or performing high-precision and high-statistics measurements on well-known processes.

1.1.3 EXPERIMENTAL STRATEGIES

The leading approach to search for physics beyond the SM is based first on an upgrade of the LHC to the High-Luminosity LHC [13]. This phase would be followed by the construction of a larger collider, capable of reaching unprecedented levels of both luminosity and

energy [3, 9, 14, 15]. This would allow an extensive study of the properties of the Higgs boson and the direct search of physics beyond the TeV scale: several colliders have been designed for this task, but only few of them will actually be realized, due to their prohibitive construction costs. These facts have been explicitly acknowledged by the Conseil Européen pour la Recherche Nucléaire (CERN) in several occasions, such as the “Update of the European Strategy for Particle Physics” (ESPP) published in 2020. Specifically, this document states (article 3.A) [16]:

Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a center-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study [...] should be established as a global endeavor and be completed on the timescale of the next Strategy update.

Among the proposed future colliders, the only ones with a large enough support to be regarded as realistically feasible are:

- The linear colliders, such as the International Linear Collider (ILC) and the Compact Linear Collider (CLIC), respectively in Japan and at CERN [17, 18].
- The circular colliders, such as the Future Circular Collider (FCC) and the Circular Electron-Positron Collider (CEPC), respectively at CERN and in China. Both of them feature an initial $e^+ - e^-$ stage, followed by a later hadron-hadron stage [19–23].

Figure 1.2 shows the estimated timelines of construction of each collider.

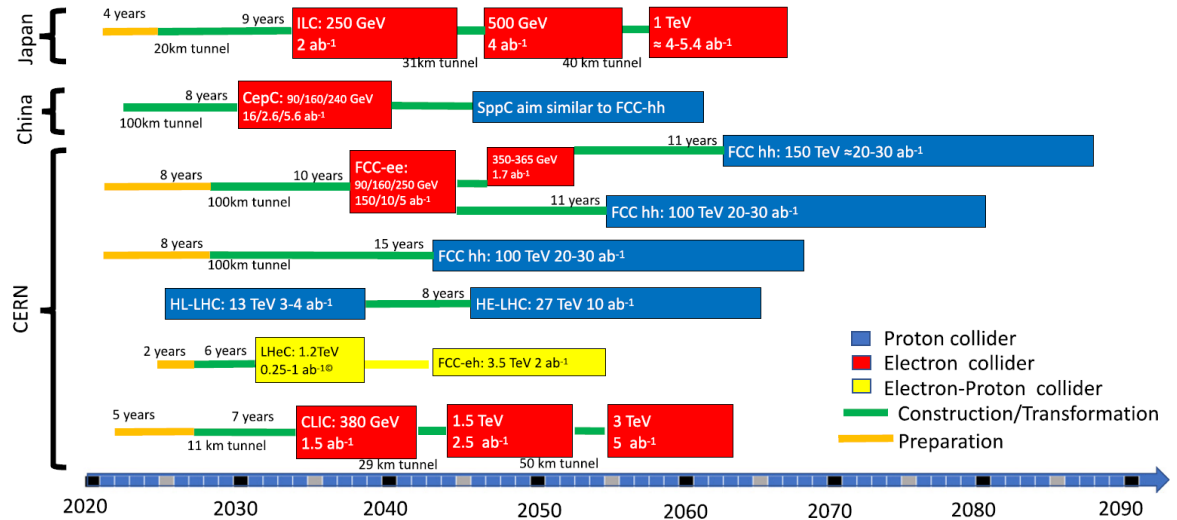


Figure 1.2: Hypothetical timelines for the preparation (orange), construction (green) and beginning of data taking (red, blue and yellow) of the future colliders across the world [15].

The construction of a new collider is the leading approach in the search for BSM physics, but it is not the only possible one, since it focuses exclusively on the physics at the TeV scale and beyond. In fact, a 100 TeV machine would only allow the production of particles in the 10 – 20 TeV range, since the quark pairs produced in a proton-proton collision carry only a fraction of the momentum of the colliding particles. Therefore, it is of great importance to consider also complementary measurements at lower energies, with and without particle accelerators, which may help to guide the research at the energy frontier. This fact is reaffirmed in the 2020 Update of the ESPP [16], which explicitly supports the United States of America towards the construction of the Deep Underground Neutrino Experiment (DUNE) project. Moreover, the same document states (article 4.A):

*The quest for dark matter and the exploration of flavor and fundamental symmetries are crucial components of the search for new physics. This search can be done in many ways, for example through precision measurements of flavor physics and electric or magnetic dipole moments, and searches for axions, dark sector candidates and feebly interacting particles. There are many options to address such physics topics including energy-frontier colliders, accelerator and non-accelerator experiments. [...] **Experiments in such diverse areas that offer potential high-impact particle physics programmes at laboratories in Europe should be supported, as well as participation in such experiments in other regions of the world.***¹

Already in 2016, the Physics Beyond Colliders group (PBC) was formed, with the explicit mandate to “explore the scientific potential of the CERN accelerator complex and infrastructure for projects complementary to high-energy frontier colliders, and to provide input to the EPPS Update” [24]. The work of the committee has resulted in the publication of an extensive document [4], which evaluates the potential of a variety of experiments to be installed at CERN and the Deutsches Elektronen-Synchrotron (DESY), aiming at exploring either the sub-eV, the MeV–GeV or the TeV mass range. Depending on the energy scale, different physics goals could be pursued, such as the search of axions, ALPs, light dark matter and other FIPs, as well as indirect searches for new physics at high mass scales, via flavor physics experiments. Two of these proposals belong specifically to the field of kaon physics and would take place at the K12 line of the CERN Super Proton Synchrotron (SPS), where the NA62 experiment is currently taking data, aiming at measuring with a 10% precision the Branching Ratio (BR) of the following extremely rare decay [25, 26]:

$$K^+ \rightarrow \pi^+ \nu \bar{\nu} \quad (1.2)$$

where $\nu \bar{\nu}$ is a neutrino-antineutrino pair of any flavour. One of the proposals, named NA62⁺⁺ or NA62 in dump mode, represents an evolution of NA62 and is based on the possibility of operating the beam and collimators used by NA62 in a way that would allow the observation of hidden sectors particles. The other initiative proposes a structural revision of the beamline, which would allow the study of the K_L neutral kaon decays. This

¹ The bold text used here follows the original source.

phase is called KLEVER [27] and its purpose is to measure with a 20% precision the BR of the following process:

$$K_L \rightarrow \pi^0 \nu \bar{\nu} \quad (1.3)$$

These proposals evolved and merged in 2022 into a wider project: HIKE.

1.2 THE HIKE PROJECT

The High Intensity Kaon Experiments (HIKE) project (figure 1.3) is a long-term experimental programme supported externally by 114 theoretical physicists [28], which has been recently proposed to the CERN SPS Committee [5]. The project intends to continue the long-standing tradition of high-intensity kaon experiments at the CERN North Area, currently carried on by NA62. It aims both at studying well-known kaon decays and at searching for new particles and processes, in order to test the validity of the SM and to look for BSM physics in a relatively clean environment, with respect to other meson systems.



Figure 1.3: Logo of the HIKE project [5].

The HIKE project is characterized by several phases, each requiring upgrades to both the kaon beamline and the employed particle detectors, in order to address a different physics goal:

- **Phase 1: a multi-purpose K^+ decay experiment.** The goal of this phase is to improve the precision on the measurement of $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$, from 10%, which is the aim of NA62, down to 5% [29, 30], thus matching the theoretical uncertainty given by the Standard Model. A fraction of the available beam time will be spent in beam-dump mode, for the search of dark matter.
- **Phase 2: a multi-purpose K_L decay experiment.** In this phase, a broad study of the physics of the K_L neutral kaon will be performed, with particular attention on the decay modes with charged particles in the final state, such as $K_L \rightarrow \pi^0 l^+ l^-$ ($l = e, \mu$). A second dataset in beam-dump mode should also be acquired.

- **Phase 3 (KLEVER): measurement of the $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay.** This phase intends to collect a total of 60 candidate events with a signal-to-background ratio of 1 : 1 within five years of operation, thus completing the study of the K_L physics.

The schedule foreseen for the HIKE project is quite tight: the charged kaon phase should take place during LHC run 4, which is scheduled to start in 2029 (figure 1.4), while Phase 2 will take data during LHC run 5 and KLEVER afterwards. It was chosen to delay KLEVER with respect to Phase 2, since the latter features a tracking system in the experimental layout, while the former does not. Thus, it will be possible to characterize the K_L beam before the beginning of KLEVER.

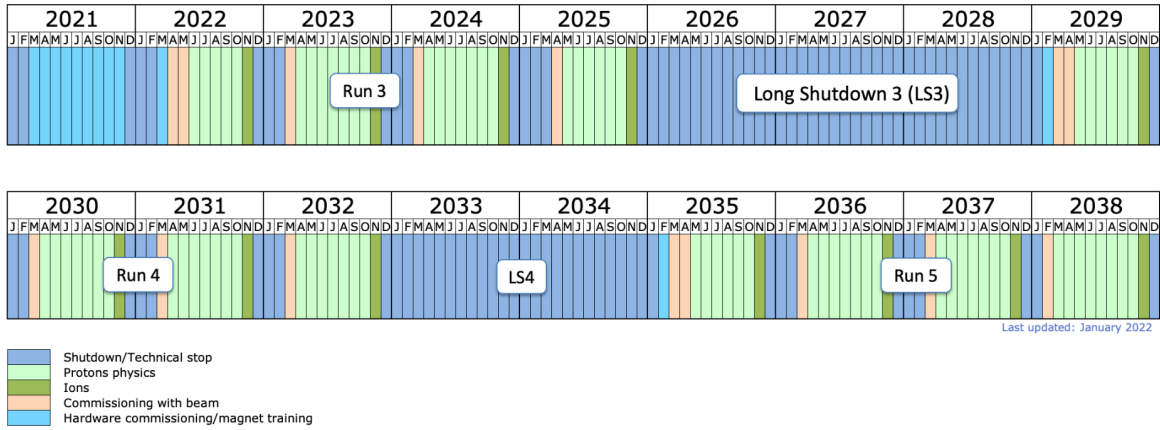


Figure 1.4: Timeline of the future upgrades of the LHC, showing the alternation between data taking and shutdown phases [31]. This timeline may be subject to further variations, due to energetic and economical reasons [32].

At the time of writing, the Letter Of Intent (LOI) of the HIKE project is still being reviewed by the SPS Committee. A positive response will lead to the official approval of the HIKE project and the publication of an official Proposal, provided that all the observations of the Committee have been addressed and that the necessary funding is available.

1.2.1 PHYSICS OPPORTUNITIES IN STANDARD MODE

The HIKE project intends to investigate the presence of BSM physics by using two complementary approaches. The first is called direct detection, meaning that it is based on the observation of processes explicitly forbidden by the SM conservation laws. This includes also the possibility of detecting particles downstream of a totally absorbing beam dump, far beyond the decay length of the primary beam: this phenomenon may be explained only assuming the intermediate production and decay of FIPs. The second approach is the indirect detection, based on the measurement of several physical quantities, which are well determined within the Standard Model. Here, a sign of new physics would be a difference between their expected and measured values. The golden items of indirect detection are the BRs of extremely suppressed decays (i.e., $\mathcal{B} \sim \mathcal{O}(10^{-11})$): the BSM contributions occur there at loop-level at the lowest order and thus compete at the same

order with the SM contributions. While direct detection is constrained to the energy scale of the primary beam, indirect detection can reach much higher scales. For instance, the kaon beam used in the HIKE project allows to directly produce particles with masses up to $\sim \mathcal{O}(100 \text{ GeV})$, while also studying indirect contributions from particles with masses up to $\sim \mathcal{O}(100 \text{ TeV})$.

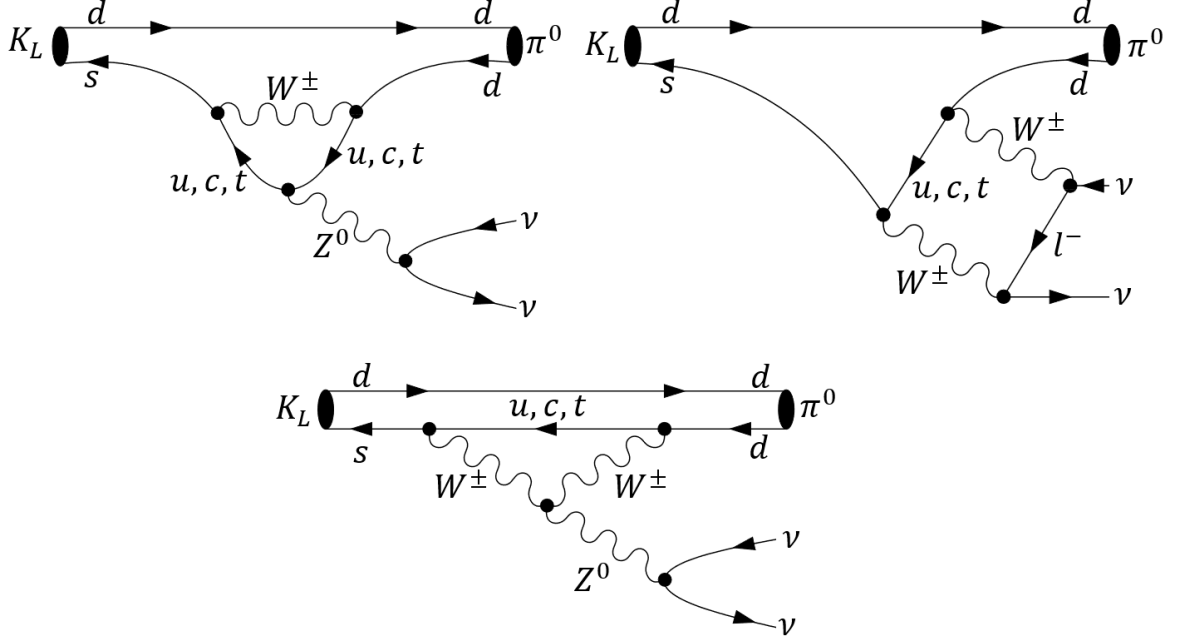


Figure 1.5: Feynman diagrams of the $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay [33], which is the main focus of the KLEVER phase.

Both the approaches are employed in the “standard mode”, namely the ordinary mode of operation of any fixed target experiment, which allows to study the following processes:

- **Decays involving Flavor-Changing Neutral Currents (FCNCs)**, generally regarded as “rare” or “ultra-rare”, since they feature $\mathcal{B} \lesssim \mathcal{O}(10^{-7})$. The measurement of their BRs allows to extract the values of several elements of the CKM matrix (e.g., V_{ts} , V_{td}) and thus to test its unitarity, while searching for new physics. The golden item of this class is the $K \rightarrow \pi \nu \bar{\nu}$ decay, with K being either K^+ or K_L (figure 1.5); other less rare processes such as $K_L \rightarrow \mu^+ \mu^-$ are nevertheless interesting.
- **Benchmarks for lepton flavour universality tests.** These processes allow to test one of the fundamental laws of the SM, which is the independence of the boson-lepton coupling on the lepton flavour. This group includes any decay featuring a lepton pair in the final state, such as:

$$K^+ \rightarrow \pi^+ l^+ l^- \quad (1.4)$$

In this case, no difference is expected between the BRs or the form factors of the decays with $\pi^+ e^+ e^-$ and $\pi^+ \mu^+ \mu^-$ final states.

- **Decays violating the conservation of lepton flavour or number.** These processes are theoretically forbidden by the Standard Model, since the latter prescribes for each

leptonic flavour the conservation of the difference between the number of leptons and anti-leptons. An explicit sign of BSM physics would be the observation of a decay such as:

$$K^+ \rightarrow \pi^+ \mu^\pm e^\mp \quad (1.5)$$

- **Decays useful for the extraction of QCD parameters**, meaning that their BRs depend explicitly on the parameters of the low-energy effective approximation of QCD, namely the chiral perturbation theory. The study of these processes could thus advance our understanding of the strong interaction. This group includes also any decay involving the radiative production of photons [34], such as:

$$K \rightarrow \pi\pi\gamma \quad (1.6)$$

- **Decays useful for the measurement of the V_{us}, V_{ud} CKM matrix elements**, which appear in the first CKM unitarity relation [35]:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985 \pm 0.0005 \quad (1.7)$$

In fact, this sum stands at 3σ from its expected value (i.e., 1). Currently, the kaon decays such as $K \rightarrow \pi l \nu$ are among the most accurate methods for the evaluation of V_{us} and V_{ud} and thus a high precision measurement of their BRs is a priority.

- **Decays involving the resonant production of FIPs**. Here, the presence of BSM physics would be revealed by the appearance of an unexpected Breit-Wigner peak in the spectrum of a well-known decay such as:

$$K \rightarrow \pi\gamma\gamma \quad (1.8)$$

More details regarding these processes are given in [5]. However, it is important to stress a few properties of the two rarest FCNC processes:

$$K^+ \rightarrow \pi^+ \nu \bar{\nu} \quad (1.9)$$

$$K_L \rightarrow \pi^0 \nu \bar{\nu} \quad (1.10)$$

These decays proceed through penguin or box diagrams, which feature the exchange of a virtual Z boson or a pair of W bosons; they are deeply suppressed due to the Glashow-Iliopoulos-Maiani mechanism and the $t \rightarrow d$ transition. The Standard Model allows to estimate very precisely their BRs [36]:

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (8.39 \pm 0.30) \cdot 10^{-11} \left(\frac{|V_{cb}|}{0.0407} \right)^{2.8} \left(\frac{\gamma}{73.2^\circ} \right)^{0.74} \quad (1.11)$$

$$\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) = (3.36 \pm 0.05) \cdot 10^{-11} \left(\frac{|V_{ub}|}{3.88 \cdot 10^{-3}} \right)^2 \left(\frac{|V_{cb}|}{0.0407} \right)^2 \left(\frac{\sin \gamma}{\sin 73.2^\circ} \right)^2 \quad (1.12)$$

where V_{cb}, V_{ub} are the CKM matrix elements and $\gamma = \arg[(-V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*)]$. Moreover, it is possible to precisely compute how these BRs should be modified, due to a variety of BSM theories [37, 38]. It is interesting to note that new-physics scenarios do not necessarily affect the two BRs in correlated ways (figure 1.6). Thus, the measurement of both these quantities is fundamental in the quest for new physics.

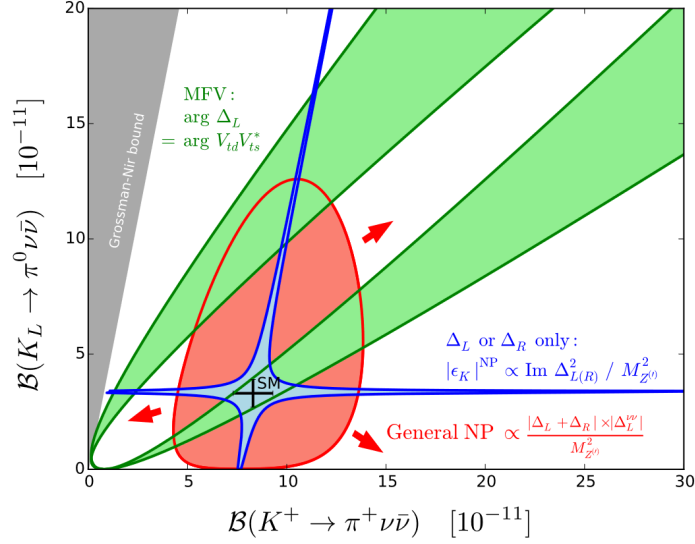


Figure 1.6: Illustration of the possible correlations between $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ and $\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})$, foreseen by the Standard Model laws (black) and by several BSM theories [39].

The current best estimation of $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ comes from the NA62 experiment, which reports, at a 68% confidence level [29, 40]:

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (10.6_{-3.4}^{+4.0})_{\text{stat}} \pm 0.9_{\text{syst}} \cdot 10^{-11} \quad (1.13)$$

where the estimation is based on a total of 20 candidate events, including background. The K_L decay has never been observed and the upper limits on its BR has been set by the KOTO experiment at the Japan Proton Accelerator Research Complex (J-PARC) [41]:

$$\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu}) \leq 3 \cdot 10^{-9} \quad (1.14)$$

with a 90% confidence level. KOTO plans to reach the required sensitivity of $\mathcal{O}(10^{-11})$ within the next 5 years and then to perform structural upgrades in the 2030s, in the framework of the broader expansion programme of the J-PARC [42]. However, even then it may not reach the precision necessary to distinguish the different BSM contributions in the BR of the K_L decay. This is due to its experimental layout, which features a highly-collimated beam of low-energy kaons [27]. On the other hand, KLEVER could be capable of reaching the required precision, by employing:

- A kaon beam with a much higher energy (i.e., with an average momentum of 40 GeV/c), which would highly facilitate the rejection of many background channels, such as $K_L \rightarrow \pi^0 \pi^0$.

- A high-performance particle detection system, featuring redundant particle identification and highly efficient photon vetoes. These are key elements for the correct identification of the signal events, since the signature of $K_L \rightarrow \pi^0 \nu \bar{\nu}$ is simply a pair of photons in the main electromagnetic calorimeter and nothing else.

These elements are fundamental not only for the success of the KLEVER phase, but also for the entire HIKE programme.

1.2.2 PHYSICS OPPORTUNITIES IN BEAM DUMP MODE

The NA62 experiment currently employs a secondary K^+ beam with a 75 GeV/c momentum, produced in the P42 beamline by the 400 GeV/c SPS proton beam, impinging on a 400 mm thick beryllium cylindrical target (T10). In the collision, a mixed hadron beam is produced: the selection of the K^+ with the desired momentum occurs in the K12 beamline [26, 43]. The T10 target is immediately followed by a first collimation stage and a triplet of quadrupole magnets, which select only the positively charged particles, with a central momentum of 75 GeV/c (figure 1.7). At a distance of 20 m from the target, four achromatic dipole magnets (A1) deflect the beam around the vertical axis. In the standard mode of operation, the first two magnets cause a vertical displacement of $\Delta y = -110$ mm to the particles with a momentum of 75 GeV/c $\pm 1\%$ ($\Delta p/p$). Between the two pairs of magnets, there are two motorized and water-cooled beam-dump units: the Target Attenuator eXperimental areas (TAX) collimators, each 1.615 m long. Due to their length, which corresponds to ≈ 10.7 nuclear interaction lengths² (λ_{int}), they absorb all the particles falling outside a variable-thickness opening bore, centered around $y = -110$ mm. In the center of the bores, a 4.5 mm tungsten layer, corresponding to ≈ 1.3 radiation lengths³ (X_0), causes positrons to lose enough energy to be distinguished from the K^+ . Then, the second pair of magnets (A1) reverses the vertical displacement of the kaon beam. Finally, a combination of passive absorbers and dipole magnets further focuses and collimates the kaon beam up to the injection in the instrumented decay volume.

The possibility to investigate the existence of FIPs and light dark matter using the beam dump mode of operation is already being exploited, since a few years, by NA62 [44, 45]. When operating in beam dump mode, a number of minor modifications occur in the K12 line: the T10 target is lifted, the A1 magnetic field is lowered and the TAX collimators are moved, in order to completely block the respective opening bores. In this way, the primary beam is completely absorbed by the copper and only hypothetical FIPs, produced in the proton interactions, reach the decay volume. Since FIPs are long-lived light particles and are expected to decay into final states involving muons, the identification of a displaced decay vertex and a muon track would be a sign of new physics [44, 45]. A critical background is represented by the production of muons from the primary beam absorption in

² The nuclear interaction length (λ_{int}) is defined as the average distance traveled by a hadronic particle before undergoing an inelastic nuclear interaction [35].

³ The radiation length (X_0) is the average distance necessary to reduce the energy of an electron (positron) by a factor $1/e$, due to radiation emission [35].

the collimators. However, it can be minimized by a convenient choice of the field strengths of the K12 magnets [46] and a careful analysis of the detectors signals. To this day, NA62 has not yet reported the observation of new physics in the analysis of the data acquired in beam dump mode. However, the search for dark matter particles and mediators is planned to continue also in the first two HIKE phases, mainly due to its null cost. In fact, a switch to the beam dump mode may be performed at any time and without opening any of the vacuum vessels. The possibility to employ this mode of operation in HIKE is granted by the fact that the latter shares with NA62 the forward geometry and several particle detectors.

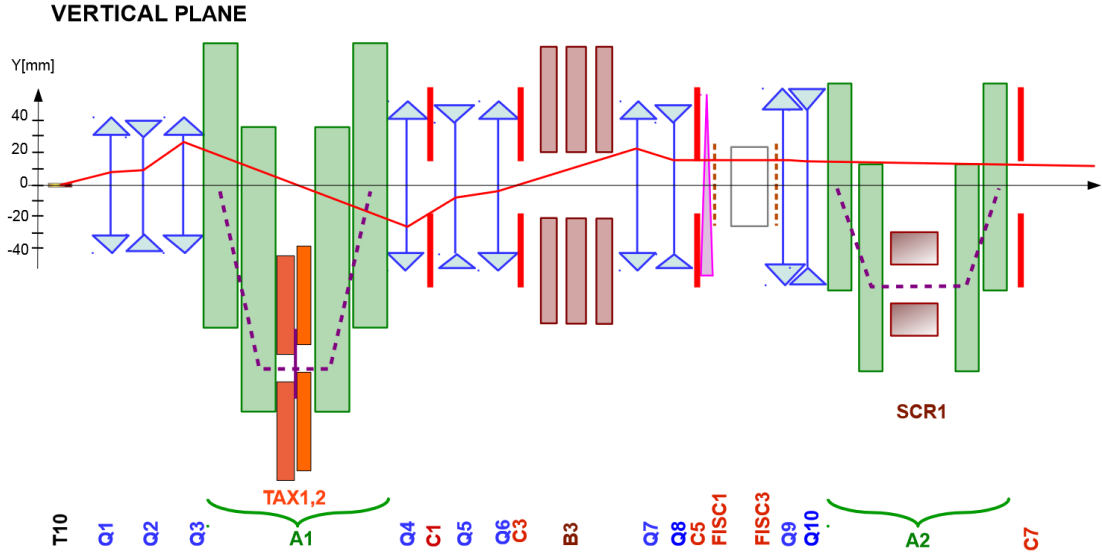


Figure 1.7: Schematic layout and optics of the K12 high-intensity K^+ beamline, from the T10 target up to the entrance of the NA62 decay volume, along the vertical axis [43]. The dashed lines here indicate the trajectories of an initially on-axis beam of 75 GeV/c K^+ .

1.2.3 KAON BEAMLINE LAYOUT

One of the key elements of the HIKE physics programme is the increase of the kaon beam intensity by a factor 4 – 6 [5]. Both the proton extraction beamline (P42) and the kaon production beamline (K12), as well as the targets located there (T4, T10) would be involved in this operation. Figure 1.8 shows schematically their current structure, inside the SPS.

Currently, the P42 beamline provides the primary proton beam to the kaon production target (T10) in spills of 4.8 s, with a peak intensity of $2 \cdot 10^{13}$ protons per pulse, which is kept for a “flat-on-top time” of ~ 3 s. Several upgrades are required, in order to reach both a higher peak intensity and a longer flat-on-top interval (~ 4 s):

- A reduction of the proton beam attenuation due to the presence of the T4 target, which provides the secondary beams to the H6 and H8 extracted beamlines. A first option would be to increase the beam width along the vertical axis, so that most of

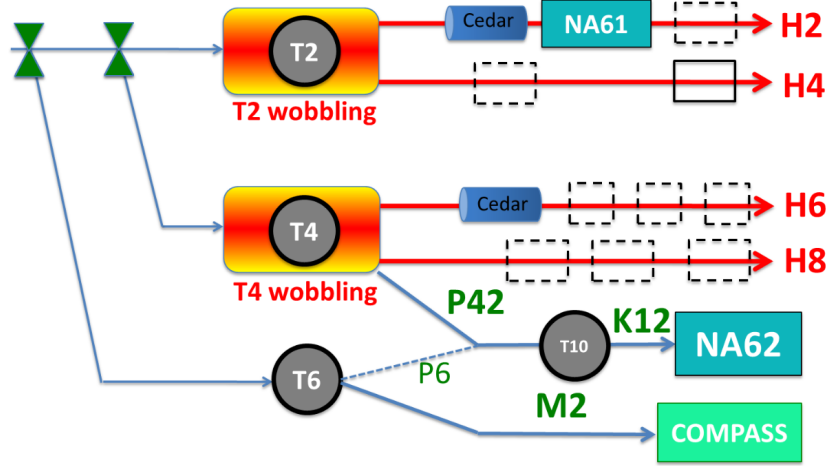


Figure 1.8: Scheme of the beamlines structure in the CERN North Area. The beamlines of interest for the HIKE project, which is planned to be housed in the same hall as NA62, are P42 (proton extraction) and K12 (kaon production) [47].

it bypasses the target without interacting. Alternatively, it could be possible to run dedicated spills cycles, in which the beam is deflected around T4.

- A general upgrade of the T10 target and TAX beam dumps, in order to comply with the more stringent radiation protection and overheating constraints.
- A general upgrade of the beam monitoring instrumentation, which has not been updated since the 1980s and is showing strong ageing effects, including beam losses [48]. This intervention is already scheduled, as a part of a broader consolidation program for the CERN North Area [49].

While these upgrades are necessary already for Phase 1, there is a particular intervention scheduled only for Phases 2–3: the increase of the incidence angle of the protons on the T10 target (figure 1.9), which defines the kaon production angle (θ_K). For both NA62 and Phase 1, a zero production angle is employed, while Phase 2 requires $\theta_K = 2.4$ mrad and KLEVER $\theta_K \geq 8$ mrad. These increments are obtained by simply tuning the magnetic fields of the last three steering dipoles of the P42 beamline. The values here reported are the compromise between two opposite arguments: on the one hand, a smaller θ value increases the K_L flux and hardens its spectrum, thus facilitating the rejection of background channels with extra π^0 or photons. On the other hand, at larger angles there is a significant reduction of the Λ^0 flux, whose decay constitutes the main background to $K_L \rightarrow \pi^0 \nu \bar{\nu}$:

$$\Lambda^0 \rightarrow \pi^0 n \quad (1.15)$$

Through a full FLUKA simulation of the beamline, it was found that at 8 mrad nearly all the Λ^0 decay before reaching the instrumented volume [5]. For Phase 2 this background is much less of a concern, while the acceptance of $K_L \rightarrow \pi^0 l^+ l^-$ is greatly increased for higher beam energies, thus $\theta_K = 2.4$ mrad was considered acceptable. Other possible ways to reduce the Λ^0 flux are a reduction of the primary beam momentum (from 400 GeV/c

to 300 GeV/c) and the increase of the distance between T10 and the final collimators. This option would allow the Λ^0 to decay before the instrumented volume, but it would require to move upstream the T10 target, with complex radiation protection implications. An alternative could be to move all the detectors downstream, but this would require the excavation of a new tunnel. All these options and their costs are still being discussed with the CERN Civil Engineering group.

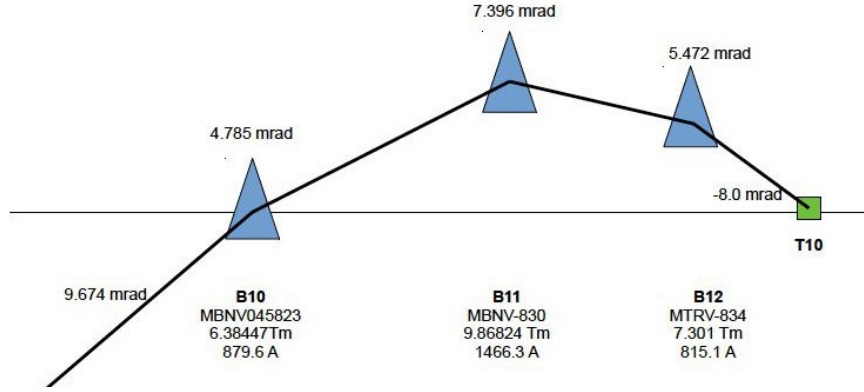


Figure 1.9: Modifications of the T10 steering dipole magnets to increase the kaon production angle in the KLEVER phase [5].

The interventions concerning T10 and the K12 beamline are different for each HIKE phase: since Phase 1 features a charged kaon beam similar to the one currently available, no upgrades are required. Instead, the beamline for Phases 2 – 3 is significantly different (figure 1.10): the 400 GeV/c proton beam impinges on the T10 target at a non-zero angle. The hadrons falling out of an acceptance window are absorbed by a passive collimator and the remaining part of the primary beam is swept out by a strong dipole magnet. A second collimation stage is given by the TAX beam dump, which is conceptually identical to the one employed by NA62, but with the $1.3 X_0$ tungsten layer being replaced by a thick high-Z absorber, in order to reduce by a factor $\mathcal{O}(100)$ the flux of high-energy photons produced upstream. Finally, a set of three collimators (i.e., the defining, the cleaning and the final collimator) determine the maximum opening angle of the outgoing beam (± 0.4 mrad). Any charged particle produced before the final collimator is swept out by three bending magnets.

The FLUKA simulation of the beamline allowed to quantify the particle content of the new K12 neutral beam [5]. The main figures of merit obtained with this simulation are reported in table 1.1, assuming an incidence angle of the protons on T10 of 8 mrad: the KLEVER phase was chosen as a reference since it features the most stringent requirements, in terms of veto efficiency. The FLUKA simulation data show that the neutral beam exiting the T10 target is strongly contaminated by neutrons and photons with variable energies. Neutrons represent a critical background, since they cannot be attenuated without equally affecting the neutral kaons and they leave undesired signals in the particle detectors. The spurious photons in the main beamline represent a problem for a different reason: given the fact that they do not scatter, they are absorbed entirely by the Small Angle Calorimeter

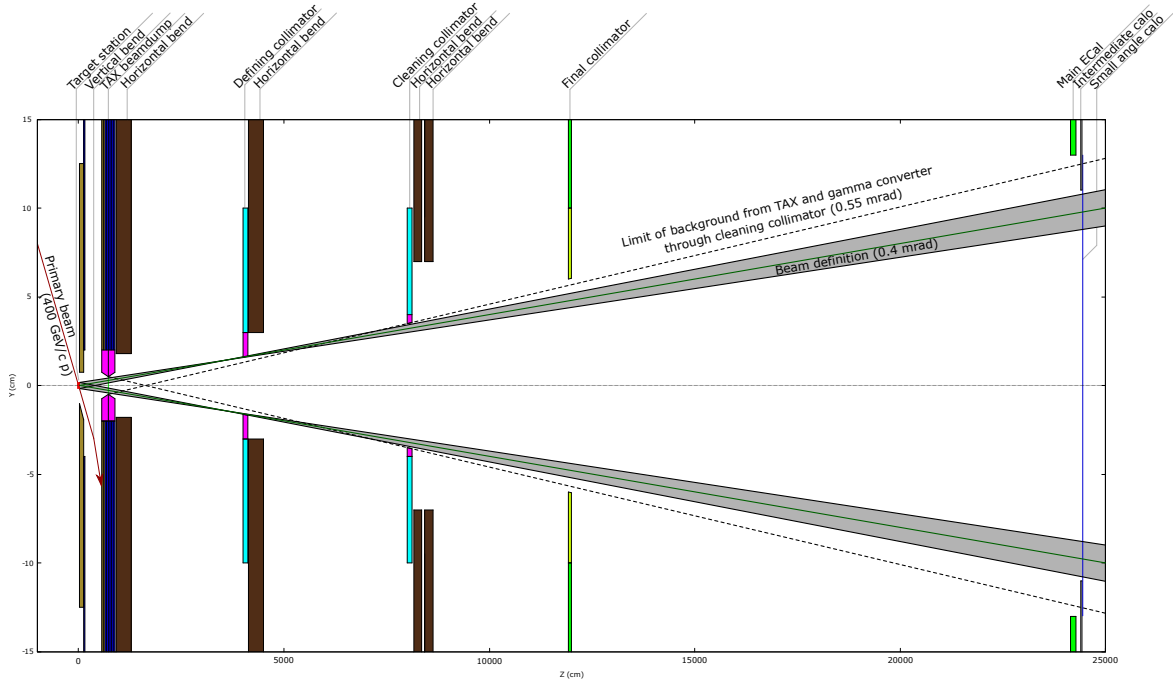


Figure 1.10: Baseline design of the K12 beamline, upgraded for HIKE Phase 2 and KLEVER, including the kaon production and collimation stage and the instrumented volume [5]. The primary proton beam, impinging on the T10 target at a non-zero angle, is shown in red.

(SAC), which is located at the end of the beamline and must measure with high efficiency the photons produced by the decay of highly-boosted neutral pions. In order not to blind the SAC with the spurious photons, a photon converter has been added between the two layers of the TAX beam dump. The baseline solution for this absorber is a $9.4 X_0$ tungsten prism (which is ≈ 7.3 photon conversion lengths), which reduces the flux of high-energy photons (> 5 GeV) from more than 10 GHz before the converter, down to 50 MHz at the SAC. Other solutions with lighter materials are currently being evaluated, but high-Z elements are still preferred, since their smaller length causes a weaker attenuation of the hadron beam. An interesting possibility is to employ an oriented tungsten crystal, since it has been demonstrated that it features a reduction of the X_0/λ_{int} ratio, with respect to the non-oriented counterpart [50]. A more detailed description of the physics of the oriented crystals is given in chapter 2.

1.2.4 PARTICLE DETECTORS

Due to its physics goals, each of the HIKE phases requires a complex experimental layout, featuring particle detectors capable of providing highly efficient, precise and redundant measurements of energy, time, position and momentum [5, 27, 51]. For Phase 1, the baseline experimental setup is inspired from NA62 and includes both newly built and already existing detectors. The beamline is divided in three sectors (figure 1.11):

Particle	Energy	Before conv. [GHz]	After conv. [GHz]	After FC [MHz]
γ	$> 1 \text{ GeV}$	27.9	6.10	198
	$> 5 \text{ GeV}$	14.6	0.47	53
	$> 10 \text{ GeV}$	10.3	0.12	21
	$> 30 \text{ GeV}$	4.2	0.01	4
n	$> 1 \text{ GeV}$	2.9	2.82	440
K_L	$> 1 \text{ GeV}$	0.9	0.87	140

Table 1.1: Particle fluxes inside the KLEVER beamline, determined by a full FLUKA simulation [5]. The rates reported in the last three columns correspond to before and after the converter (conv.) and after the final collimator (FC). A primary beam intensity of $6.7 \cdot 10^{12}$ pot/s (protons on target / second) was assumed in the calculation of these values.

1. **The upstream region**, which extends from the T10 target up to the beginning of the vacuum tank. The K^+ beam is produced with an average momentum of 75 GeV/c. A ring-focusing Cherenkov detector named Kaon TAGger (KTAG) discriminates the kaons from other positively charged particles. Afterwards, a multi-plane silicon pixel detector named Giga TracKer (GTK) measures the trajectory, momentum and time of arrival of each particle. Finally, two plastic scintillator detectors, namely the Veto Counter and the ANTI-0 hodoscope, reject the background events.
2. **The decay volume**, which is the vacuum tank where the K^+ decay in-flight. A plastic scintillator detector (CHANTI, Charged Anti-Coincidence Detector) vetoes the events originated by particles scattered from the upstream sector or the beam halo. Along the decay volume, several sampling calorimeters consisting of lead and scintillator tiles compose the Large Area Veto (LAV), which identifies and rejects the decay products emitted at large angles (i.e., beyond the acceptance of the downstream calorimeters). Finally, a straw tube spectrometer placed inside a dipole magnet measures the momentum and flight direction of the charged particles.
3. **The downstream region**, where the beam is dumped. Here, a Ring-Imaging Cherenkov detector (RICH) and a plastic scintillator timing layer provide additional and complementary measurements of the single-event time. The particle identification is performed by the RICH, along with the following calorimeters, thanks to their different sensitivities:
 - a) The Main Electromagnetic Calorimeter (MEC), which allows the identification of photons, electrons and positrons. The baseline solution for this detector is an upgraded version of the NA62 liquid krypton calorimeter. An alternative solution is under study, based on a shashlik calorimeter with lead absorbers and plastic scintillator layers.
 - b) The Intermediate Ring Electromagnetic Calorimeter, which employs the same technology of the MEC but features a different shape (i.e., a small ring), in order to extend the angular coverage of the latter and fill its blind spots.

- c) The SAC, which is a small high-Z homogeneous electromagnetic calorimeter (section 1.3). This detector covers an angular range of ± 2 mrad with respect to the beam axis.
- d) The Hadronic Calorimeter, composed of iron absorbers interleaved with plastic scintillators, either with a high-granularity or a shashlik layout.
- e) The HAdronic Sampling Calorimeter (HASC), with lead absorbers and plastic scintillator layers, placed around the beam pipe.

Finally, a plastic scintillator MUon Veto detector (MUV) is placed after 80 cm of iron, in order to identify the muon tracks.

Some of these detectors are already in use in the NA62 experiment, but will need upgrades in order to comply with the higher beam intensity. For instance, in order to avoid pile-up effects, the plastic scintillators should be finely-grained and readout by small and fast photodetectors, such as Silicon PhotoMultipliers (SiPMs) or Micro-Channel Plate PhotoMultiplier Tubes (MCP-PMTs). The performance of all the detectors in the beamline determine the random veto efficiency (ε_v), namely the fraction of events passing the signal selection criteria, which are due to random activity in the detectors. ε_v must be better than 65%, in order to reach the sensitivity required for Phase 1.

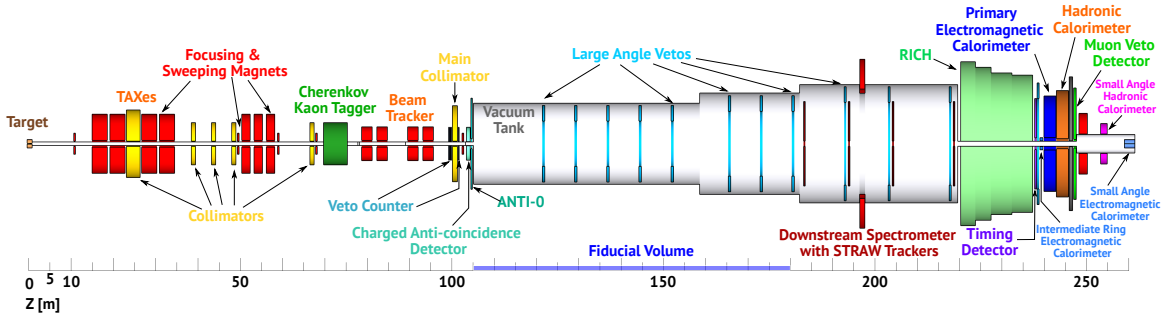


Figure 1.11: HIKE Phase 1 beamline and experimental layout [5].

For the HIKE Phase 2, the majority of the upgrades will be focused on the kaon production beamline, as described in section 1.2.3. The new K12 design requires the removal of KTAG, GTK and CHANTI, in order to leave space to the increased number of collimation stages (figure 1.12), which allows the decay of nearly all the K_S and Λ^0 produced by the primary beam. Moreover, the straw tube spectrometer is moved downstream, outside of the decay volume, thus leaving space for more LAV units. Finally, the RICH and SAC detectors are removed.

The experimental design of the KLEVER phase is more complex with respect to Phase 2, due to the required extremely high level of efficiency. The main process of interest for this phase ($K_L \rightarrow \pi^0 \nu \bar{\nu}$) has a very simple signature, with only a pair of photons in the MEC and a large missing transverse momentum, due to the unobserved $\nu \bar{\nu}$ pair. This requires a large number of neutral and charged particle vetoes and also a hermetic coverage for

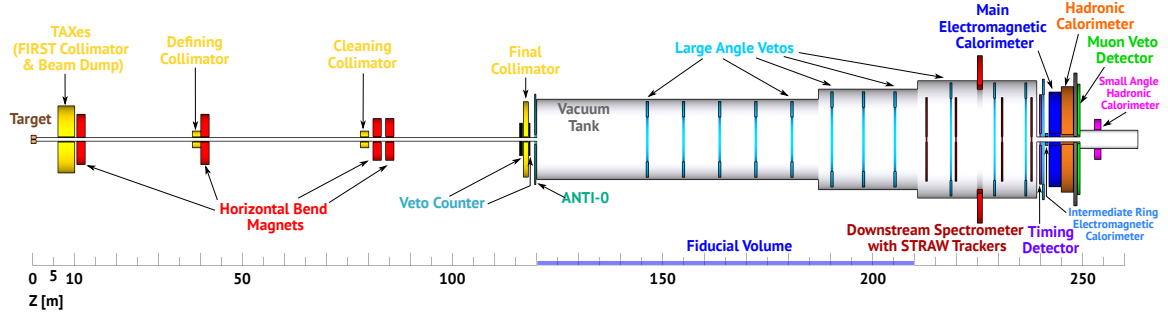


Figure 1.12: HIKE Phase 2 beamline and experimental layout [5].

photons emitted even at large angles (up to 100 mrad). Thus, the beamline is modified as follows (figure 1.13):

- The decay volume is longer and features an Active Final Collimator instead of the passive unit employed in Phase 2. This is a thick LYSO scintillator collar, which performs the beam collimation while vetoing photons produced in the upstream sector. Moreover, a shashlik electromagnetic calorimeter (Upstream Veto) identifies the $K_L \rightarrow \pi^0 \pi^0$ decays by detecting photons emitted at large angles. Finally, the number of LAV stations is increased.
- Several detectors are removed from the downstream region, namely the straw tube tracker, the timing layer, the MUV and the HASC. The particle identification is performed instead by the MEC and a Charged Particle Veto, composed of two high-efficiency planes of plastic scintillators. The MEC now defines also the single-event time. The reconstruction of the π^0 decay vertices is performed by a Pre-Shower Detector, composed of a thin converting layer ($0.5 X_0$) followed by two tracking planes with a spatial resolution of $\sim 100 \mu\text{m}$. Finally, a SAC is placed at the end of the beamline, with an angular opening of $\pm 2 \text{ mrad}$.

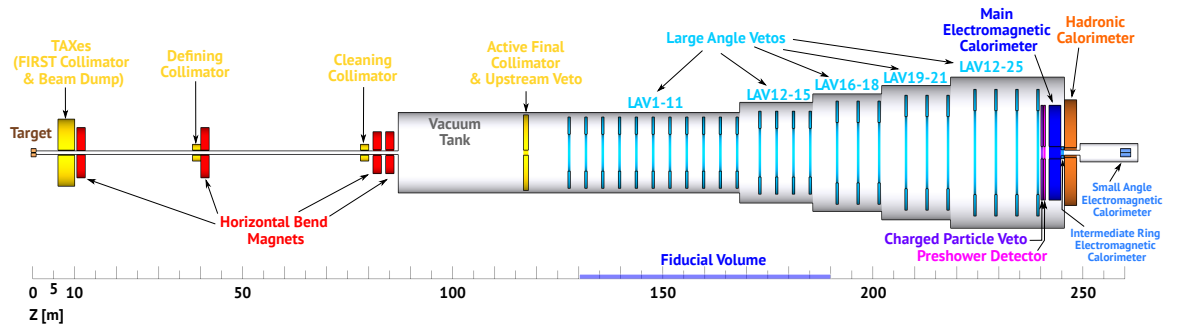


Figure 1.13: Baseline solution for the HIKE Phase 3 (KLEVER) beamline and experimental layout, i.e., without the 150 m extension of the ECN3 cavern [5].

Since the KLEVER phase is the most complex of the HIKE programme, it sets the requirements for all the particle detectors employed there or in the previous phases. In order to keep the random veto efficiency at an acceptable level, the time resolution of the SAC and the MEC should be better than 100 ps. An extensive discussion of the requirements for

each detector is given in [5, 27, 51]. It is now of interest to discuss in detail the design and performance required for the SAC, since it is the main focus of this thesis work.

1.3 THE SMALL ANGLE CALORIMETER

The Small Angle Calorimeter (SAC) is the detector responsible for the observation of photons emitted at small angles (i.e. $\lesssim 2$ mrad). This is a key element of the KLEVER experimental setup, due to the abundance of K_L decay modes which result in the production of more than two photons. In fact, the failed observation of a photon may easily lead to misidentify a background event for a physics signal, thus spoiling the measurement of $\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})$. This detector could be relevant also during Phase 1, although less critical, since the K^+ beam can be magnetically deflected in the acceptance volume of other detectors. Thus, the SAC should be finished before the beginning of LS3: in this way, it could be tested during Phase 1, before its main use in KLEVER. In order to reach the required veto accuracy, the SAC must satisfy a variety of constraints, in terms of [5]:

- **Photon detection inefficiency** ($\bar{\eta}$), which must be (figure 1.14):

- $\bar{\eta} \lesssim 5\%$ for photons with an energy $E_\gamma < 5$ GeV.
- $\bar{\eta} < 1\%$ for $5 \text{ GeV} < E_\gamma < 30 \text{ GeV}$.
- $\bar{\eta} < 10^{-4}$ for $E_\gamma > 30 \text{ GeV}$.

These values have been derived from a full simulation of the KLEVER setup [52], by considering the number of $K_L \rightarrow \pi^0 \nu \bar{\nu}$ events with two photons on the MEC, at least one photon in the SAC and no signals in any of other vetoes. In fact, these are the events which would be interpreted as $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decays, if the SAC failed to fire.

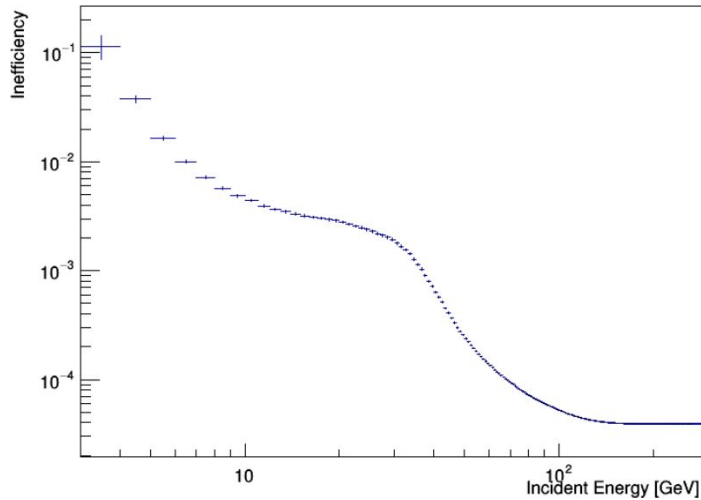


Figure 1.14: Efficiency required for the SAC, in order to veto the $K_L \rightarrow \pi^0 \pi^0$ decay [52].

- **Time resolution**, which must be better than 100 ps. Correspondingly, the pulse-to-pulse resolution, defined as in [53], should be at the level of ~ 1 ns.

- **Radiation hardness**, since the SAC performance should not degrade significantly during the data acquisition. In particular, it has been estimated that five years of operation in the KLEVER beamline will lead to the absorption of an equivalent neutron fluence of $\sim 10^{14}$ n/cm² and a photon dose up to several MGy.
- **Transparency to hadrons**. It has been estimated that the SAC will constantly be exposed to 440 MHz of neutrons, 130 MHz of neutral kaons and smaller rates of other heavy hadrons (section 1.2.3). This is a problem not only for the radiation hardness, but also due to the possible onset of a hadronic shower inside the SAC itself. In order to mitigate this effect, the SAC should feature a total interaction length (λ_{int}) much smaller than its total radiation length (X_0). Moreover the SAC should achieve a n/γ discrimination capability, for instance by employing a fine transverse segmentation and a suitable analysis strategy (e.g., pulse-shape discrimination).

Several designs have been evaluated, among which a compact Si-W sampling calorimeter, with oriented tungsten tiles as absorbers and a fine transverse segmentation (figure 1.15 on the left). This layout is based on the same physical phenomenon employed for the photon converter, located between the two TAXes in the upstream sector, namely the accelerated shower development due to the coherent interactions in the oriented crystal lattice [27, 50, 51, 54–56]. Thus, the tungsten layer could absorb photons more efficiently than a completely amorphous calorimeter with the same physical length. This layout was discarded due to the high cost of the tungsten crystals and the technical difficulty of developing a radiation hard silicon pad detector, capable of achieving the required time resolution.

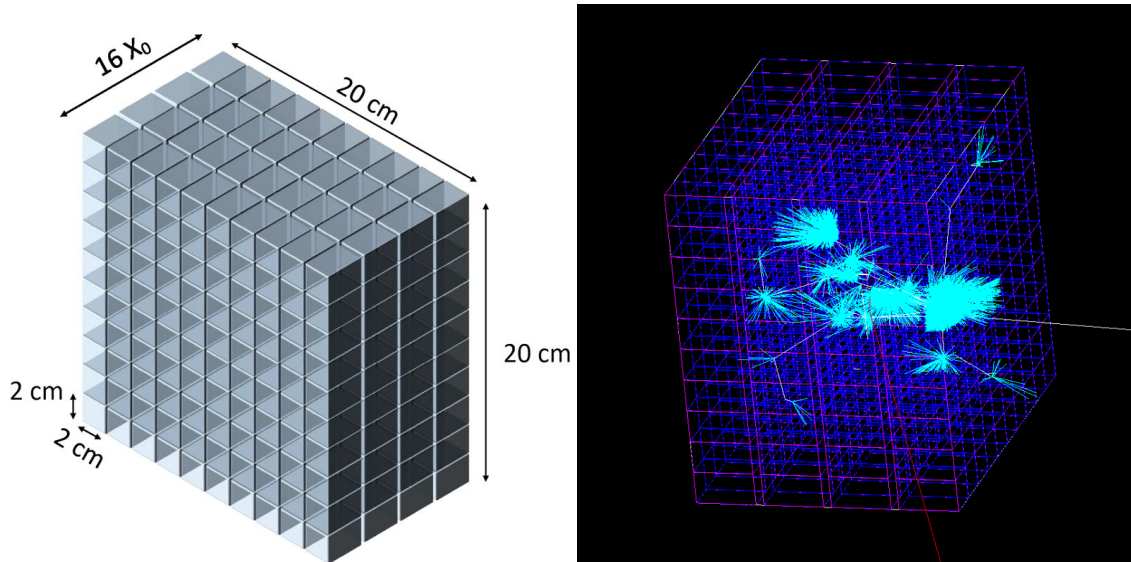


Figure 1.15: Design of the KLEVER SAC. Left: segmentation of the calorimeter in the transverse plane [5]. Right: Geant4 simulation of a 1 GeV photon (yellow) incident on the SAC, composed of four layers of PbF₂ crystals, with a 5 mm inter-layer gap [52]. The tracks of the secondary electrons (Cherenkov photons) are shown in red (cyan).

The solution currently under study is a highly-segmented, homogeneous calorimeter composed of high-Z crystals with a very fast output. An optimal active material could be lead fluoride (PbF_2), a Cherenkov radiator with an intrinsically short light production time and optimal calorimetric performances, as already demonstrated by the PADME experiment [53]. However, preliminary studies suggest that PbF_2 may lose transparency to Cherenkov light after the absorption of a photon dose of several kGy [57]. While this effect may be cured through thermal annealing and bleaching with UV light, it is fundamental to study alternative options. A backup solution could be lead tungstate (PbWO_4), which is known in particle physics for its large light output and its optimal radiation hardness. Recently, an optimized version of PbWO_4 has been developed, namely PbWO_4 -Ultra Fast (PWO-UF): it features both scintillation and Cherenkov light emission, with a prompt light production time of 640 ps, a light yield of 7 ph/MeV and a large radiation tolerance [58]. Independently from the active material, the SAC layout may be the following: four 10×10 layers of $20 \times 20 \times 40 \text{ mm}^3$ high-Z crystals, corresponding to a total length of $\sim 16 X_0$. In order to minimize the gaps between subsequent crystals, compact photodetectors are required, such as small PMTs or SiPMs. The development of the SAC detection system is currently being carried on in synergy with the CRystal calorImeter with Longitudinal Information (CRILIN) group, which is independently developing an electromagnetic calorimeter satisfying requirements similar to the KLEVER ones [59]. A Geant4 simulation of the 4-layers design, with PbF_2 crystals, has shown that [52]:

- For the photons with the highest energies (i.e., $\gtrsim 30 \text{ GeV}$), a $\sim 10\%$ loss of electromagnetic (e.m.) shower containment is expected. This effect seems to be independent on the gaps between subsequent layers (for gaps of $0 - 20 \text{ mm}$).
- For photons with $E_\gamma \geq 5 \text{ GeV}$, the inefficiency requirement is satisfied.
- Approximately 30% of the neutrons in the neutral beam generate a signal in the SAC above the threshold used for the events selection.

These results confirm that this design is already a viable solution for the Small Angle Calorimeter. However, there is a possible way to further improve the SAC performance in terms of both the e.m. shower containment and the transparency to neutral hadrons: the use of oriented PbF_2 (or PWO-UF) crystals. The coherent interactions in an oriented lattice could, in fact, be exploited to increase the total radiation length of the SAC while keeping constant its total nuclear interaction length [54]. It must be noted that these effects are observed only for photons with $E_\gamma \gtrsim 10 \text{ GeV}$ and for incidence angles smaller⁴ than $\sim 1 \text{ mrad}$, with respect to the crystallographic axes. This is not intrinsically a problem, since the most critical energy interval is $E_\gamma > 30 \text{ GeV}$ and the SAC features an angular acceptance of $\pm 2 \text{ mrad}$. However, it implies that after the first $5 - 7$ oriented radiation lengths, due to the transverse spread of the e.m. showers, there is no further gain in terms of energy resolution. This would suggest a SAC design with only the first (and at most the second) oriented crystal layer. However, the distinguishing feature of the SAC is not

⁴ In chapters 2 and 4 we demonstrate that the coherent effects are maximal within $\sim 1 \text{ mrad}$ from the crystal axis. However, even at $\sim 8 \text{ mrad}$ they are still visible, even if less significant.

its energy resolution, but rather its photon detection efficiency. The latter is limited by the punch-through effect, which is the possibility for a photon to effectively disappear from the detection volume⁵, either due to inactive regions (such as gaps or readout fibers) or to the statistical fluctuations of the absorption process. This phenomenon is reduced in longer crystals, but is found to be not null even at $25 X_0$, where the inefficiency may be $\mathcal{O}(10^{-4})$ [35, 60, 61]. Punch-through photons do not spread laterally, thus they are still exposed to the enhanced crystalline field even beyond $7 X_0$. This is the reason why the current goal for the SAC is a design with all the four layers oriented, with a significant efficiency increase, with respect to the completely amorphous alternative.

In order to quantify the angular dependence of the coherent interactions in an oriented high-Z crystal exposed to a high energy photon beam, the STORM and KLEVER collaborations have performed a beamtest at the CERN SPS during August 2021. This test allowed also to measure the time resolutions of two readout systems based on SiPMs, developed independently by the CRILIN and STORM collaborations. The aim of this thesis is to describe the setup employed at the CERN SPS (chapter 3) and the results of such measurements (chapters 4-5). The importance of the results of this work in the broader framework of the STORM project is discussed in chapter 2 and in the conclusions.

⁵ Here we neglect the possibility of photonuclear interactions, due to their null cross-section at the GeV scale.

THE PHYSICS OF ORIENTED CRYSTALS

When a beam of charged particles impinges on a solid target, a great variety of physical phenomena may occur, usually resulting in the deviation of the particles trajectories and the loss of a fraction of their energy. It has been found that the incident particles behave differently if the target features an ordered structure, such as a crystalline lattice [62]. In this case, the cross-sections and the other interaction parameters acquire a non trivial dependence on the angle between the incidence direction and the symmetry axes of the target. This effect was first theorized in 1912, when J. Stark hypothesized the existence of open channels inside crystal lattices, which allowed protons and heavy ions to penetrate in the target much deeper than their expected ranges. This phenomenon, which was later named channeling, remained largely unexplored until the 1960s, when J. Lindhard published an extensive discussion of its phenomenology [63]. This publication immediately prompted a number of theoretical works, concerning a variety of incident particles and energies. Experiments and numerical simulations soon confirmed the validity of some of these theories, while showing the limited accuracy of others [64].

A decade later, M. Kumakhov theorized an increase of the bremsstrahlung cross-section for electrons channeled along a crystalline axis, due to the interactions occurring with the lattice atoms during the time required for the production of a photon [65]. A similar increase was also theorized and then experimentally observed for electron-positron pair production [66–68]. Later, it was discovered that these effects are particularly enhanced for electrons and photons featuring an energy in the multi-GeV region, namely in the Strong Field (SF) condition, due to the Lorentz boost of the longitudinal component of the crystalline fields [69–71].

Such phenomena will be described in this chapter: the physics of channeling and the radiative processes near a crystal axis will be analyzed, with a particular focus on the Strong Field condition and its applications in high energy physics experiments.

2.1 CRYSTALLINE LATTICES

A crystal is a highly-organized solid composed of atoms arranged in an ordered and symmetrical structure, namely the crystalline lattice [72]. The most important property of a crystal is the spatial periodicity: the entire solid is constructed by spatially repeating a

fundamental building block, the unit cell, which is defined by three non-coplanar vectors $(\vec{a}, \vec{b}, \vec{c})$. The periodicity of the crystal implies invariance under translation, meaning that any given couple of lattice vertices (nodes) satisfies the following equation:

$$\vec{r}' = \vec{r} + m_1\vec{a} + m_2\vec{b} + m_3\vec{c} \quad (2.1)$$

where $\vec{r}$ and $\vec{r}'$ are the nodes coordinates and $m_i \in \mathbb{Z} \forall i$. If $\vec{r}$ is the origin of the coordinate system, the m_i coefficients are the coordinates of the $\vec{r}'$ node, expressed in units of lattice constants. In principle, there is no unique way to choose $(\vec{a}, \vec{b}, \vec{c})$, but conventionally $\vec{a}$ is set as the shortest lattice period, $\vec{b}$ as the shortest period not parallel to $\vec{a}$, and $\vec{c}$ as the shortest period not coplanar to $\vec{a}$ and $\vec{b}$. The vectors defined in such a way are named primitive and the resulting solid is the Bravais lattice: in three dimensions, it is possible to generate up to 14 different Bravais lattices, depending on the properties of their primitive vectors.

There are two particular subsets of crystal nodes which are relevant for the channeling phenomenon: the planes and the axes (or strings). A plane may be described by the following equation:

$$\frac{n_a}{a_0} + \frac{n_b}{b_0} + \frac{n_c}{c_0} = 1 \quad (2.2)$$

where n_a, n_b and n_c are the nodes coordinates, expressed in units of lattice constants, while a_0, b_0 and c_0 are the intersections between the plane and the coordinate axes. Since n_a, n_b and n_c are integers, it is possible to define four integer numbers (n, h, k, l) such that:

$$\frac{n}{n_a} = h, \quad \frac{n}{n_b} = k, \quad \frac{n}{n_c} = l \quad (2.3)$$

Thus, eq. (2.2) may be rewritten as:

$$n_a h + n_b k + n_c l = n \quad (2.4)$$

The (h, k, l) constants are the Miller indices and they uniquely characterize a set of parallel planes, each one corresponding to a different value of n ; they are normally fixed to the lowest triplet which determines the same set of planes. These indices are also used to describe the components of the vectors which are normal to all the planes. Axes and planes may be distinguished by adopting the following convention:

- (hkl) denotes a plane.
- $[hkl]$ denotes all the axes which are orthogonal to the (hkl) plane.
- $\langle hkl \rangle$ denotes all the axes which are identical to $[hkl]$, under global rotations.

The formalism of the Miller indices is shown in figure 2.1. In an infinite lattice there are axes and planes in any direction, with arbitrarily high Miller indices. However, the large majority of them features a large node-to-node spacing and consequently a small atomic density. Thus, any particle incident on a high-index axis interacts with the crystal lattice as if the latter was an unordered structure. This condition is called “random orientation”

and is essential in channeling experiments, since it allows to normalize the acquired data without changing the crystal under study.

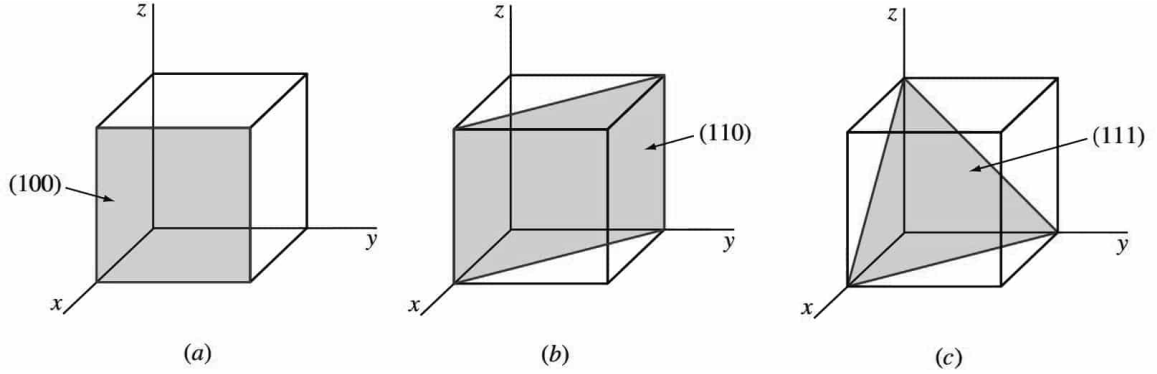


Figure 2.1: Miller indices nomenclature for three crystallographic planes [73]. The corresponding axes (i.e., $\langle 100 \rangle$, $\langle 110 \rangle$ and $\langle 111 \rangle$) are the most commonly studied in channeling physics experiments.

Since the properties of all mutually parallel axes are the same, it is convenient to adopt a representation common to all of them, namely the crystallographic stereogram [56]. This is simply a projection of the lattice on a 2D plane, using as coordinates the misalignment angles defined with respect to a given crystallographic axis ($\theta_{x,y}^{\text{mis}}$). In a stereogram, the $(0,0)$ point represents the reference axis, while the other points correspond to virtual axes, angularly displaced with respect to the reference, by:

$$\Delta\theta = \sqrt{(\theta_x^{\text{mis}})^2 + (\theta_y^{\text{mis}})^2} \quad (2.5)$$

If $\Delta\theta \gtrsim 50$ mrad, the corresponding axes are treated as directions of random orientation. Finally, any crystallographic plane which crosses the reference axis is represented in a stereogram as a straight line:

$$\theta_y^{\text{mis}} = m\theta_x^{\text{mis}} \quad (2.6)$$

with $m \in \mathbb{R}$. A pictorial view of a stereogram is shown in figure 2.2.

2.2 MOTION OF A CHARGED PARTICLE IN A CRYSTAL LATTICE

2.2.1 AXIAL CHANNELING

The channeling phenomenon was first observed in the early 1960s, measuring the ion penetration ranges inside crystal targets [75]. A major contribution to the quantitative description of these effects was later given by J. Lindhard [63]. The idea at the basis of his work was that the energy loss of a heavy particle inside a crystalline lattice cannot be described by means of the Bethe-Bloch equation, since the spatial density of the collision centers is highly non uniform. For this reason, a charged particle incident on an aligned

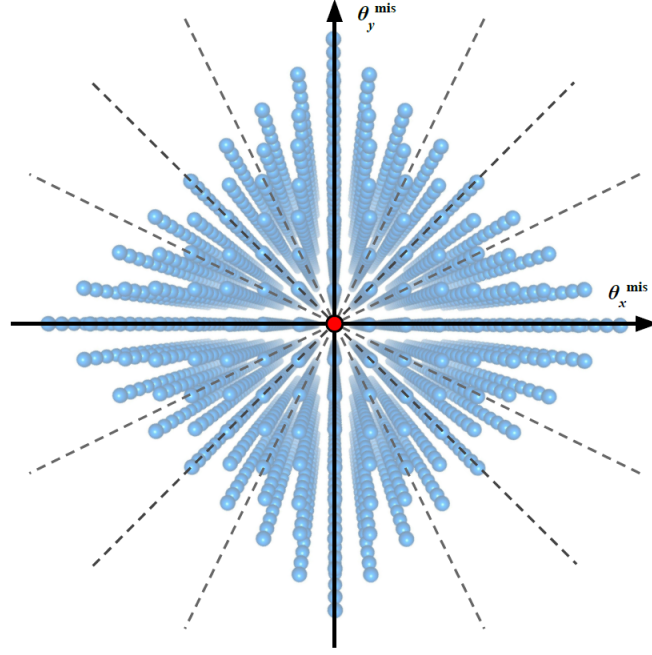


Figure 2.2: Pictorial representation of a crystallographic stereogram, superimposed on a perspective view of the corresponding crystal lattice [74]. The black (dashed) lines denote the crystal planes, while the red dot is the reference crystallographic axis.

single crystal undergoes a series of correlated soft collisions, while avoiding the harder ones (“close encounter”). In this way, the particle remains close to the channel inside the lattice and is able to reach much longer paths than expected.

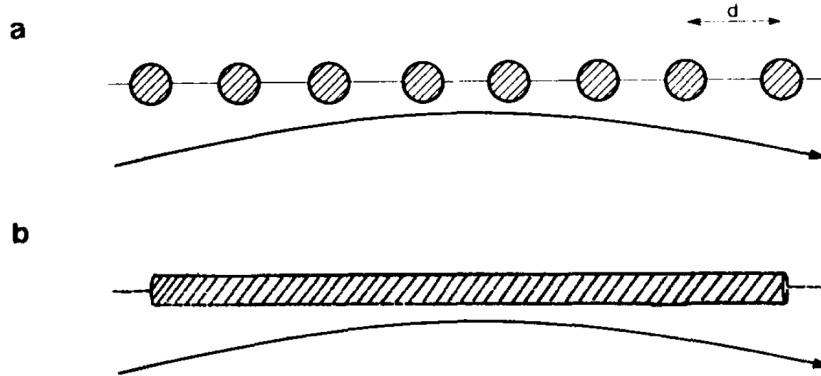


Figure 2.3: Motion of a particle channeled close to a lattice string [76]. (a) true deflection of the particle, due to the correlated soft collisions with the string nuclei. (b) continuum approximation of the string.

Following Lindhard’s work [63, 75–78], let us consider a heavy positively charged particle of mass m , incident on a string of atoms, oriented along the z axis (figure 2.3). Let $\vec{r}_\perp$ be the coordinate perpendicular to the z axis and d the string spacing. To the lowest approximation order, it is possible to neglect the interactions of the particle with other neighboring strings, since their mutual distance is an order of magnitude larger than their effective action radius. The trajectory of the particle is thus determined by a series of collisions with the string atoms, each resulting in a small deflection ($\Delta\theta$). Each collision is described in

the impulse approximation, by evaluating the total momentum transferred to the particle as the integral over the transit time ($\Delta t \sim d/v$, where v is the particle speed) of the force generated by the string potential ($V(\vec{r}_\perp, z)$). Rigorously, the latter should be computed as the sum of the screened Coulomb potentials generated by all the nuclei along the string. However, Lindhard replaced the sum with the average potential observed along the string axis:

$$U(\vec{r}_\perp) = \frac{1}{d} \int_{-\infty}^{+\infty} dz V(\vec{r}_\perp, z) \quad (2.7)$$

In this way, each target nucleus is modeled as a continuous segment, whose potential includes the smaller contributions generated by the neighboring atoms in the string (figure 2.3b). This is the core of the so-called continuum approximation, which is based on the intuition that the string spacing is smaller than the effective range of the single-atom potential. An important consequence of this approximation is the separation of the axial and transverse motion: since the potential given by eq. (2.7) does not depend explicitly on the z coordinate, the momentum component along this axis ($p_z = \vec{p} \cdot \hat{z}$) is conserved and so is the corresponding kinetic energy:

$$E_z = \frac{p_z^2}{2m} = \text{cost.} \quad (2.8)$$

The transverse motion is instead governed by the averaged potential energy function ($U(\vec{r}_\perp)$), following the energy conservation law:

$$E_\perp = \frac{p_\perp^2}{2m} + U(\vec{r}_\perp) = \text{cost.} \quad (2.9)$$

For relativistic particles propagating along a crystal axis, this argument is still valid and the same equations may be used, by accounting for the analytical expression of the relativistic kinetic energy:

$$E_\perp = \frac{p_\perp^2}{2m\gamma} + U(\vec{r}_\perp) = \text{cost.} \quad (2.10)$$

where $\gamma = (1 - v^2/c^2)^{-1/2}$ is the Lorentz factor of the moving particle and m its rest mass. In order to integrate the equations of motion and find the allowed channeling trajectories, it is necessary to specify the shape of $V(\vec{r}_\perp, z)$. For instance, the so-called “standard” screened Coulomb potential is given by [75]:

$$V(\vec{r}_\perp, z) = \frac{Z_1 Z_2 e^2}{r} \left[1 - \frac{r}{\sqrt{r^2 + C^2 a^2}} \right] \quad (2.11)$$

where $r = \sqrt{r_\perp^2 + z^2}$, Z_1 and Z_2 are the projectile and target charges, expressed in units of elementary charge (e), $C^2 \sim 3$ and a is the screening length, which may be computed as:

$$a = \frac{0.89 a_0}{\sqrt{Z_1^{2/3} + Z_2^{2/3}}} \quad (2.12)$$

where a_0 is the Bohr radius for the hydrogen atom. Inserting the standard potential in eq. (2.7) and computing the integral, the following potential energy function is obtained:

$$U(\vec{r}_\perp) = \frac{Z_1 Z_2 e^2}{d} \log \left[1 + \left(\frac{C a}{r_\perp} \right)^2 \right] \quad (2.13)$$

This potential has been found to be relatively imprecise, when compared with the experimental data. A better agreement is found by convolving the standard potential with a gaussian kernel, which models the thermally-induced displacements of the string atoms. It can be shown that the thermally-averaged standard potential takes then the form [75]:

$$U(\vec{r}_\perp) = \frac{Z_1 Z_2 e^2}{d} \log \left[1 + \frac{C^2 a^2}{|\vec{r}_\perp|^2 + \rho^2/2} \right] \quad (2.14)$$

where ρ^2 is the two-dimensional mean square thermal displacement of the string atoms. It is possible to increase even further the agreement between the predictions and the experimental data by using more complex potentials, based for instance on the Doyle-Turner single-atom potential [68, 75]. One of such functions is shown in one and two dimensions in figure 2.4. Finally, if the incident particle charge is small enough for the interaction to be treated as a perturbation, it is also possible to perform accurate Hartree-Fock calculations of the string potential [75].

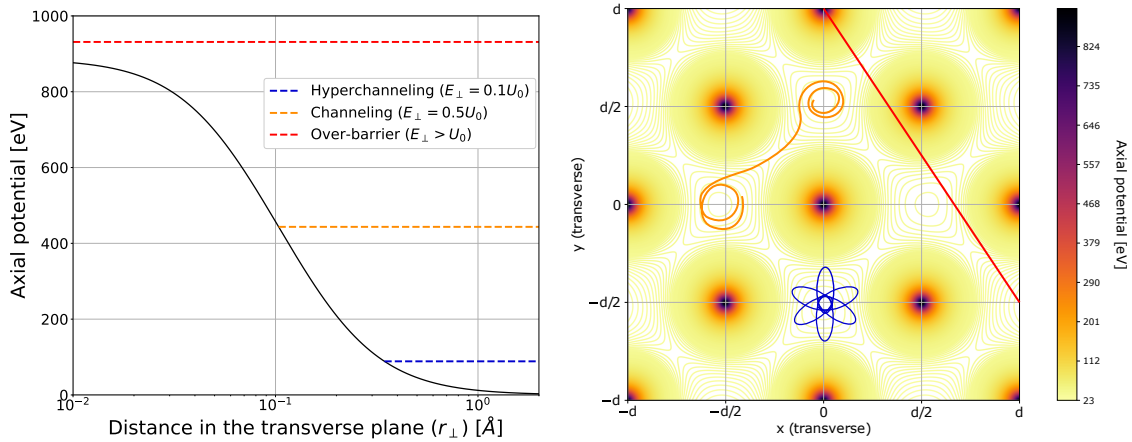


Figure 2.4: Left: potential generated by a single atomic string in a W crystal, in the transverse plane with respect to the $\langle 111 \rangle$ axis. Right: contour plot of the potential generated by several parallel strings in their transverse plane, computed by summing the corresponding displaced single-atom potentials. The colored lines (blue, orange, red) show the different possible motions in the lattice, depending on the initial energy of the particle.

Depending on the initial energy of the incident particle ($E_\perp$), with respect to the height of the string potential barrier (U_0), different trajectories in the transverse plane may be observed (figure 2.4 on the right):

1. If $E_\perp \ll U_0$, the particle is trapped at the bottom of the potential well and features a highly localized oscillating trajectory (rosette orbit). This condition is called hyperchanneling [79].

2. If $E_{\perp} \lesssim U_0$, the particle is still trapped inside the potential well, but due to the strings thermal vibrations it may sometimes leap from a well to another. This effect is also known as doughnut scattering and leads to a complex trajectory in the transverse plane, since a given incident particle will oscillate close to a number of different strings inside the lattice [80].
3. If $E_{\perp} > U_0$, the particle is unbound and thus free to move inside the lattice. However, if the incidence angle is small enough, some physical processes are still affected by the continuum string potential: for instance, the bremsstrahlung cross-section of particles moving beyond the channeling region is found to be largely enhanced, if compared with its standard value [70]; this phenomenon is described in more detail in section 2.3.4. More in general, the continuum approximation has been shown to reliably model a number of physical phenomena for incidence angles even up to $\sim 1^\circ$ [64].

The condition of an incident particle being trapped in the potential barrier is called “under-barrier”, as opposed to the “over-barrier” $E_{\perp} > U_0$ condition. The above discussion allows to compute the largest incidence angle for which channeling is appreciable (θ_c). When the incident particle is far away from the crystal, its energy is purely kinetic and may be computed following eq. (2.9), which may be rewritten in order to show the dependence of $E_{\perp}$ on the incidence angle (θ):

$$E_{\perp} = \frac{1}{2}pv \sin^2 \theta \sim \frac{1}{2}pv\theta^2 \quad (2.15)$$

where $p = (p_{\perp}, p_z)$ is the particle initial momentum, v the modulus of its initial velocity and $\theta = \arctan(p_{\perp}/p_z) \ll 1$. In order to escape from the potential well, the particle total energy should be approximately equal to the well depth:

$$E_{\perp} \sim U_0 \quad (2.16)$$

where U_0 may be estimated as the maximum value of $U(\vec{r}_{\perp})$. It is also possible to set $U_0 = U(\rho)$, in order to include the effects of the thermal displacements of the string atoms. Thus, the particle may escape the potential well, if:

$$\frac{1}{2}pv\theta^2 \sim U_0 \quad (2.17)$$

Solving for θ the critical angle for the channeling phenomenon is found:

$$\theta_c = \sqrt{\frac{2U_0}{pv}} \quad (2.18)$$

In the ultra-relativistic regime this expression becomes simply $\theta_c \sim \sqrt{2U_0/E}$, where E is the total energy of the incident particle. Independently from the analytical expression

chosen for the potential, it can be shown that the non relativistic limit of θ_c may be rewritten in the form which was first derived by Lindhard [91]:

$$\theta_c \sim \sqrt{\frac{4Z_1Z_2e^2}{pvd}} \quad (2.19)$$

Using this expression, it is possible to estimate the angular acceptance of the channeling phenomenon. The dependence of θ_c on $\sqrt{U_0/E}$ means that:

- A higher-potential axis features a broader angular acceptance.
- The angular acceptance of the channeling phenomenon is larger for a particle with a smaller energy.

For light charged particles ($Z \sim 1$) incident on a high- Z crystal, with an energy in the typical range of the channeling experiments (MeV–GeV), the critical angles range from $\sim 50 \mu\text{rad}$ to $\sim 1 \text{ mrad}$. Figure 2.5 shows the θ_c curves computed by means of eq. (2.18), for the axes of a pure W and a PbWO_4 crystal.

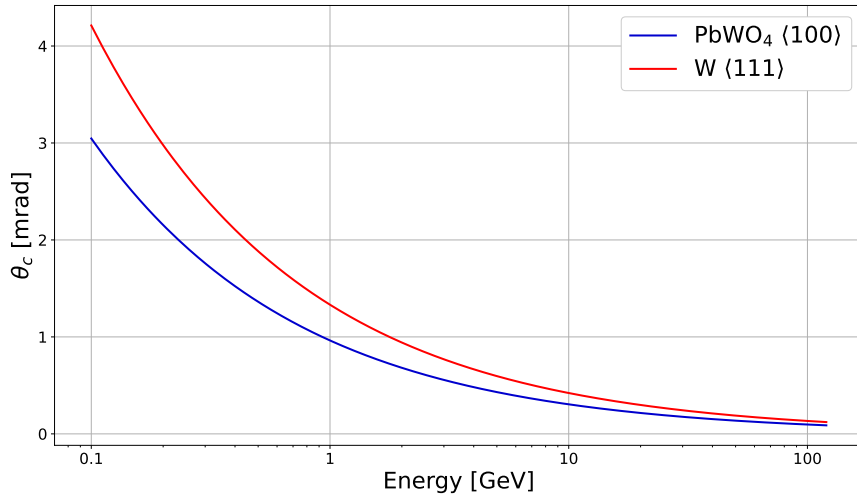


Figure 2.5: Channeling critical angles for the highest-potential axes of a pure W and a PbWO_4 crystal, computed as $\theta_c = \sqrt{\frac{2U_0}{pv}}$. Here, we assumed $U_0 = 887 \text{ eV}$ for the $\langle 111 \rangle$ axis of the W crystal and 464 eV for the $\langle 100 \rangle$ axis of PbWO_4 .

2.2.2 PLANAR CHANNELING

The channeling phenomenon is also observed when a charged particle impinges on a crystal with a small angle with respect to the direction of one of its planes (figure 2.6). This process is known as planar channeling and is mathematically treated identically as the axial channeling, meaning that a continuum planar potential may be computed by smearing the single-atom potential over two dimensions [75, 76]:

$$V(x) = Nd_p \int_{-\infty}^{+\infty} dx V(r_\perp, z) \quad (2.20)$$

where x is the coordinate perpendicular to the plane, N is the atom density of the crystal and d_p the separation between adjacent planes. Without including thermal effects, the standard continuum potential is found to be [91]:

$$U(x) = 2\pi Z_1 Z_2 e^2 N d_p \left[\sqrt{x^2 + C^2 a^2} - x \right] \quad (2.21)$$

The thermal averaging of this potential has a less dramatic effect with respect to the axial case, since static planar potentials remain finite at the center of the planes. Following the same approach of the previous section, it is possible to compute the critical angle for planar channeling, obtaining [91]:

$$\theta_c \sim \sqrt{\frac{4Z_1 Z_2 e^2 N d_p C a}{p v}} \quad (2.22)$$

Note here the presence of the additional $N d_p C a$ factors, with respect to the axial critical angle (eq. (2.19)). Differently from the axial channeling, here the under-barrier condition (i.e., $\theta < \theta_c$ and $E_{\perp} < U_0$) corresponds to an incident particle confined to a single channel in the transverse plane, located between adjacent crystallographic planes. Since the planar potential well-depth is smaller than the axial one by a factor ~ 10 , the planar angular acceptance turns out to be narrower [91]:

$$\theta_c^{planar} \sim \frac{1}{3} \theta_c^{axial} \quad (2.23)$$

These estimates have been recently confirmed by a more rigorous treatment of the channeling phenomenon, with respect to the continuum approximation, for positive charged particles [81].

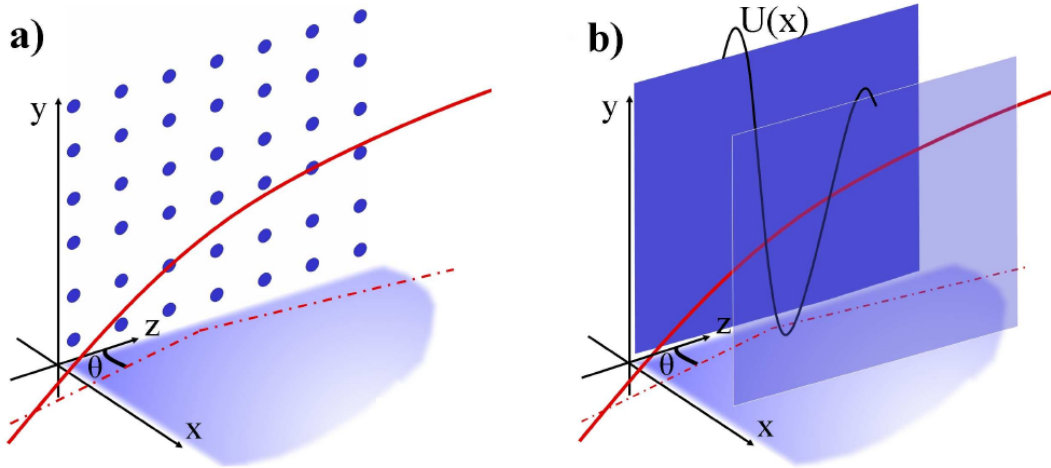


Figure 2.6: Pictorial representation of planar channeling [56].

2.2.3 DECHANNELING

In the previous sections, the exact conservation of the channeled particle transverse energy ($E_{\perp}$) was assumed. This is a lowest-order approximation, which is acceptable in the description of the channeling phenomenon in an ideal crystal. However, in real crystals there is a number of effects which may lead to a variation of the transverse energy and eventually result in the escape of the incident particle from its bound state. This process is called dechanneling and its main causes are [76, 82]:

- The scattering of the primary particle on point charges, such as atomic electrons or thermally displaced nuclei.
- The possible defects in the crystal structure.
- The differences between the (approximated) continuum and the real lattice potential.

Dechanneling is a complex phenomenon and its full description is achieved only through Monte Carlo simulations. However, a simplified dechanneling model may be developed, by considering only the most significant dechanneling cause, which is the multiple scattering on the target nuclei. This process can be described, with the simplest approximation, by means of a dechanneling probability function ($D(z)$), which is computed as [82]:

$$D(z) = e^{-z/L_D} \quad (2.24)$$

where L_D is the dechanneling length. This equation implies that only a fraction $1/e$ of the initially channeled particles will still be in an under-barrier state, after traveling a length L_D . The dechanneling length depends on both the intensity of the crystalline potential and the energy of the incident particles: for instance, L_D has been found to be 0.5 cm (21.9 cm) for 500 MeV/c (400 GeV/c) protons incident on a silicon crystal [83]. This means that the fraction of the dechanneled particles is smaller than $\sim 5\%$, for a ~ 1 mm crystal [83]. More details on this phenomenon and its description are given in [62, 76, 82–85].

2.2.4 POSITIVE AND NEGATIVE CHARGED PARTICLES

Up to now, only the channeling phenomenon for positive charged particles incident on a crystal lattice has been described. A similar picture is found also for negative particles, since in this case the interaction potentials are equal in shape but opposite in sign (figure 2.7). Thus, the points of minimum potential for negative and positive particles are located, respectively, very close and very far from the crystal axes and planes [64, 76]. For this reason, several differences in the channeling motions are observed: the positive particles are usually focused in stable trajectories in-between strings or planes, with the possibility of moving frequently from one channel to another. On the other hand, the negative particles are bound to a single string, with a large close-encounter probability, due to the large density of scattering centers. This fact leads negative particles to experience a much more severe dechanneling effect, especially during the motion along a crystal axis.

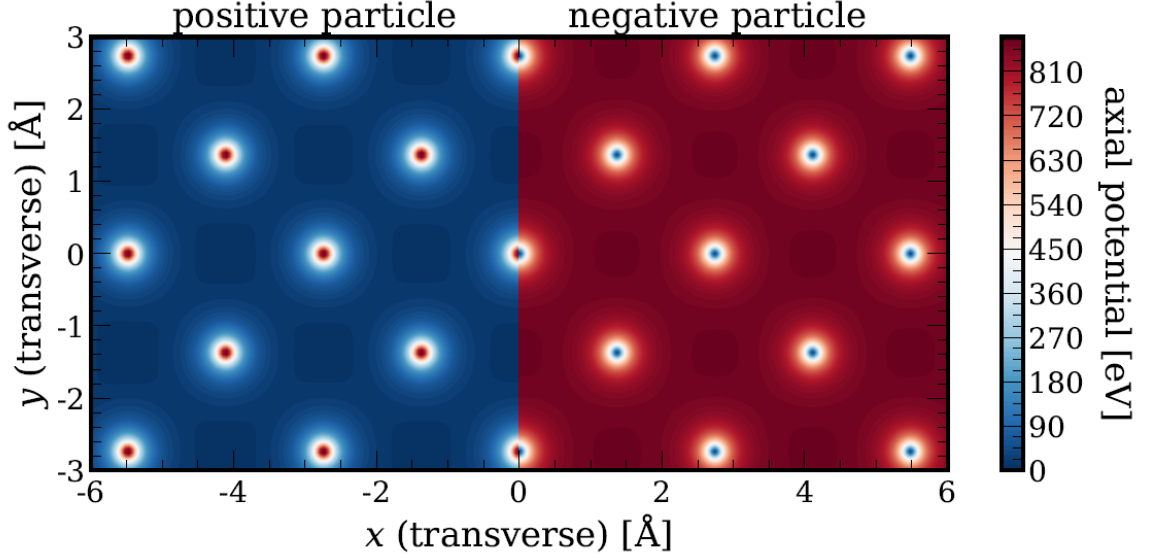


Figure 2.7: Comparison of the potentials generated in the transverse plane by the $\langle 111 \rangle$ axis in a pure W crystal, for positive (left) and negative (right) charged particles [74].

2.3 RADIATIVE PROCESSES

It is well known from classical physics that an accelerated charged particle emits electromagnetic radiation during its motion [35]. If the acceleration derives from the interaction with an atomic electric field, the process is known as Standard Bremsstrahlung (SB): this is the dominant energy loss mechanism for electrons and positrons with an energy beyond ~ 10 MeV. Since the e.m. interactions of a particle in motion in an amorphous medium are independent one from each other, there is no coherence among all the emitted photons; however, this is not true if the medium is an ordered structure, such a crystalline lattice. The properties of the radiation emitted in this case depend on the energy and incidence angle of the charged particle¹ (figure 2.8) [64, 76]:

- If the particle is channeled (i.e., it is in an under-barrier state) and features an energy lower than ~ 100 MeV, the large number of interactions with the crystalline lattice leads to the production of Channeling Radiation (CR), with an intensity larger than the SB prediction and a dipole angular distribution [78]. At higher energies (i.e., ~ 1 GeV) the amplitude of the channeling oscillations are smaller than the variation scale of the transverse electric field. Thus, the electron moves in an approximately constant potential and emits harder radiation, which features a synchrotron-like spectrum.
- If the incident particle is in an over-barrier state, its trajectory is weakly affected by the lattice electric field. However, the periodic interactions with the potential generated by different axes and planes lead to the production of photons, with a smaller intensity than the CR value but larger than the SB prediction [78]. This phenomenon

¹ In this section, we describe only the radiative emissions of light charged particles, such as electrons and positrons.

is known as Coherent Bremsstrahlung (CB) and is observed for incidence angles, with respect to the crystalline axes, as large as $\sim 1^\circ$ [76].

It has been pointed out that this division is partially incomplete [64]. In fact, a different phenomenon is observed for electrons and positrons exposed to an electric field more intense than the Schwinger critical field ($\mathcal{E}_0$), namely the field strength above which non linear electromagnetic effects occur in vacuum [86]. This regime, known as Strong Field (SF), is characterized by the emission of quantum synchrotron radiation, with an intensity larger than the SB value by a factor 10 – 100 [64]. This is a universal phenomenon, meaning that it can be observed for both under-barrier and over-barrier charged particles, as long as the incidence angle is smaller than ~ 1 mrad and the initial energy is larger than ~ 10 GeV [69]. A scheme of the incidence angle and energy required to observe each radiative process, including the SF regime, is shown in figure 2.9. The values of the energy and angular thresholds here reported are first-order estimations of the processes effective ranges and do not account for temperature or material dependencies.

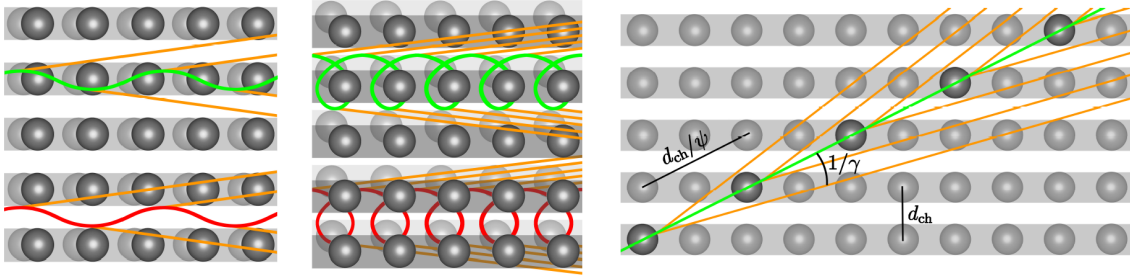


Figure 2.8: Comparison between the emission of axial Channeling Radiation (left), planar CR (center) and Coherent Bremsstrahlung (right) [74]. The electron (positron) trajectories are shown in green (red) and the emitted photons are shown in orange.

2.3.1 STANDARD BREMSSTRAHLUNG

The Standard Bremsstrahlung phenomenon takes place when a charged particle undergoes a number of uncorrelated scattering events while crossing an amorphous medium. For high energy electrons and positrons, under the complete atomic screening approximation, the SB differential cross-section is [64, 76, 88]:

$$\frac{d\sigma}{d\hbar\omega} = \frac{16}{3} Z^2 \alpha r_e^2 \frac{1}{\hbar\omega} \left[1 - \frac{\hbar\omega}{E} + \frac{3}{4} \left(\frac{\hbar\omega}{E} \right)^2 \right] \log(183Z^{-1/3}) \quad (2.25)$$

where $\hbar\omega$ is the energy of the emitted photons, Z is the atomic number of the target material, α is the fine structure constant, r_e is the electron classical radius and E is the energy of the charged particle. This cross-section scales as $\sim 1/\hbar\omega$: this means that the SB emission spectrum is more intense in the low-energy (soft) region than in the high energy (hard) tail. The angular distribution of the emitted radiation is a narrow cone centered around the electron trajectory (figure 2.10), with an opening angle $\sim 1/\gamma$. The uncertainty

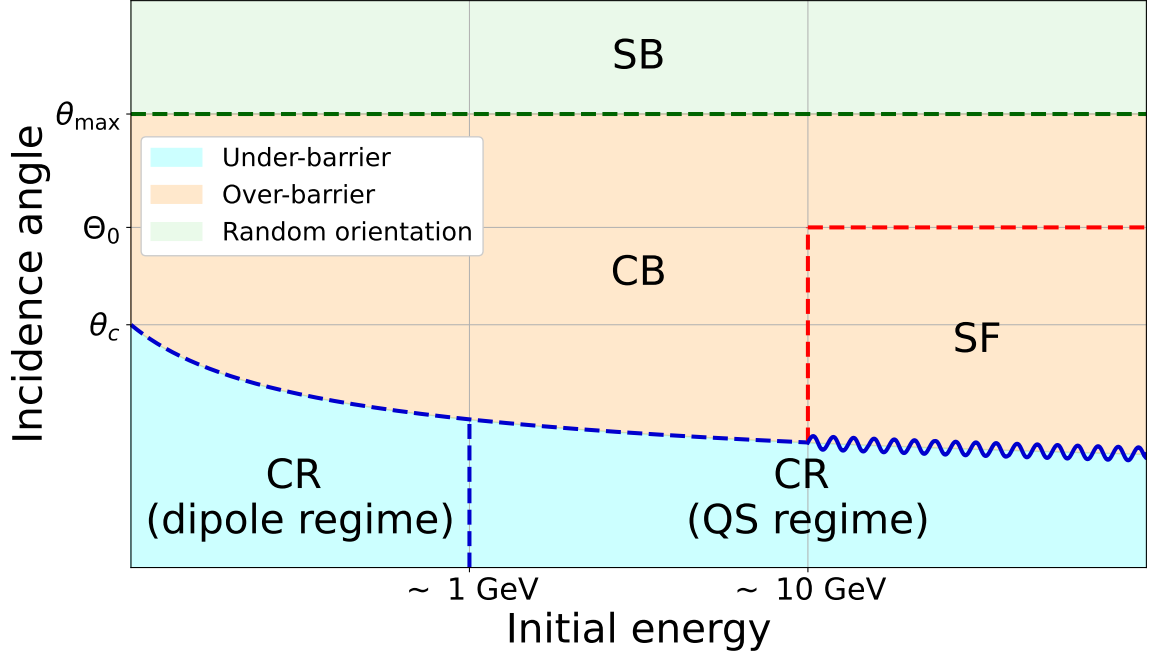


Figure 2.9: Scheme of the radiative processes of a charged particle incident on the axis of an oriented crystal, as a function of the incidence angle and energy. θ_c is the channeling critical angle, Θ_0 the Strong Field critical angle (section 2.3.4) and $\theta_{\max}$ the angle beyond which directional effects in oriented crystals are negligible. The relative proportions of the angles are not represented accurately². The wavy blue line indicates that, in the Strong Field (SF) regime, the features of the emitted radiation are identical, for both channeled and over-barrier electrons.

on the emission direction is equivalent to an uncertainty on the point of emission: thus, it is natural to define the radiation formation length (l_f), namely the distance traveled by the parent electron during the emission of a photon [64, 89]. In an amorphous medium, usually³, only a single interaction event occurs, leading to the emission of radiation and the scattering of the parent particle outside the light emission cone (i.e., $\Delta\theta \gg 1/\gamma$). Since a channeled particle remains close to the crystalline axis, multiple interactions may occur along the formation length, leading to an increase of the emission intensity. One way to compute the formation length is to consider the distance required for the emitted photon to be separated from the emitting particle by one reduced wavelength ($\lambda/2\pi$) [64, 89]:

$$l_f = \frac{2\gamma^2 c}{\omega} \quad (2.26)$$

where γ is the Lorentz factor of the charged particle. For electrons and positrons with an energy larger than the critical energy (E_c), which is a parameter of the order of 10 – 100 MeV for most materials, the Standard Bremsstrahlung is the dominant slowing down process [35, 90]. Thus, it is natural to measure the distance traveled by a high energy charged particle in units of radiation length (X_0), namely the length required for the particle to lose

³ At very high energies ($\gtrsim 100$ TeV), the multiple Coulomb scattering is appreciable even in a single formation length: the resulting quantum mechanical interference between the different scattering amplitudes leads thus to the suppression of the bremsstrahlung cross-section. This is known as Landau-Pomeranchuk-Migdal (LPM) effect [64].

all but a fraction $1/e$ of its initial energy, due to only radiative emissions. In general, the radiation length depends on the density (n) and the atomic number of the target material and it scales as $Z^{-2}n^{-1}$ [35, 90].

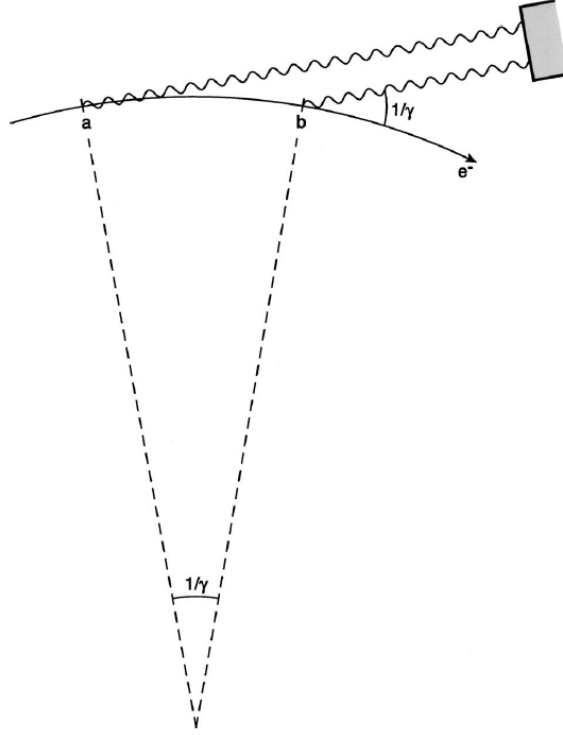


Figure 2.10: Radiation emitted by an electron moving in an electromagnetic field [64]. The $\widehat{ab}$ arc is the radiation formation length (l_f).

2.3.2 CHANNELING RADIATION

When an electron (positron) is channeled along a crystalline axis, the multiple interactions with the continuum potential lead to the emission of Channeling Radiation. This process is fundamentally different from the SB, since in this case the emitting particle is in an under-barrier state and features a trajectory quite different from a free particle. Traditionally, CR is divided in three groups, depending on the initial energy of the emitting particle [64]:

- At low energies (i.e., 10 – 100 MeV), the emission process is similar to an atomic de-excitation, since the emitting particle is subject to an electric potential with a low number of (quantized) energy levels. The particle motion is then described as an eigenfunction of the lattice potential and the CR emission corresponds to the transition between states with different energies: the energy of the emitted photons is computed in the rest frame of the moving particle, where the lattice length is Lorentz-contracted and thus the transverse potential ($U(\vec{r}_\perp)$) is enhanced by a factor γ . The resulting value, in the laboratory frame, is [76, 78]:

$$\hbar\omega = \frac{-\Delta E_\perp}{1 - \beta \cos \theta_\gamma} \sim \frac{2\gamma^2(-\Delta E_\perp)}{1 + (\gamma\theta_\gamma)^2} \quad (2.27)$$

where $\Delta E_{\perp}$ is the energy transition, βc is the charged particle initial velocity and θ_{γ} is the angle between the emission direction and the z axis. Since the quantized energy shifts have a value of ~ 10 eV and the photon energies are enhanced by a γ^2 factor, the CR spectrum extends in the keV region and presents a multi-peaked shape (figure 2.11 on the left). Similarly to the SB, the CR is strongly forward-oriented, meaning that the emission is more intense at smaller θ_{γ} .

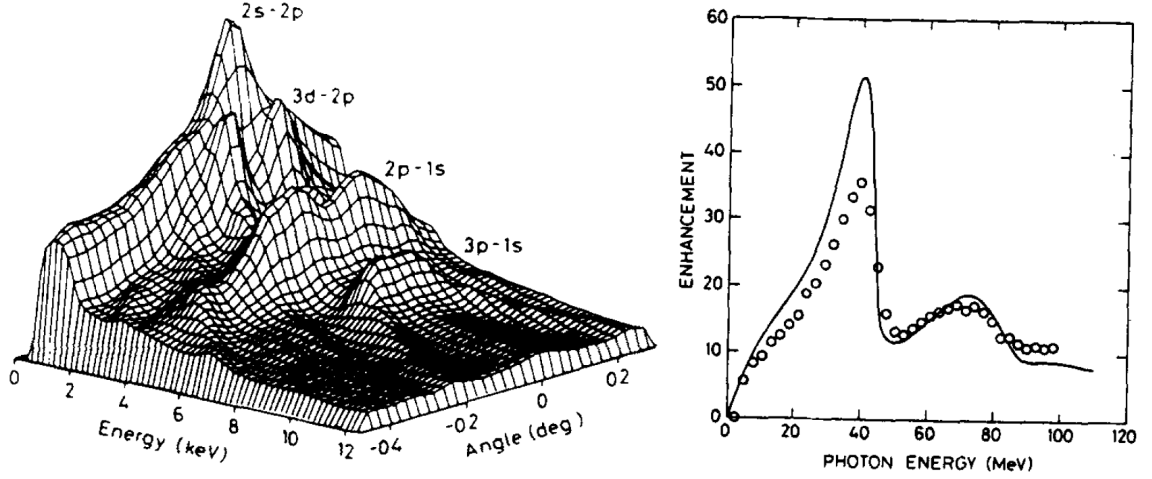


Figure 2.11: Channeling Radiation spectra [91]. Left: axial CR emitted by 4 MeV electrons incident on the $\langle 111 \rangle$ axis in a pure silicon crystal at room temperature. Right: intensity of the planar CR emitted by 6.7 GeV positrons incident on the (110) plane in a pure silicon crystal, normalized to the SB spectrum. The solid curve is the theoretical prediction and the points represent the experimental data.

- At intermediate energies (i.e., ~ 100 MeV–1 GeV), the number of available states increases significantly and their relative spacing decreases. This allows to describe the photon production classically, as a dipole-like emission process: the resulting spectrum is generally broad and featureless and its peak scales as $\sim \gamma^{3/2}$ [78]. A particular case is represented by the positron planar channeling, since the transverse potential is either harmonic, for initial energies smaller than ~ 1 GeV, or weakly anharmonic. In this case, the spectrum features a two-peaked shape (figure 2.11 on the right).
- As the initial energy increases above ~ 1 GeV (i.e., $\gamma \sim 1000$) and the particle transverse momentum enters the ultrarelativistic regime, the previous results become inaccurate. This is due to the fact that the longitudinal and transverse motion are not separated anymore, as demonstrated by the dependence of the longitudinal velocity (β_z) on the transverse momentum ($p_{\perp}$) [64, 89]:

$$\beta_z^2 \sim 1 - \frac{1}{\gamma^2} \left[1 + \left(\frac{p_z}{mc} \right)^2 \right] \quad (2.28)$$

where the terms of order $p_{\perp}/p_z$ were neglected. In this energy regime, the transverse oscillations of the charged particle in the crystal channel ($\Delta\theta < \theta_c \sim \gamma^{-1/2}$) are smaller than the opening angle of the emission cone ($\theta_{\gamma} \sim 1/\gamma$). This means that the

transverse distance traveled during a formation length is smaller than the variation scale of the transverse potential: the CR production is then locally equivalent to the emission of radiation from a particle moving in an intense and constant potential [64, 91]. From the classical theory of electromagnetism, it is known that the trajectory of a particle moving at relativistic energies in a constant field is a circular arc [92]. Moreover, the interactions with the constant field lead to the emission of synchrotron radiation, with a broad spectrum shifted towards the harder region (figure 2.12). The spectrum features an exponential cut-off (ω_c), which may be computed as [91]:

$$\omega_c = \frac{3c\gamma^3}{2R} \quad (2.29)$$

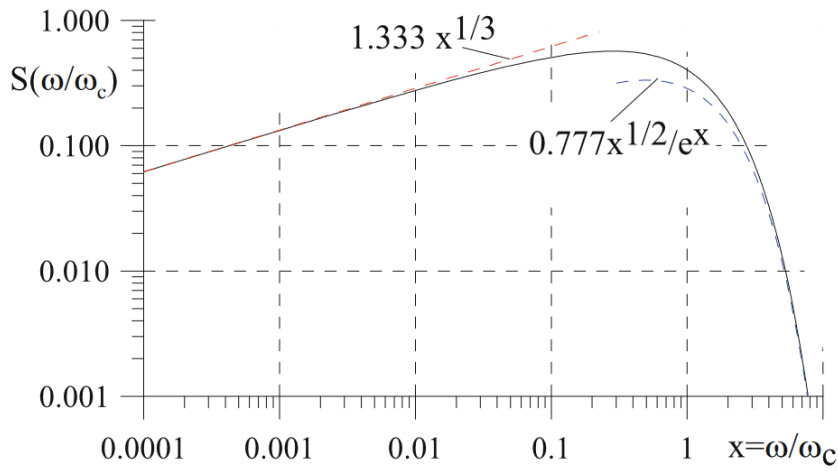


Figure 2.12: Synchrotron radiation emission spectrum [93].

In the last decades, it has been pointed out that this scheme of the CR emission is incomplete, since a further increase of the electron (positron) energy in the multi-GeV region leads to the breakdown of the synchrotron radiation description [64]. In fact, a classical calculation of the motion of a particle in a magnetic field⁴ of strength B shows that the end-point of the spectrum can be computed as [64, 76]:

$$\frac{\hbar\omega_c}{E} \sim \frac{3}{2}\gamma \frac{B}{B_0} = \frac{3}{2}\gamma k_f = \frac{3}{2}\chi \quad (2.30)$$

where E is the particle initial energy, B_0 is the Schwinger critical magnetic field, k_f is the magnetic field strength expressed in units of B_0 and $\chi = \gamma k_f$. This expression shows that, in the large γ limit, an unphysical result is obtained, since the photon spectrum extends beyond the energy of the emitting electron. This is due to the fact that in this energy range it is necessary to account for the electron recoil induced by the emitted photon, since the latter may carry a large fraction of the available momentum. While it is possible to perform

⁴ As pointed out in [64, 89], it is equivalent to consider the field responsible for the emission of CR as electric or magnetic, as long as the trajectory of the emitting particle is the same.

a classical calculation of the corrected critical frequency⁵, an accurate and coherent inclusion of the photon recoil is achieved only in the framework of Quantum ElectroDynamics (QED) [64, 91, 94]. The resulting description is the emission of hard quantum synchrotron radiation, with an intensity smaller than the predictions of the classical synchrotron model, but still larger than the SB by a factor of 10 – 50 (figure 2.13) [64, 89]. This process is observed theoretically for $\chi \sim 1$, namely for initial energies of 10 – 100 GeV [68].

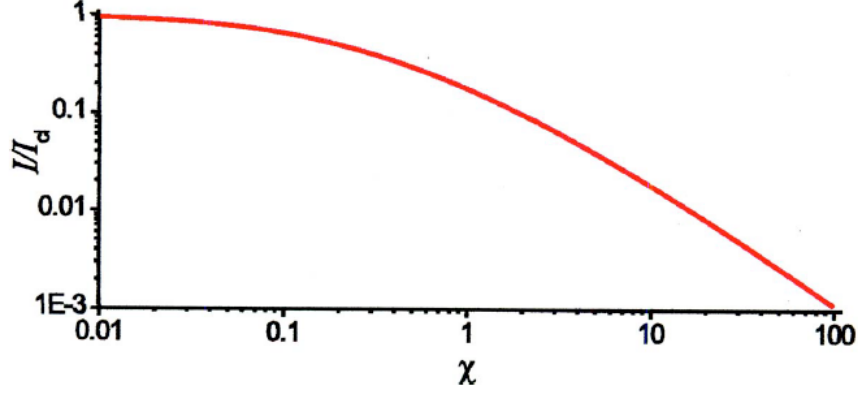


Figure 2.13: Intensity of the synchrotron radiation emitted by a particle moving in a constant electromagnetic field, as a function of the χ factor of the emitting particle [93].

2.3.3 COHERENT BREMSSTRAHLUNG

An electron or positron incident on a lattice axis with an angle larger than θ_c , but small enough for the continuum approximation to be valid, cannot be captured in an under-barrier state. Physically, this means that the multiple interactions with the crystal axes and planes lead to a small deviation from the initial trajectory and to the periodic production of coherent radiation. This phenomenon is known as Coherent Bremsstrahlung and is described, under the Born approximation, as a weak perturbation of the motion of a quantum particle interacting with the quantized lattice field [64]. The resulting CB total cross-section for the interaction with N atoms is [91]:

$$\frac{d\sigma}{d\hbar\omega d^3\vec{q}} = \left[\frac{d\sigma}{d\hbar\omega d^3\vec{q}} \right]_{\text{single atom}} \cdot \left| \sum_{n=1}^N e^{i\vec{q} \cdot \vec{r}_n} \right|^2 \quad (2.32)$$

where $\hbar\vec{q}$ is the recoil momentum of the atomic nucleus and the sum in the right term yields N for an amorphous medium. In the $N \rightarrow \infty$ limit, for an oriented lattice, the sum yields [91]:

$$\left| \sum_{n=1}^N e^{i\vec{q} \cdot \vec{r}_n} \right|^2 = N \frac{(2\pi)^3}{N_0 \Delta} |S(\vec{g})|^2 \sum_{\vec{g}} \delta(\vec{q} - \vec{g}) \quad (2.33)$$

⁵ A classical inclusion of the parent particle recoil leads to the following substitution in eq. (2.30) [92]:

$$\frac{\hbar\omega_c}{E} \rightarrow \frac{\hbar\omega_c}{E} \left(1 - \frac{\hbar\omega_c}{E} \right) \quad (2.31)$$

where $\vec{g}$ is a reciprocal lattice vector (i.e., the Fourier transform of a lattice vector), $S(\vec{g})$ is a structure factor and N_0 is the number of atoms contained in a unit cell of volume V . This is essentially an interference pattern: the CB spectrum is thus expected to feature a multi-peaked shape, which is physically due to the periodic (coherent) emission of radiation (figure 2.14). While the peak intensity may be ~ 5 times as large as the SB yield, the tail of the CB spectrum is found to be at the SB level, since a non-coherent bremsstrahlung contribution from thermally displaced nuclei is always present. Similar spectra have been measured at a small incidence angle for a variety of initial energies, while for the largest angles the lines structure is smoothed and a single and broader peak is observed (figure 2.14) [91].

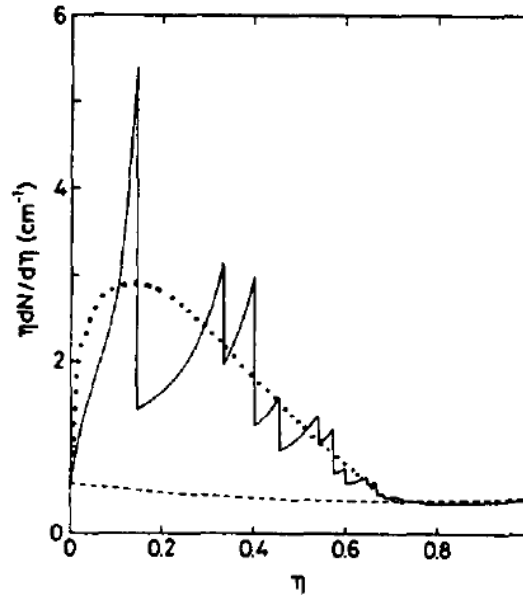


Figure 2.14: Coherent Bremsstrahlung spectrum, recorded for 10 GeV positrons and electrons incident on a pure germanium crystal kept at room temperature, with an angle of 1 mrad from the $\langle 110 \rangle$ axis [91]. The spectrum is normalized to the SB emission intensity.

2.3.4 STRONG FIELD REGIME

The description given for the Coherent Bremsstrahlung process is derived using the Born approximation, which assumes that both the incident and scattered state of an interacting charged particle are plane waves. In order for this approximation to be valid, the particle motion in the transverse plane must be weakly affected by the interactions with the crystal potential. In particular, this requires the angular oscillations in the transverse plane ($\Delta\theta$) to be smaller than the opening angle of the emission cone [76]:

$$\Delta\theta \lesssim \frac{1}{\gamma} \quad (2.34)$$

An estimation of $\Delta\theta$ is obtained using the conservation of the transverse energy and expressing the relativistic kinetic energy as in eq. (2.15):

$$\frac{p^2}{2m\gamma}\theta^2 = \frac{p^2}{2m\gamma}(\theta + \Delta\theta)^2 - U_0 \quad (2.35)$$

where θ is the incidence angle and U_0 is the lattice potential well depth. Assuming that the oscillations are small with respect to the incidence angle (i.e., $\Delta\theta \ll \theta$), it follows:

$$\Delta\theta = \frac{U_0}{mc^2\gamma} \frac{1}{\theta} \quad (2.36)$$

This result allows to rewrite eq. (2.34) in the following form [64]:

$$\theta > \frac{U_0}{mc^2} = \Theta_0 \quad (2.37)$$

The critical angle here defined (Θ_0) is the minimum incidence angle for which the Born approximation may be applied and thus the Coherent Bremsstrahlung is observed [76]. For energies greater than ~ 10 GeV and incidence angles smaller than Θ_0 , the angular oscillations of the particle are small enough for the lattice potential to be described as approximately constant. Once again, it may be shown that the resulting particle trajectory is a sequence of circular arcs, interrupted by the emission of hard synchrotron radiation: this condition is known as the Strong Field regime and the process is sometimes called magnetic bremsstrahlung [64, 95]. This is exactly the same radiative process observed for channeled electrons and positrons featuring an energy larger than ~ 1 GeV, discussed in section 2.3.2: in fact, the emission of radiation occurs in a small segment and thus it is not affected by the nature of the global trajectory. In other words, it is irrelevant to distinguish between channeled and over-barrier particles: the properties of the emitted radiation are universal and depend only on the spatial distribution of the electric field amplitude [95]. Channeling should then be considered only in the calculation of the incident particle flux at each point along a crystalline axis [91].

There are several approaches to the description of the Strong Field-enhanced bremsstrahlung process [64]: J. Lindhard proposed a method based on the application of the correspondence principle to the classical synchrotron radiation spectrum. In fact, in this way it is possible to account for the quantum recoil induced by the photon emission and the effects of the electron spin [91, 96, 97]. A more accurate model is based on the Constant Field Approximation (CFA), meaning that the electric field is considered as approximately constant along the formation length and the transverse motion of the incident particle is described by means of two-dimensional Schrödinger-like equations, corrected for the ultrarelativistic energies [64, 98]. An even more accurate technique was developed by V. N. Baier and his colleagues: this is the Baier-Katkov quasiclassical operator method, which allows to compute a number of physical quantities (e.g., the interactions cross-sections),

given an electric potential with an arbitrary spatial distribution [68–71, 95]. For instance, this method allows to evaluate the general photon emission probability as [95]:

$$\frac{dW_\gamma^g(E, \hbar\omega)}{d\hbar\omega} = W_\gamma(E, \hbar\omega) + \left(\frac{m\Theta_0}{U_0}\right)^2 W_\gamma^{(1)}(E, \hbar\omega) \quad (2.38)$$

where $W_\gamma, W_\gamma^{(1)}$ are functions which do not depend on the particle incidence angle, since the Strong Field effects are angle-independent (as long as $\theta \lesssim \Theta_0$). The first term on the right-hand side of this equation is found with the CFA approximation, while the second is a first-order correction to the CFA. An excellent agreement between these predictions and the experimentally observed radiation spectra has been found (figure 2.15): in particular, an enhancement of the bremsstrahlung probability of 10 – 100 has been observed, with respect to the SB value [64, 98]. Using the CFA, it is also possible to compute a better estimate of the spectrum critical frequency [64]:

$$\frac{\hbar\omega_c}{E} \sim \frac{\chi}{1 + \chi} \quad (2.39)$$

where, as expected, even in the limit $\chi \rightarrow \infty$, it is observed that the energy of the emitted photon is not larger than the energy of the parent electron. It can also be shown that the Strong Field parameter (χ) defined in eq. (2.30) is approximately given by [64, 68]:

$$\chi \sim \frac{U_0 \gamma \hbar c}{(mc^2)^2 a_s} \quad (2.40)$$

where a_s is the atomic screening distance and m is the electron mass. Theoretically, Strong Field effects are visible only in the condition $\chi > 1$, where the lattice electric fields are more intense than the Schwinger critical field. However, it has been found that the quantum corrections to the classical synchrotron spectrum are already visible for $\chi > 0.1$ [64]. Eq. (2.40) allows to accurately compute the minimum energy required for the observation of the SF effects. For instance, for electrons and positrons incident on the $\langle 111 \rangle$ axis in tungsten, assuming a screening length of 0.215 Å and a potential well amplitude $U_0 = 887$ eV, the condition $\chi = 1$ corresponds to an initial energy of ~ 13.6 GeV, while $\chi = 0.1$ corresponds to $E \sim 2$ GeV [55]. More details on the Strong Field effects can be found in literature [64, 68–71, 89, 95].

2.4 ELECTRON-POSITRON PAIR PRODUCTION

When a high energy photon interacts with an electromagnetic field, it may annihilate and then create a lepton-antilepton pair: this process is known as Standard Pair Production (SPP). In particular, the electron-positron pair production is related to the emission of a photon from a moving electron (SB), by the crossing symmetry (figure 2.16) [35]. The

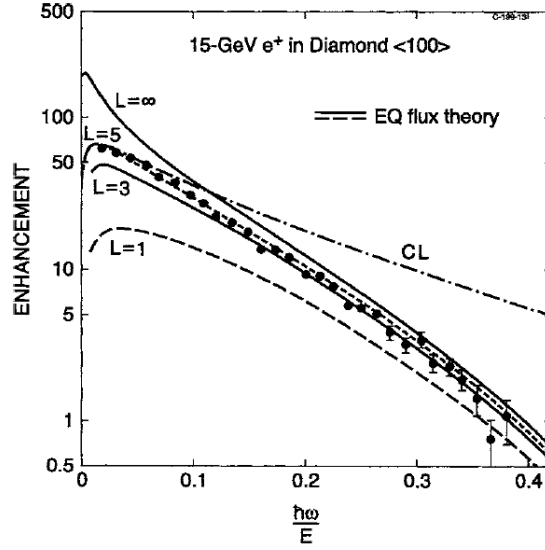


Figure 2.15: Relative enhancement of the photon emission probability for 15 GeV positrons incident on the $\langle 100 \rangle$ axis in a 80 μm diamond crystal [98]. The points are the experimental data and the lines show the values predicted with the CFA approximation, considering different pathlengths (L). The “CL” line is the classical synchrotron spectrum, which exceeds the CFA approximation in the region where the recoil of the emitting electron is larger.

differential cross-section for the electron-positron pair production is given by the Bethe-Heitler formula, which mirrors the Standard Bremsstrahlung formula [91]:

$$\frac{dN_{pp}}{d\eta} = \frac{16}{3} Z^2 \alpha r_e^2 n c \left(\frac{3}{4} - \eta + \eta^2 \right) \log \left(183 Z^{-1/3} \right) \quad (2.41)$$

where η is the ratio of the energy of the created positron (E_+) and the photon energy ($\hbar\omega$), n the density of the medium and Z, α and r_e are the same as in eq. (2.25). The electron-positron pair production is a threshold process, meaning that it is observed only for incident photons with an energy larger than $\sim 2mc^2$, where m is the electron mass; for energies beyond ~ 100 MeV, this is the dominant photon absorption mechanism [35]. The number of photons that undergo pair production in a target of thickness t is given by [35]:

$$N(t) = N_0 \left[1 - e^{-7t/9X_0} \right] \quad (2.42)$$

where N_0 is the number of incident photons and $\frac{9}{7}X_0$ is the pair production mean free path. Similarly to the SB case, it is possible to define a pair production length, namely the average distance required to transversely separate the created pair by two Compton wavelengths (i.e., $\lambda_c = \hbar/mc$, where m is the electron mass):

$$l_f^{pair} = 2\gamma_p \lambda_c \frac{2\gamma_p^2 c}{\omega} \quad (2.43)$$

where $\hbar\omega$ is the photon energy and $\gamma_p = \hbar\omega/mc^2$ is the Lorentz factor of the emitted pair. Similarly to the SB case, the opening angle of the emitted pair is $\theta_{pair} \sim 1/\gamma_p$.

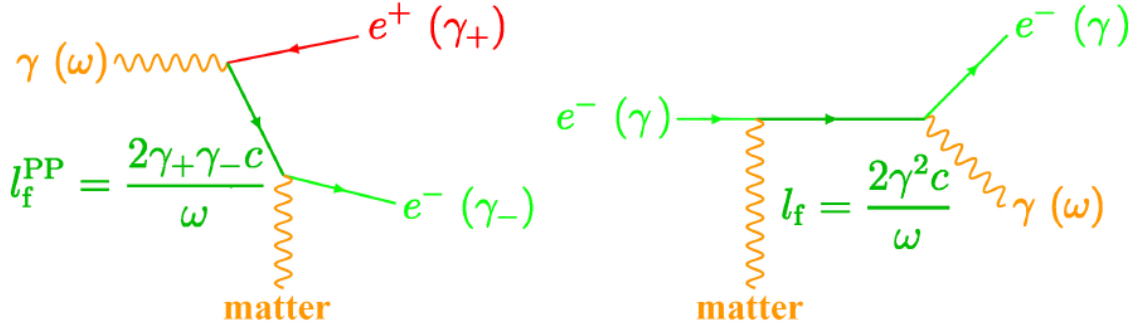


Figure 2.16: Feynman diagrams of electron-positron pair production (left) and bremsstrahlung (right).

Since photons carry no electric charge, SPP could be expected to be identical in an amorphous medium and in an oriented crystal. However, the lattice electric field is able to influence the lepton pair while it is still in the virtual state (i.e., the internal green line in figure 2.16): for this reason, the pair production probability in an oriented single crystal is larger than the SPP yield [76]. The minimum energy needed to affect the pair production process is computed by requiring that the opening angle of the emitted pair is smaller than the channeling critical angle. The following threshold energy is thus obtained [78]:

$$\hbar\omega_{\min} \sim \frac{2(mc^2)^2}{U_0} \quad (2.44)$$

where m is again the electron mass. For the $\langle 111 \rangle$ axis in a pure W crystal, $U_0 = 887$ eV [55] and thus $\hbar\omega_{thr} \sim 600$ MeV. However, a tangible enhancement of the pair production probability is actually observed when the Strong Field condition is satisfied, namely for [64]:

$$\hbar\omega_{thr} \sim \frac{\sqrt{2}u_1(mc^2)^2}{U_0\lambda_c} \quad (2.45)$$

where u_1 is the average thermal displacement of the crystal atoms in a single direction [62]. A more accurate estimate is found using the CFA, as described in [68]: a comparison of the values obtained in the two cases is shown in table 2.1. Beyond these thresholds and for incidence angles smaller than Θ_0 , the Strong Field Pair Production (SFPP) total probability, namely the integral of the corresponding differential cross-section, is found to be larger than the SPP value by a factor 10 – 100. The maximum enhancement is approximately given by [64]:

$$\max \left(\frac{N_{pp}^{CFA}}{N_{pp}^{BH}} \right) \sim \frac{U_0 m a_s d}{3Z^2 \alpha^2 \hbar^2 \log(183Z^{-1/3})} \quad (2.46)$$

where N_{pp}^{CFA} and N_{pp}^{BH} are the total SFPP and Bethe-Heitler probabilities, a_s is the screening length of the target material and d is the inter-string spacing. For high- Z materials, this result corresponds to an enhancement of the total cross-section of a factor ~ 150 and is reached for photon energies of approximately $100 \hbar\omega_{thr}$ (i.e., in the multi-TeV region) [64]. After the peak value and up to few hundreds of TeV, N_{pp}^{CFA} decreases as $(\hbar\omega)^{-1/3}$, while at even higher energies, the SFPP is suppressed by a mechanism similar to the LPM effect

[64]. In the Strong Field regime, both the CFA and the Baier-Katkov methods may be used to compute a number of quantities of interest, as described in [64, 66–71, 89, 95, 98]. For instance, figure 2.17 shows the computed pair production probability as a function of the initial photon energy, for a number of different crystalline lattices.

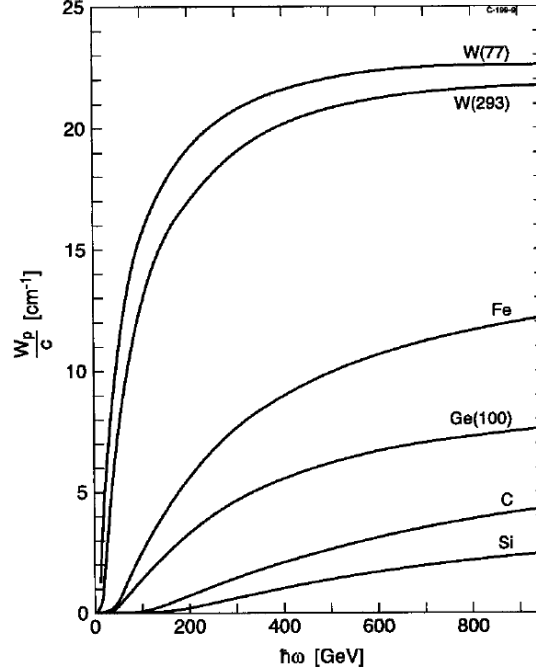


Figure 2.17: Pair production probability as a function of the energy of the photons incident on the $\langle 111 \rangle$ axis of a pure C, Si, Fe or W crystal and on the $\langle 110 \rangle$ axis of a pure Ge crystal [64]. The temperature of each crystal is assumed to be 293 K, unless differently stated on the curves (e.g., “W(77)” refers to a tungsten crystal kept at 77 K).

Material	Axis	Temperature	Estimation with eq. (2.45)	Values from [68]
Si	$\langle 110 \rangle$	293 K	102 GeV	120 GeV
Ge	$\langle 110 \rangle$	280 K	74 GeV	70 GeV
Ge	$\langle 110 \rangle$	100 K	45 GeV	50 GeV
W	$\langle 110 \rangle$	293 K	14 GeV	22 GeV
W	$\langle 110 \rangle$	77 K	8 GeV	13 GeV

Table 2.1: Comparison of the minimum photon energies required to observe a Strong Field enhancement of the pair production probability ($\hbar\omega_{thr}$) [64, 89].

Since the incident photons cannot be channeled along a crystalline axis, the results obtained with the CFA and the Baier-Katkov method are valid for every incidence angle smaller than the Strong Field threshold (Θ_0). For angles larger than Θ_0 , the spatial variations of the lattice potential are not negligible: the CFA breaks down and the enhancement of the pair production probability must be computed, as in the case of the Coherent Bremsstrahlung, with the Born approximation. The resulting process is known as Coherent Pair Production (CPP): similarly to the CB, in this regime there is a smaller but still

visible enhancement of the pair production probability, with respect to the SPP yield. More details on this process are given, for instance, in [64, 76, 89, 98].

2.5 APPLICATIONS

The study of the physical processes occurring inside the oriented crystals is interesting for a number of different reasons. On one hand, the possibility to reach electromagnetic fields strengths larger than the Schwinger critical field opens up the possibility to study QED effects which would be otherwise observable only in very exotic conditions. In fact, for a long time it was thought that such processes could be observed only in astrophysical sources (such as high energy pulsars, i.e., magnetars), or in the interactions between cosmic rays with an energy of ~ 1 PeV and the Earth magnetic field [64]. Instead, with the high-intensity particle beams currently available at the LHC, it would be possible to acquire enough statistics to study such QED effects in a relatively reasonable time [99].

There is a large number of interesting experimental applications of the Strong Field phenomena which occur in an oriented crystal. For instance, the enhanced bremsstrahlung probability could be exploited in the design of a hybrid target for a future high-intensity positron source [100]. Similarly, a photon converter based on an oriented tungsten layer could be employed in the renewed K12 beamline, which was proposed in the context of the HIKE project (section 1.2.3) [5]. Finally, it could be possible to design an innovative homogeneous e.m. calorimeter, by exploiting the combined increase of both the bremsstrahlung and the pair production probabilities (section 1.3). In fact, the Strong Field enhancement of these effects results in a reduction of the “effective” radiation length of the oriented material, with respect to the value obtained in random orientation: the same amount of material budget could thus contain an e.m. shower much more efficiently [50, 95]. An exaggerated⁶ graphical representation of this effect is shown in figure 2.18.

It is well known that an electromagnetic shower spreads out in the transverse plane, with respect to the direction of incidence of the primary particle (i.e., the longitudinal direction) [90]. This spread is usually expressed in terms of the Molière radius (R_M), namely half of the radius of the cylinder which contains, on average, 95% of the shower energy deposit [35]. The angular spread of the shower implies that, after the first few radiation lengths, all the secondary particles are scattered beyond the Strong Field angular acceptance (Θ_0). Thus, the orientation of the deeper crystalline layers inside an e.m. calorimeter would not increase the shower containment efficiency. However, it would still reduce the photon detection inefficiency, since a non interacting photon never breaks the Strong Field condition and thus is subject to the enhanced lattice field for the whole length of the active

⁶ Figure 2.18 should not be considered as a quantitative description of the development of an e.m. shower in an oriented crystal. Recent experiments have shown that a $\sim 30\%$ reduction of the radiation length is attained, when a $1 - 2 X_0$ long PbWO_4 crystal is aligned with a 120 GeV/c electron beam [56]. Moreover, it must be considered that this effect vanishes after the first few radiation lengths, due to the lateral spread of the e.m. shower.

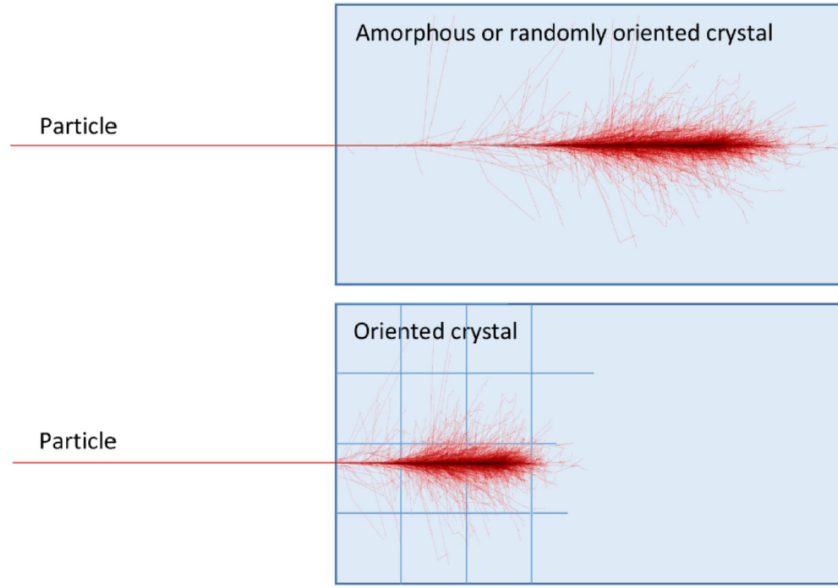


Figure 2.18: Pictorial representation of the reduction of the distance required to fully contain an e.m. shower due to the Strong Field effects [74].

material. This is the primary argument which supports the use of oriented crystals for the construction of the KLEVER Small Angle Calorimeter (section 1.3).

The current design proposed for the SAC is a “hybrid” homogeneous calorimeter, meaning that the active layers are segmented on the longitudinal axis, to allow the insertion of multiple planes of photodetectors. One of the arguments supporting this choice is the fact that the longitudinal development of the e.m. shower in an oriented crystal is different with respect to an amorphous medium. This difference may be described in terms of the depth of the shower peak ($t_{\max}$), namely the point along the longitudinal direction where the largest number of secondary particles is produced. In an amorphous medium, it is well known that $t_{\max}$ scales as the natural logarithm of the incident particle energy (E) [90]:

$$t_{\max} \sim \log \left(\frac{E}{E_c} \right) + t_0 \quad (2.47)$$

where E_c is the critical energy, $t_0 = -0.5 (+0.5)$ for electrons (photons) and $t_{\max}$ is measured in units of radiation lengths. In an oriented crystal, it has been shown that $t_{\max}$ and the shower profile are almost independent on the energy of the incident particle, within the 1 GeV–1 TeV range (figure 2.19) [55]. Thus, the sampling of the energy deposit profile could be exploited to perform Particle IDentification (PID) and distinguish photons, electrons and positrons from neutral hadrons.

Starting from the 1980s, the Strong Field phenomena have been observed in a number of experiments [64, 89]. The data acquired in such experiments allowed to confirm the validity of the theories which describe the emission of radiation inside oriented single crystals. However, the tested samples were limited in number, composition and length: in fact, most of the targets were thin ($\lesssim 0.5 X_0$) and/or composed of light materials

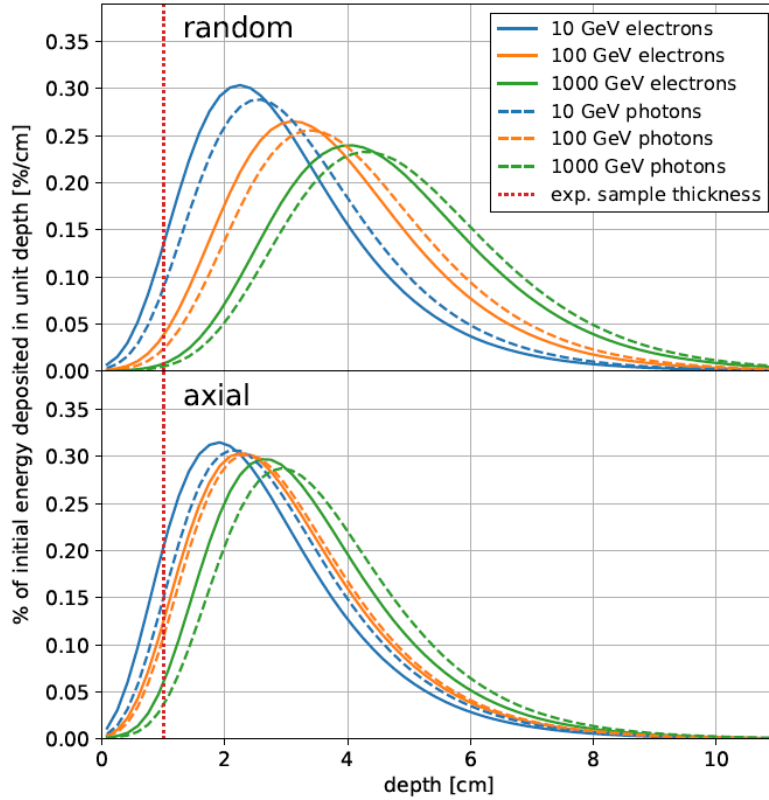


Figure 2.19: Simulation of the development of the e.m. showers initiated by electrons (continuous lines) and photons (dashed lines) inside a tungsten absorber [55]. Top: randomly oriented target. Bottom: oriented crystalline target (along the $\langle 111 \rangle$ axis).

(e.g., Si, C). Thus, the data collected in such experiments are insufficient to accurately predict the development of the e.m. shower in any practical application. For this reason, the STORM collaboration and the previous projects, namely ELIOT and AXIAL, performed a number of experiments at the CERN SPS and DESY extracted beamlines. The goal of these experiments was to characterize the enhancement of the bremsstrahlung and pair production probabilities inside the high-Z materials which are typically used in the listed applications of the Strong Field effect (e.g., tungsten, PbWO_4 , etc.). The data acquired during these years will allow:

- a more accurate theoretical understanding of the Strong Field effects in oriented single crystals;
- the development of a Monte Carlo code which allows to simulate the energy loss of an electron, positron or photon in an oriented single crystal;
- the design of proof-of-concept particle detectors and instruments based on oriented crystals in Strong Field conditions.

More details on the experiments performed by the STORM collaboration are given in [50, 51, 54–56, 87, 101–105]. A two-week long beamtest was performed in August 2021 at the CERN SPS, on the H2 line. During the first week, a $1 X_0$ and a $2 X_0$ PbWO_4 crystals were exposed to a 120 GeV/c electron beam. During the second week, the same $1 X_0$

PbWO_4 crystal and a $2 X_0$ PbF_2 crystal were exposed to a tagged photon beam. These tests allowed to study the enhancement of the bremsstrahlung and pair production probabilities in an oriented scintillating crystal and an oriented Cherenkov radiator. The main difference between these experiments and the results previously reported in literature is the fact that in 2021 the visible light produced inside two thick oriented crystals, as a result of the electromagnetic interactions, was readout with Silicon PhotoMultipliers. Thus, for the first time, the direct detection of the scintillation (Cherenkov) light was used to characterize the Strong Field effects⁷ in a crystal exposed to a beam of either high energy electrons or photons. While the results regarding the first week are described in detail in [56], this thesis focuses on the measurements performed during the second week.

⁷ The STORM collaboration reports to have successfully measured the scintillation light emitted by a thin oriented PbWO_4 crystal, in a beamtest performed in 2018 [87]. At the time of writing, the analysis of the data acquired in such beamtest have not been published yet. Thus, the reports of the results obtained in the STORM 2021 and the KLEVER 2021 beamtests are effectively the first published studies of this type.

THE KLEVER 2021 BEAMTEST AT THE CERN SPS

In August 2021 the STORM and KLEVER collaborations performed a beamtest at the CERN SPS, on the North Area H2 line, in a joint effort towards the development of the Small Angle Calorimeter for the KLEVER experiment. The first goal of this beamtest was to measure the reduction of the radiation length of two aligned single crystals in Strong Field conditions, exposed to a beam of high energy photons. The second and equally important goal was to evaluate the performances and the time resolution of the Silicon PhotoMultipliers coupled to the crystal samples.

The results obtained during this beamtest allowed to assess the feasibility of using oriented Cherenkov (or scintillating) crystals coupled to SiPMs, for the construction of the KLEVER SAC.

The crystal samples and the photodetectors are presented in the first part of this chapter, while the second part describes the experimental setup installed on the H2 line. The last section presents the results of the preliminary alignment and calibration measurements, which were performed before the physics runs. The characterization of the crystal samples and the photodetection systems are presented in [chapter 4](#) and [chapter 5](#).

3.1 BEAMTEST GOALS

The KLEVER Small Angle Calorimeter is a hybrid homogeneous calorimeter, composed of four layers of PbF_2 or PbWO_4 crystals coupled to compact and fast photodetectors, such as SiPMs or small PMTs ([section 1.3](#)). The goals of the HIKE physics programme and the high intensity of the KLEVER neutral beam impose a number of requirements on the performances of the SAC: for instance, the time resolution should be better than 100 ps for incident photons featuring an energy larger than ~ 1 GeV. Moreover, the photon detection inefficiency should be smaller than 10^{-4} , for 30 GeV photons, and the calorimeter should be as transparent as possible to neutrons and other neutral hadrons [[5](#)]. These constraints require the optimization of both the active material and the photodetection system: for the choice of the former, fully oriented crystals in Strong Field conditions are being studied, since they feature the same nuclear interaction length and a significantly smaller radiation

length than the randomly aligned crystals. Thus, a SAC with such crystals would achieve a larger photon detection efficiency, without becoming more sensitive to neutral hadrons.

At the same time, the KLEVER collaboration, together with the Muon Collider group, is developing a high-speed photodetection system, based on SiPMs readout by a custom Front-End Electronics (FEE). An important step in the development of the SAC has been the one-week long beamtest which was performed in August 2021, on the H2 line at the CERN SPS. During this beamtest, three Cherenkov radiators and a scintillating crystal (two oriented and the others randomly aligned) were exposed to a highly collimated beam of high energy photons. The following goals were pursued:

- The observation of the Strong Field enhancement of the pair production cross-section and the corresponding reduction of the radiation length in different materials.
- The measurement of the dependence of the intensity of the SF effects on the photon energy and the incidence angle.
- The measurement of the timing performances of the photodetectors coupled to the crystal samples.

These results are fundamental for the development of the KLEVER Small Angle Calorimeter.

3.1.1 THE CRYSTAL SAMPLES

During the KLEVER 2021 beamtest, the following crystal samples were exposed to a high energy photon beam:

- Two non oriented samples of β -PbF₂, each one with a total thickness along the beam axis of 40 mm ($\sim 4.3 X_0$) and a transverse area of 1 cm $\times$ 1 cm. These samples did not feature a macroscopically oriented structure and thus they were only used for the time resolution measurements and for calibration purposes (section 4.2.3).
- An oriented sample of β -PbF₂, with a thickness along the beam axis of 18.6 mm ($\sim 2 X_0$) and a transverse area of 9.3 mm $\times$ 18.6 mm. The reference axis for this sample was the $\langle 110 \rangle$ one.
- An oriented sample of standard¹ PbWO₄, with a thickness along the beam axis of 9 mm ($\sim 1 X_0$) and a transverse area of 30 mm $\times$ 30 mm. The reference axis for this sample was the $\langle 100 \rangle$ one.

The PbF₂ samples were produced by SICCAS [106] and were coupled to the CRILIN photodetection system (section 3.1.2). The PbWO₄ sample was produced by the Institute for Nuclear Problems of the Belarusian State University [107] and was coupled to the STORM photodetection system (section 3.1.2). For the measurements on the H2 line, the following mechanical supports were employed:

¹ This sample was not of the PWO-UF type.

- The PbF_2 samples were brush painted with white reflective paint except for the front face, to allow the crystals alignment, and were housed inside a prototype case (named “Proto-0”), developed by the Muon Collider collaboration for the CRILIN calorimeter (figure 3.1) [59]. Proto-0 is a light-tight case made of common acrylonitrile butadiene styrene plastic, which provides a stable mechanical support for up to two $1\text{ cm} \times 1\text{ cm}$ crystals, along with their photodetectors (section 3.1.2).
- The PbWO_4 sample was coated with a white reflective paint and mounted on a custom holder structure, which was covered with a black light-tight case (figure 3.2).

The relative angle between the axes of the crystals and the incidence direction of the photon beam was controlled with a high precision goniometer (section 3.2.6). The main features of the crystal samples are summarized in table 3.1. Table 3.2 presents the physical and crystallographic parameters of $\beta\text{-PbF}_2$ and PbWO_4 , while figure 3.3 shows their lattice structures.

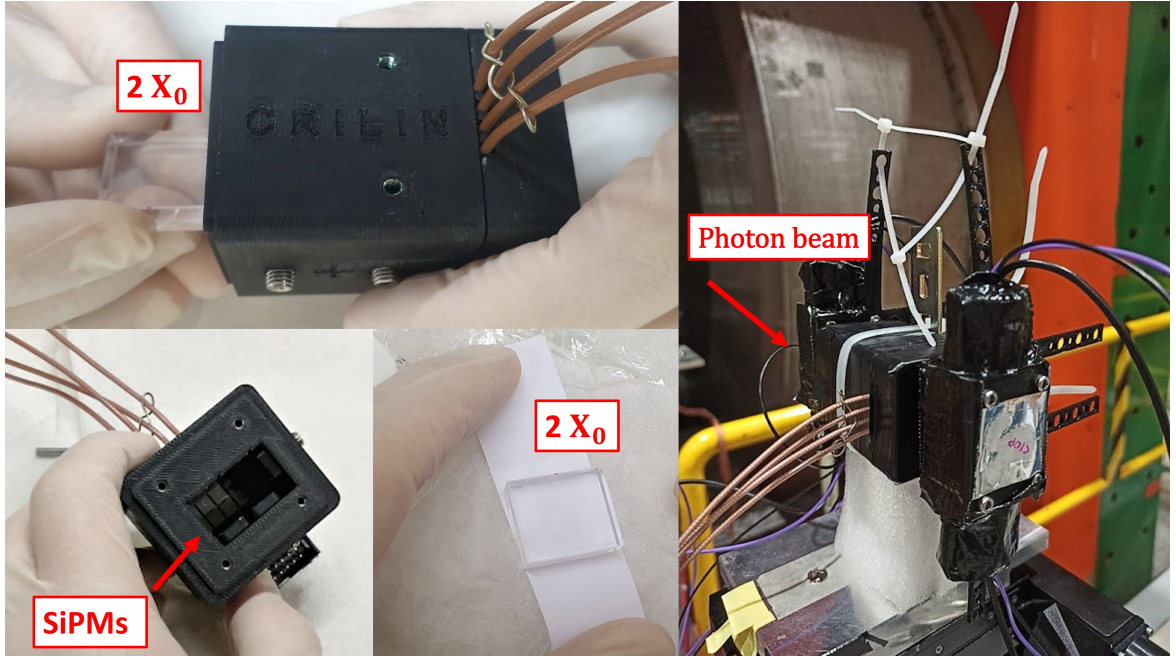


Figure 3.1: Left: photos of the Proto-0 prototype case (CRILIN) and the oriented PbF_2 crystal sample. Right: mechanical support of Proto-0 on the H2 line.

The data reported in table 3.2 show that the potential generated by the PbWO_4 $\langle 100 \rangle$ axis is larger than the potential of the PbF_2 $\langle 110 \rangle$ axis. This implies that the SF induced enhancement of the pair production cross-section should be larger in PbWO_4 than in PbF_2 . In the KLEVER 2021 beamtest, this enhancement was measured for both crystals considering the relative increase of the following observables:

- The multiplicity of the charged particles exiting the crystals.
- The “missing energy”, namely the difference between the energy of the photons impinging on the crystals and the total energy of all the particles exiting from the samples.

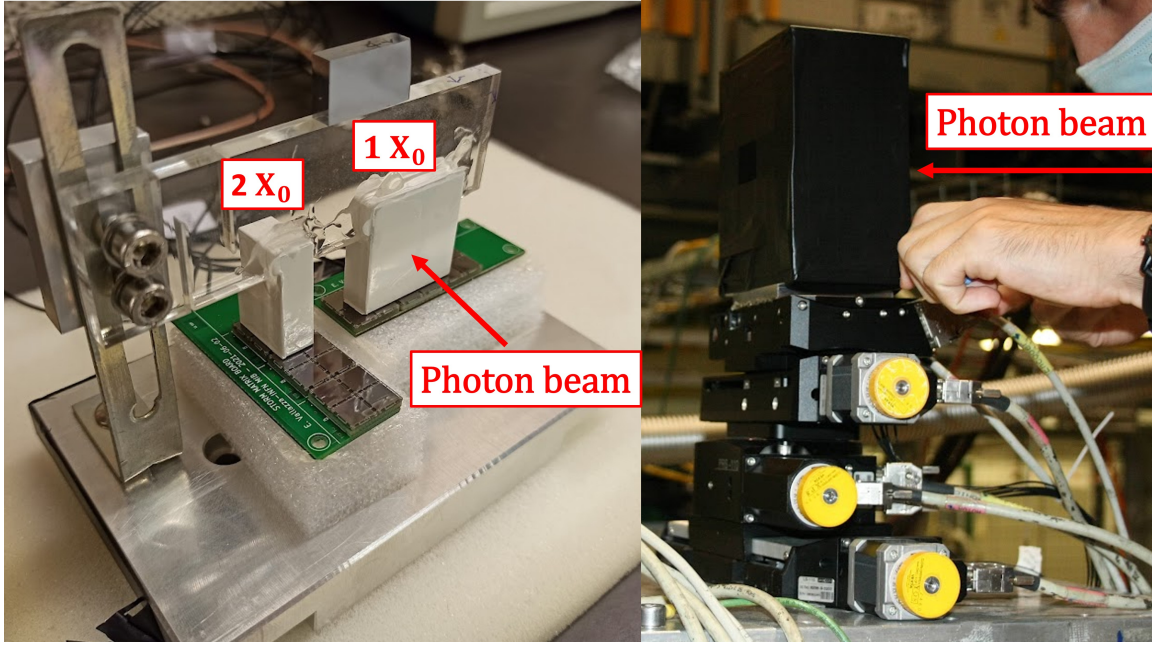


Figure 3.2: Left: the $1 X_0$ PbWO_4 crystal is coupled to the STORM photodetection system and mounted on the mechanical holder. Right: the crystal is placed on the goniometer and covered with a light-tight case.

Parameter	Samples		
Material	$\beta\text{-PbF}_2$	$\beta\text{-PbF}_2$	PbWO_4
Number of samples	2	1	1
Length along the beam axis	$\sim 4.3 X_0$	$\sim 2 X_0$	$\sim 1 X_0$
Transverse thickness	$1 \text{ cm} \times 1 \text{ cm}$	$9.3 \text{ mm} \times 18.6 \text{ mm}$	$9 \text{ mm} \times 9 \text{ mm}$
Producer	SICCAS	SICCAS	INP
Reference axis	[not oriented]	$\langle 110 \rangle$	$\langle 100 \rangle$
Photodetection system	CRILIN	CRILIN	STORM

Table 3.1: Crystal samples studied in the KLEVER 2021 beamtest.

- The intensity of the scintillation (Cherenkov) light emitted inside the crystals.

While the first two observables represent the standard way to characterize the SF effects in an oriented crystal, the third is a novelty (section 2.5). In fact, only the STORM collaboration has ever reported a characterization of the SF effects by directly detecting the scintillation light produced inside an oriented crystal [56, 103, 111]. This measurement was performed in the STORM 2021 beamtest, where two oriented crystals were exposed to a 120 GeV/c electron beam [56]:

- The $1 X_0$ PbWO_4 sample which was tested also with the photon beam in the KLEVER 2021 beamtest (table 3.1).
- A $2 X_0$ PbWO_4 sample produced by Moltech [112]. The reference axis for this sample was the $\langle 001 \rangle$ one.

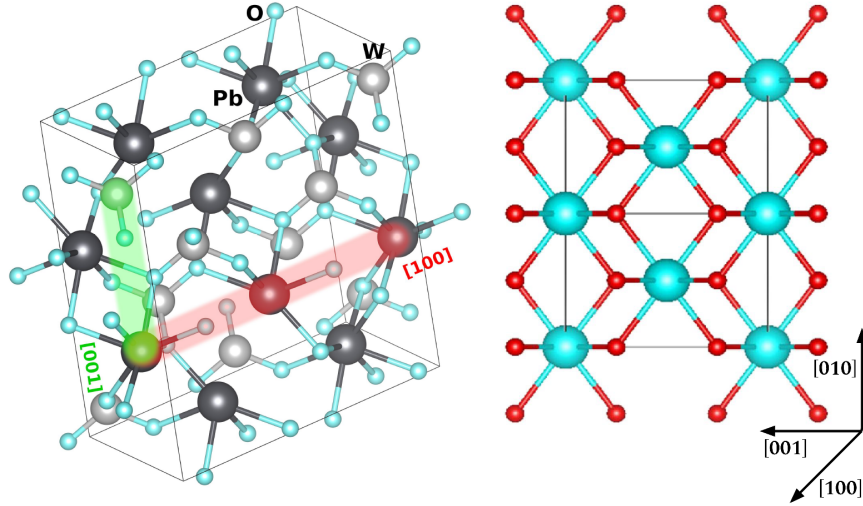


Figure 3.3: Lattice structures of the oriented crystals studied in the KLEVER 2021 beamtest. Left: PbWO_4 , which features a scheelite-type structure, characterized by a tetragonal lattice [50, 56]. Right: PbF_2 , which features a Body Centered Cubic (BCC) lattice [74].

The spectra of the energy deposited inside these crystals by the electron beam are shown in figure 3.4. These data may be used as a benchmark to test the consistency of the results obtained in the KLEVER 2021 beamtest. In fact, due to the symmetry between the bremsstrahlung and the pair production processes, the relative increase of the scintillation light emitted in the $1 X_0$ PbWO_4 sample should be identical, for an incident electron or photon beam with the same energy. Moreover, the relative increase of the scintillation (Cherenkov) light emitted in the $2 X_0$ PbWO_4 sample should be comparable with the increase measured in the PbF_2 sample, since they feature the same length and similar axial potentials. Thus, the results obtained in the two beamtests will provide a complete characterization of the SF effects in a light emitting high-Z oriented crystal with a thickness of $1 - 2 X_0$.

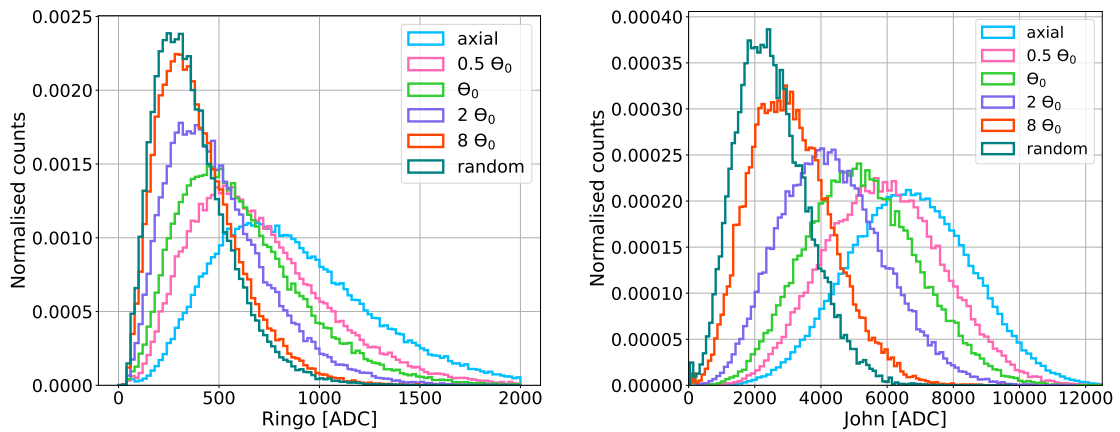


Figure 3.4: Pulse Height spectra of a SiPM matrix coupled to an oriented crystal exposed to a 120 GeV/c electron beam [56]. Left: the $1 X_0$ PbWO_4 sample described in table 3.1, with the beam aligned on the $\langle 100 \rangle$ axis. Right: a $2 X_0$ PbWO_4 sample, with the beam aligned on the $\langle 001 \rangle$ axis.

Physical parameters [35]		
Parameter	PbF ₂	PbWO ₄
Density (ρ)	7.78 g/cm ³	8.30 g/cm ³
Relative mass fractions	Pb: 84.6 %	Pb: 45.6 %
	F: 15.5 %	W: 40.4 %
		O: 14.0 %
Minimum ionization (ε_{MIP})	9.34 MeV/cm	10.20 MeV/cm
Radiation length (X_0)	0.94 cm	0.89 cm
Nuclear interaction length (λ_{int})	22.10 cm	20.27 cm
Critical energy for electrons (E_c)	9.35 MeV	9.64 MeV
Molière radius (R_M)	2.12 cm	1.96 cm
Crystallographic parameters		
Parameter	PbF ₂	PbWO ₄
Lattice structure	Body Centered Cubic [108]	Tetragonal [50]
Reference axis	$\langle 110 \rangle$	$\langle 100 \rangle$
Interatomic pitch (d)	4.19 Å [109]	5.45 Å [110]
Effective screening length (a_{eff})	0.205 Å	0.218 Å
Axial potential well depth (U_0)	332 eV	464 eV [74]
θ_c for 10 GeV/c electrons	0.257 mrad	0.305 mrad
θ_c for 100 GeV/c electrons	0.081 mrad	0.096 mrad
Θ_0	0.650 mrad	0.908 mrad
χ for 10 GeV/c electrons	0.240	0.314
χ for 100 GeV/c electrons	2.400	3.140
Electron energy such that $\chi = 0.1$	4.166 GeV	3.184 GeV
Electron energy such that $\chi = 1.0$	41.659 GeV	31.844 GeV

Table 3.2: Physical and crystallographic parameters of the crystal samples tested in the KLEVER 2021 beamtest. The effective screening lengths of the crystals were computed as the weighted average of the screening length of each atom in the mixture, with the weights being the atomic relative mass fractions. The screening lengths of the single atoms (with an atomic weight Z) were computed as $a_s = 0.215 \text{ Å} \cdot \sqrt[3]{Z/74}$ [62]. The axial channeling critical angles (θ_c) were computed by means of eq. (2.18). The PbF₂ potential well depth was computed using the method described in [109]. The Strong Field critical angles were computed by means of eq. (2.37). The χ factors were computed by means of eq. (2.40), assuming as screening lengths the previously computed values of a_{eff} . The electron energies for which χ assumes a fixed values were computed inverting eq. (2.40).

3.1.2 THE PHOTODETECTORS

Due to the high intensity of the HIKE kaon beam, the SAC must feature a time resolution better than 100 ps, for the detection of photons with an energy larger than ~ 1 GeV (section 1.3). This requirement could be well satisfied by a photodetection system based on SiPMs, which are solid state light detectors composed of several thousands of microcells (pixels), integrated on a common substrate and connected in parallel to a single output (figure 3.5) [113]. Each pixel is a Single-Photon Avalanche Diode (SPAD), namely a re-

versely biased $p - n$ junction in the Geiger-Muller regime, a few Volts above the breakdown voltage (V_{bd}). In this condition, the electric field generated in the junction depletion layer is large (i.e., of the order of 10^5 V/cm). Thus, the absorption of a photon in the silicon matrix produces a free electron-hole pair, which can trigger a self-sustaining avalanche [114]. The same process is caused if a charge is produced due to a thermal excitation. The avalanche stops when the current produced by the SPAD and flowing through a quenching resistor is large enough to lower the bias voltage below the breakdown value, thus turning off the detector. The bias voltage must then be restored, in order to allow the detection of another photon: during this time interval, the detector is effectively blind.

The trigger of a single SPAD in the SiPM matrix is enough to produce a detectable output signal. Since each pixel is connected to the same output, the simultaneous detection of more than one photon produces a current spike whose amplitude is given by the product of the number of triggered cells (N) and the amplitude of the output current of a single cell. The relation between the number of incident photons (N_{ph}) and the number of fired cells is [115]:

$$N = N_0 \left[1 - \exp \left(-\frac{N_{ph} \cdot \text{PDE}}{N_0} \right) \right] \quad (3.1)$$

where N_0 is the number of available pixels and the Photon Detection Efficiency (PDE) is a parameter of the SiPM, which depends on the silicon quantum efficiency, the probability of triggering an avalanche and the geometrical fill factor of the sensor [113, 115].

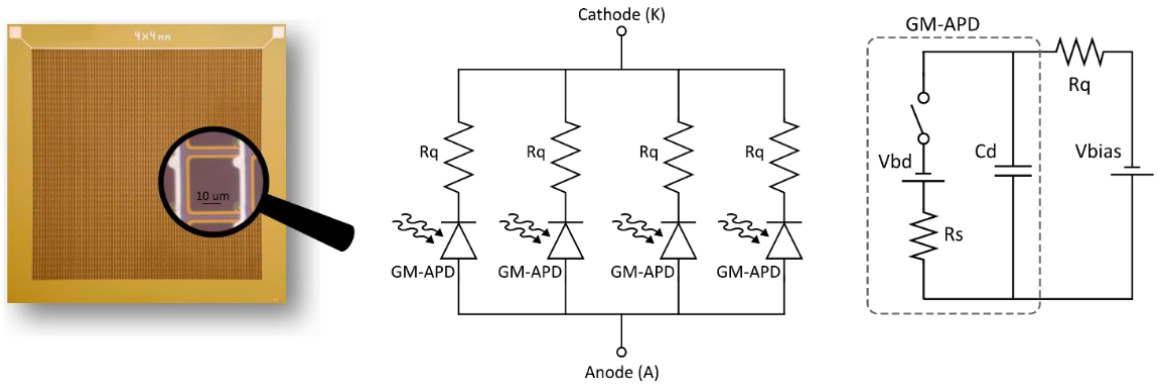


Figure 3.5: Left: picture of a $4 \text{ mm} \times 4 \text{ mm}$ SiPM matrix [116]. Center: parallel connection of the SPADs (GM-APD, i.e., Geiger-Muller Avalanche Photodiode) in a SiPM [116]. Right: equivalent circuit of a SPAD, connected in series with a quenching resistor and an external bias [116].

The SiPM technology has evolved significantly during the last few decades. Nowadays, SiPMs are widely used in a variety of fields, since they are compact and reliable photodetectors and require a small bias voltage [113, 114]. Due to the large dynamic range, the optimal time resolution and the insensitivity to the magnetic fields, they are witnessing an increasingly wide-spread use in particle and nuclear physics [117], for instance in the detection of the scintillation (Cherenkov) light emitted by a high-Z crystal. Thus, they represent an optimal choice for the photodetection system of the KLEVER Small Angle

Calorimeter. A detailed review of the features and performances of SiPMs is given in [113, 114, 117, 118].

Previous studies have shown that a SiPM coupled to a scintillator may reach a time resolution smaller than 50 ps [119]. However, in order to satisfy the requirements of the KLEVER SAC, a careful optimization of both the SiPMs parameters and the FEE is necessary. In fact, the time resolution of a SiPM + FEE chain depends on [118, 120, 121]:

- The junction capacitance of the SiPM, which is proportional to the total active area and is inversely proportional to the time resolution.
- The overvoltage (V_{ov}), namely the difference between the bias voltage and V_{bd} . A large overvoltage increases the magnitude of the electric field in the depletion region of the SiPM and thus leads to a faster development of the avalanche process.
- The number of cells triggered in a single event (N_{pe}), since the time resolution is proportional to $1/\sqrt{N_{pe}}$.
- The rise time of the SiPM output signals.
- The way the analog signals produced by the SiPMs are processed and the speed of the processing circuits.

It has been shown that, for a SiPM coupled to a scintillating crystal, the dependence between the time resolution (σ_t) and the energy deposited in the silicon matrix (E) is non linear [122, 123]. In particular, the following parametrization has been suggested:

$$\sigma_t(E) = \frac{a}{\sqrt{E}} \oplus c \quad (3.2)$$

where a and c are the parameters of the model, namely the stochastic term and the constant term, and E is measured in GeV. This expression is similar to the energy resolution of an electromagnetic calorimeter, without considering the b/E term [90]. In the case of the time resolution, the stochastic term is related to the intrinsic fluctuations of the e.m. shower² and also to the rise time of the electronics output signals [124]. The constant term is related to the intrinsic limits of the photodetection system and may increase in a detector with many readout channels, due to the intercalibration errors. Thus, for the development of the SAC, it is necessary to measure both parameters: a should be smaller than $100 \text{ ps} \cdot \text{GeV}^{1/2}$ and c should be as small as possible.

During the KLEVER 2021 beamtest, the following photodetectors and FEE chains were coupled to the crystal samples:

- A prototype of the readout system which is being developed for the CRILIN calorimeter, in the framework of the Muon Collider project [125–127]. This system was used to readout the Cherenkov light emitted by the PbF_2 samples (figure 3.6). Each

² These fluctuations are negligible for the Cherenkov radiators such as PbF_2 , but not for the scintillators, due to the presence of components with different time constants.

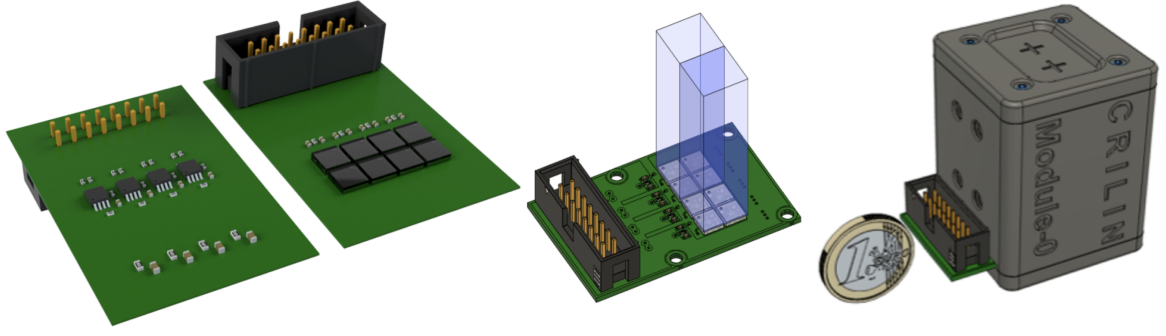


Figure 3.6: CAD rendering of the Proto-0 prototype case readout board [124].

1 cm $\times$ 1 cm crystal³ was coupled to a square matrix of 4 surface-mounted UV-extended SiPMs (S14160-4050HS model, from Hamamatsu, table 3.3) [128]. These SiPMs were connected in two series of 2 photosensors each, thus halving the equivalent capacitance of the detectors and achieving a better time resolution [119]. Since the active area of each SiPM is 4 mm $\times$ 4 mm, the use of 4 SiPMs for the readout of a single crystal assures the coverage of the whole crystal surface. Each series of 2 SiPMs was connected to an independent low-noise amplification stage, followed by a pole-zero cancellation circuit and a second non-inverting stage, implemented on a custom Printed Circuit Board (PCB) [59, 124]. The amplified and shaped signals produced by each series could be further amplified, with a gain factor of either 1x or 9x and then they were separately readout and digitized (section 3.2.10). This FEE chain was designed to minimize the rise time of the SiPMs signals and to maximize the time resolution of the system.

In all the measurements performed on the H2 beamline, the SiPMs were biased at 40.5 V, corresponding to an overvoltage of 2.5 V. The characterization of the oriented PbF₂ sample was performed setting the adjustable gain of two channels to 1x and the other two to 9x. In the time resolution measurements performed with the non oriented PbF₂ samples, all the adjustable gains were set to 1x.

Before the KLEVER 2021 beamtest, this readout system was characterized at the BeamTest Facility (BTF) of Laboratori Nazionali di Frascati (LNF). More details about these tests and the CRILIN readout system are given in [57, 59, 125–127].

- The STORM photodetection system was used to readout the scintillation light emitted by the PbWO₄ sample (figure 3.7). It consists of 3 arrays of SiPMs (ARRAYC-60035-4P model, from Onsemi) [130]. Each array is composed of a 2 $\times$ 2 matrix of individual 60035 C-Series sensors, which are low-noise, blue-sensitive and high gain SiPMs, with an active area of 6 mm $\times$ 6 mm (table 3.3) [129]. Each SiPM is surface-mounted on a 14.2 mm $\times$ 14.2 mm PCB. The three arrays were assembled on a custom readout board (Insulab laboratory, figure 3.7), by SCEN S.r.l. [131]. The board provides the bias to all the arrays and allows to readout separately the three analog output signals.

³ The oriented PbF₂ was instrumented with two square matrices of 4 SiPMs each, since it features a transverse area of 9.3 mm $\times$ 18.6 mm.

Parameter	S14160-4050HS [128]	60035 C-Series [129]
Photosensitive area	4 mm × 4 mm	6 mm × 6 mm
Pixel pitch	50 μ m	35 μ m
Number of pixels	6331	18980
Geometrical fill factor	74%	64%
Breakdown voltage (V_{bd})	38	26
Recommended operating bias	$V_{bd} + 2.7$ V	$V_{bd} + 2.5$ V
Terminal capacitance	900 pF	3400 pF
Peak sensitivity wavelength	450 nm	420 nm

Table 3.3: Features of the SiPMs used in the CRILIN and STORM photodetection systems.

In all the measurements performed on the H2 beamline, the SiPMs were biased at 30 V, corresponding to an overvoltage of 4 V. Before the KLEVER 2021 beamtest, this readout system was characterized at the Insulab laboratory and in the STORM 2021 beamtest. More details about these tests and the STORM readout system are given in [56, 103, 111].

Both the CRILIN and STORM photodetection systems were kept at room temperature in all the measurements performed on the H2 beamline.

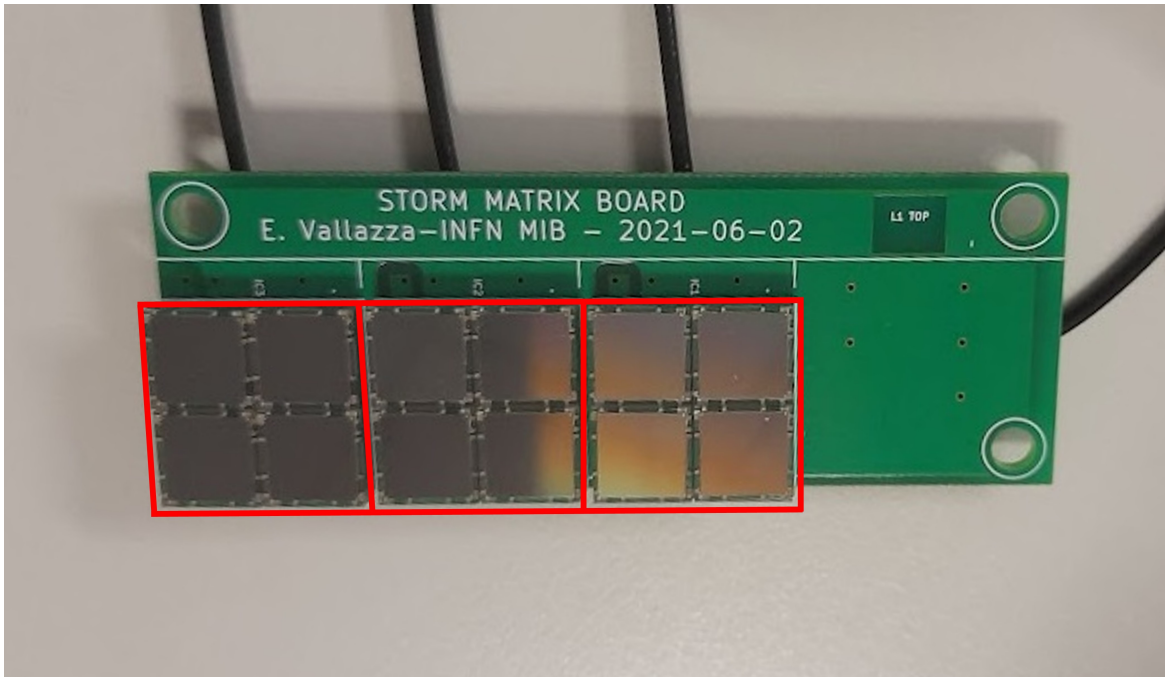


Figure 3.7: The STORM photodetection system, consisting of three arrays of 2×2 SiPM matrices connected to a readout board

3.2 THE EXPERIMENTAL SETUP

The KLEVER 2021 beamtest was performed on the North Area H2 extracted beamline, at the CERN Preveessin site (figures 3.8 and 3.9). This is a multi-purpose facility, where fixed target experiments may be temporarily installed. The beam which can be delivered to such experiments is either the primary SPS proton beam, featuring a momentum of 400 GeV/c, or a mixed hadron beam, with a momentum of 10 – 400 GeV/c [132]. It is also possible to produce tertiary electron beams with a variable purity (10% – 99.5%), an energy of 20 – 120 GeV and a $\Delta p/p$ acceptance of 2% [133]. Moreover, high energy muon beams may be generated, by dumping a secondary hadron beam on a thick collimator and exploiting the $\pi \rightarrow \mu$ decay [134]. The beam composition and the features of the transported particles, namely the momentum and the polarity, are a function of the configuration of the target station, the collimator settings and also the materials present in the beamline. More details about the H2 beamline are given in [132–134].

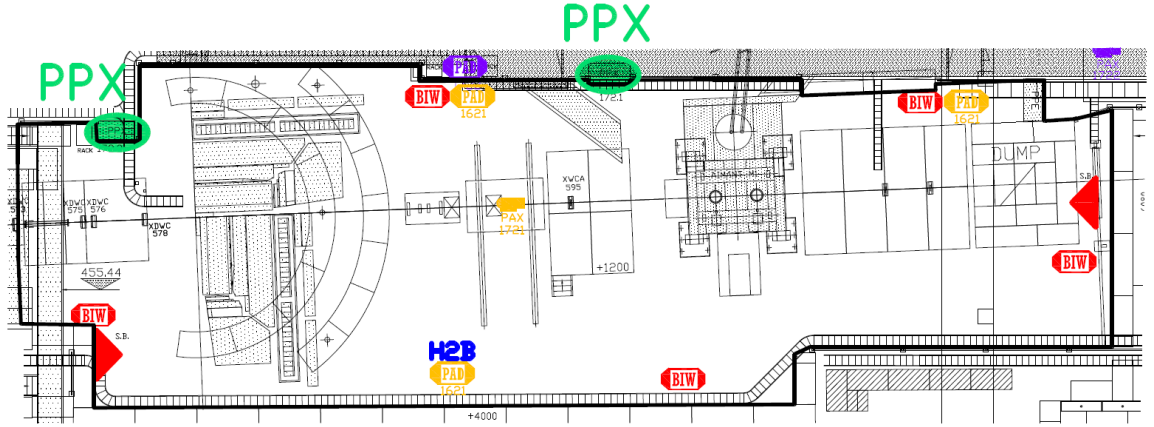


Figure 3.8: Layout of the experimental area of the H2 extracted beamline [133]. The beam is delivered along the horizontal line placed in the middle of the picture, from left to right.



Figure 3.9: The experimental hall of the H2 beamline, viewed from above. In the picture, the beam goes from right to left.

3.2.1 GENERAL OVERVIEW

Figure 3.10 presents a simplified scheme of the experimental setup installed on the H2 line. The following detectors were placed on the beamline, in order of position:

- A Plastic Scintillator Trigger (PST), which generates the trigger (section 3.2.2).
- Two silicon telescopes (T1 and T2), which are double-sided silicon strip detectors (section 3.2.3), used to reconstruct the trajectories of the incident particles.
- A Micro-Channel Plate detector (MCP), which was used to produce the reference timestamp for the time resolution measurements (section 3.2.4).
- A Bremsstrahlung Target (BT), composed of a 1 mm thick copper foil ($\sim 0.07 X_0$) with a transverse area of $10 \text{ cm} \times 10 \text{ cm}$, which was used to produce a beam of tagged photons.
- A silicon chamber (C1), which is composed of two single-sided silicon strip detectors in a $x - y$ configuration (section 3.2.3).
- A bending dipole magnet, which was used to horizontally sweep the electron beam (section 3.2.5).
- The crystal sample under study, mounted on a remotely-controlled goniometer (section 3.2.6) and coupled to the SiPMs and the FEE.
- A Multiplicity Counter (MC), consisting in a plastic scintillator coupled to a PMT (section 3.2.7).
- A silicon chamber (C2), identical to C1 and used as a multiplicity counter.
- A homogeneous BGO calorimeter (γ CAL), used to measure the energy of the particles exiting from the crystal samples (section 3.2.8).
- An electron spectrometer (eCAL), composed of a shashlik lead-scintillator sampling calorimeter and seven homogeneous Lead Glass (LG) calorimeters, used to measure the energy of the deflected electrons and thus to tag the photon energy (section 3.2.9).

In order to minimize the interactions of the electron beam with the air, vacuum beampipes were placed between the elements of the setup. More details on the components of this setup are given in the following sections and in [105, 135].

3.2.2 THE PLASTIC SCINTILLATOR TRIGGER

The trigger of the setup Data AcQuisition (DAQ) system was provided by two plastic scintillators (S1 and S2), which feature a thickness of 7 mm and a transverse area of $4 \text{ mm} \times 9 \text{ mm}$. Both scintillators are mounted on the front face of the first silicon telescope (T1, figure 3.11) and readout by standard high voltage PMTs. A hole is drilled in the

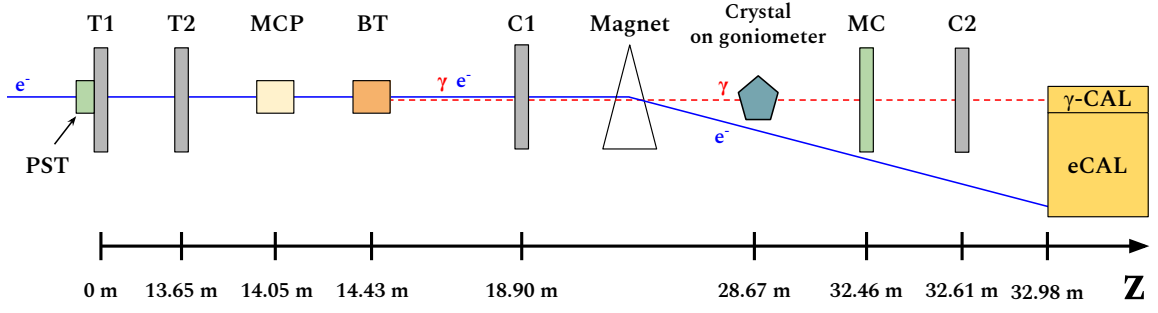


Figure 3.10: Experimental setup installed on the H2 extracted beamline. The labeling notation used here is described in the text. The reported distances were measured from the center of T1 to the center of each element.

center of the S2 scintillator, with a transverse area of $3.5 \text{ mm} \times 9 \text{ mm}$. For the majority of the data taking runs, the trigger was given by the following coincidence:

$$S1 \wedge \overline{S2} \wedge \text{spill} \quad (3.3)$$

where $S1 \wedge \overline{S2}$ is the anti-coincidence between the S1 and S2 signals and “spill” is the digital signal produced by the accelerator monitoring system, which warns that a bunch of particles has been extracted from the SPS ring and injected in the H2 line. This choice allows to trigger the DAQ system only when the charged particles cross the S2 hole, thus collimating the beam and defining a maximum beam spot size, increasing the collected statistics in the region of interest. A different trigger condition was used in the preliminary measurements performed before the physics runs (section 3.3) and also in the measurements of the CRILIN time resolution, using only the S1 signal:

$$S1 \wedge \text{spill} \quad (3.4)$$

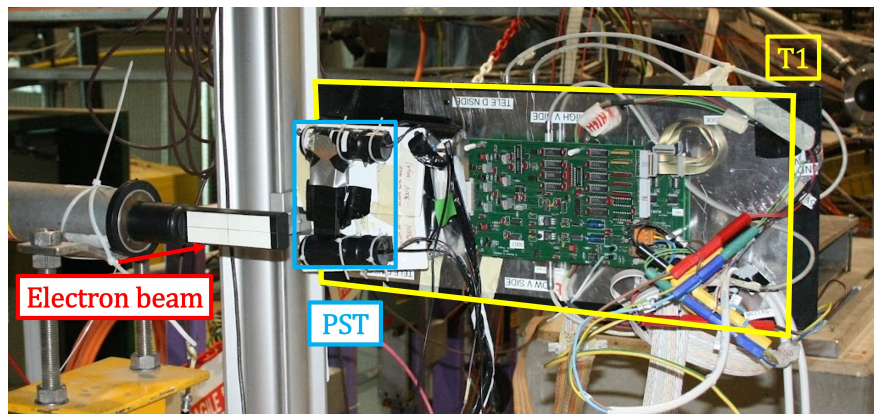


Figure 3.11: The S1 and S2 plastic trigger scintillators (PST, light blue), mounted on the T1 silicon telescope (yellow).

3.2.3 THE TRACKING SYSTEM

The tracking system was located in the upstream region of the beamline and was composed of two $x - y$ beam telescopes (T1, T2), which are 300 μm thick, 1.92 cm $\times$ 1.92 cm, double-sided silicon microstrip detectors [136]. The junction side features 384 strips, with a readout pitch of 50 μm and an implant pitch of 25 μm : a floating strip readout is exploited⁴ and only half of the strips are actually read. The ohmic side features 384 strips, with a readout and implant pitch of 50 μm . Both detectors are fully depleted when a bias voltage of 36 – 54 V is applied. The spatial resolution of the junction and ohmic side are respectively of $\sim 5 \mu\text{m}$ and $\sim 10 \mu\text{m}$ [136]: thus, the silicon telescopes reconstructed the incidence angles of the charged particles with an angular resolution of $\sim 1 \mu\text{rad}$. Moreover, the small thickness along the beam direction minimized the multiple Coulomb scattering of the beam particles.

The detectors are readout by three radiation-tolerant VA2 Application Specific Integrated Circuits (ASICs), each one featuring 128 channels and built with the 1.2 μm N-well Complementary Metal-Oxide Semiconductor (CMOS) technology. Each ASIC channel consists of a low-noise preamplifier, a shaper and a sample & hold circuit [136]. The readout is a multiplexed one, with a maximum clock rate of 10 MHz. The detectors and the ASICs are glued onto a ceramic hybrid, mounted on a fiberglass frame and contained in a steel box. The frontend electronics circuits and the ADC boards are mounted on the outer side of the box. These telescopes and the readout electronics are described in [136]. The T1 telescope is shown in figure 3.11 and in figure 3.12, on the left.

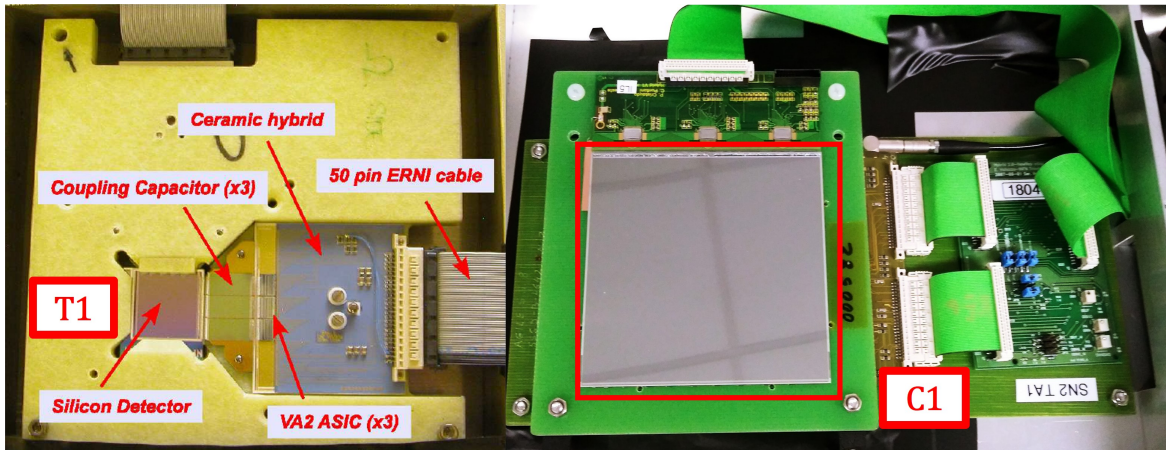


Figure 3.12: A silicon telescope [138] (left) and a silicon chamber (right), coupled to the readout ASICs.

After the telescopes, the electron beam crossed the MCP detector (section 3.2.4) and the 0.07 X_0 thick copper target (BT), thus producing a secondary photon beam. A large area

⁴ Each strip is capacitively coupled with the neighboring ones, through the interstrip capacitance. This means that the charge produced by the deposited energy is shared among multiple strips: it is thus possible to readout only half of the channels, reducing the power consumption and the data size, while achieving the same spatial resolution [137].

silicon strip detector (C1) was placed after BT, to reconstruct the trajectory of the exiting particles. This detector is one of the AGILE beam chambers and is composed of two single-sided silicon planes arranged in a $x - y$ configuration, with a thickness of $410\ \mu\text{m}$ and an active area of $9.5\ \text{cm} \times 9.5\ \text{cm}$ (figure 3.15) [139]. Each plane features a total of 384 strips, with a physical pitch of $121\ \mu\text{m}$ and a readout pitch of $242\ \mu\text{m}$. The detectors are fully depleted when a bias voltage of $36 - 54\ \text{V}$ is applied. Each silicon plane is readout by three low noise TA1 ASICs, each one featuring 128 channels and built with the $1.2\ \mu\text{m}$ N-well CMOS technology. Each ASIC channel consists of a charge sensitive preamplifier, followed by a slow shaper, a sample & hold circuit and a level sensitive discriminator [140]. The readout is a multiplexed one, with a maximum clock rate of $10\ \text{MHz}$. The ASICs and the silicon tiles are glued onto a fiberglass support (figure 3.12 on the right). The spatial resolution of each side of the silicon chamber is $\sim 30\ \mu\text{m}$ [140]. More details about the AGILE silicon chambers are given in [139, 140].

3.2.4 THE MICRO-CHANNEL PLATE

Before the bremsstrahlung target, a Micro-Channel Plate PMT detector (MCP, or MCP-PMT) was located. It is an array of $\sim 8\ \mu\text{m}$ electron channels, carved out of a lead glass matrix [141]. Each channel is a compact and independent electron multiplier with a very high gain ($\sim 10^6$), coupled to a photocathode and an anode (figure 3.13). When the photocathode region of the MCP is ionized, the extracted charges are multiplied in the microchannels and then readout by the anode: the fast multiplication process allows to achieve an optimal time resolution [142].

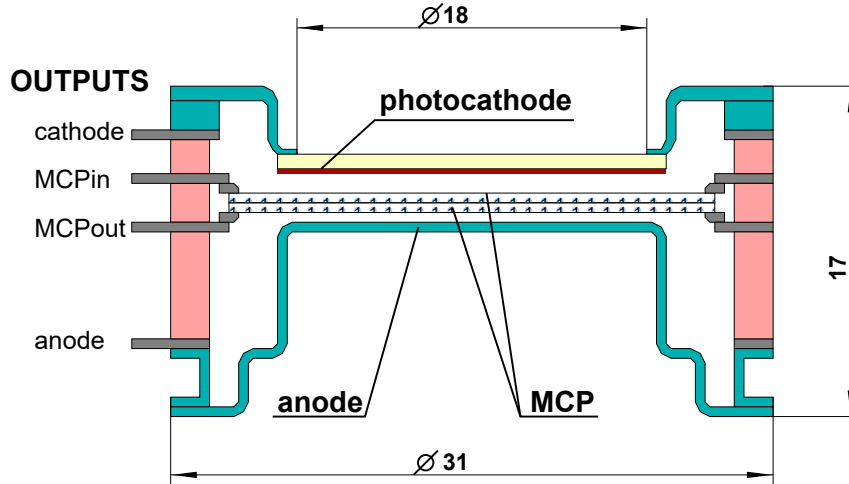


Figure 3.13: Scheme of the MCP detector [143, 144].

The MCP detector used on the H2 line was developed by the Budker Institute of Nuclear Physics [145] [146]. This detector is composed of two Micro-Channel Plates, each one consisting of a $18\ \text{mm}$ circular multialkali photocathode, two microchannels layers and a common anode [144, 146]. Each photocathode is coupled to a different $6\ \text{mm}$ thick disc of

plexiglas (with a 18 mm diameter), used as Cherenkov radiator: the Cherenkov photons produced by the impinging electron beam are multiplied in the MCP-PMT, to produce the output signal. The two MCP-PMTs are housed in a steel box with two thin borosilicate windows, to allow the passage of the electron beam (figure 3.14). The MCPs were biased at 3000 V, which corresponds to a nominal gain of $\sim 10^7$ [143]. These MCPs have a time resolution of ~ 35 ps, which makes them a perfect time reference for the SiPM time resolution measurements [146]. More details about this MCP detector are given in [144, 146, 147].

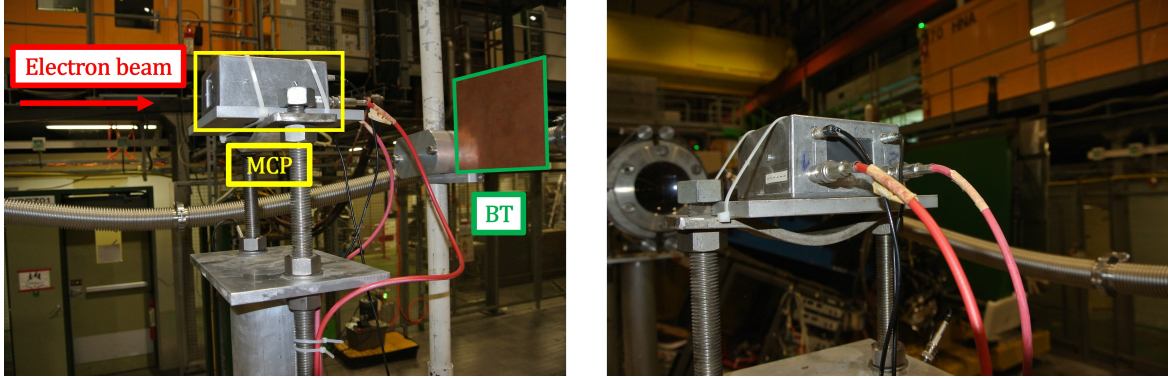


Figure 3.14: Left: MCP detector and the copper target (BT) mounted on the H2 beamline. Right: back view of the MCP detector.

3.2.5 THE BENDING MAGNET

When the electron beam hits the BT target, a secondary photon beam is produced. The exiting mixed beam crosses the C1 tracking detector and enters the square gap of the bending dipole magnet (figure 3.15), which is 2 m long and 11 cm $\times$ 11 cm wide. At the maximum operating current (850 A), the dipole magnet generates a 4.05778 T $\cdot$ m magnetic field, oriented along the y axis [148]. Thus, the magnetic field deflects the electron beam towards an electron spectrometer (section 3.2.9). The photon beam is not affected by the magnetic field and impinges directly on the crystal samples, which were mounted on a goniometer, placed 7.11 m after the edge of the gap of the dipole magnet.

3.2.6 THE GONIOMETER

The characterization of the Strong Field effects inside an oriented crystal requires to accurately control the relative angle between the beam incidence direction and the axes of the sample. The system used for this goal was based on a high precision goniometer, onto which the crystal samples were glued (figure 3.16). The goniometer was placed on a remotely-controlled XSCA table, with two translational degrees of freedom, along the x and y axis. The goniometer is composed of four different stages (figure 3.16) [149]:

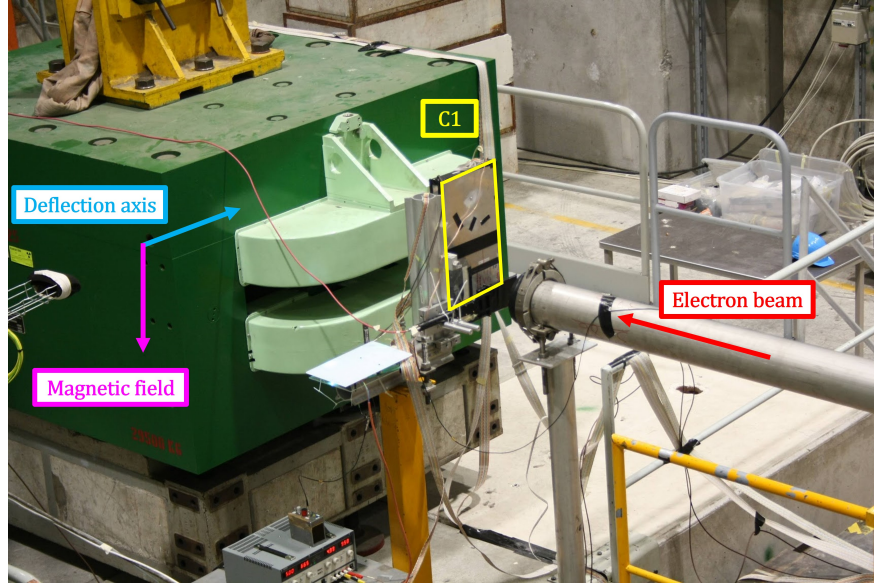


Figure 3.15: Photo of a beam chamber (C1, yellow), and the bending dipole magnet. The colored arrows describe the magnetic field lines (magenta) and the direction of deflection of the electrons (cyan).

- Two translational stages, which allow to control the position of the samples along the x axis, with a $1.5 \mu\text{m}$ accuracy, a $2 \mu\text{m}$ bidirectional repeatability and a $5 \mu\text{m}$ resolution. The range of the upper stage is 102 mm and the range of the lower stage is 52 mm.
- Two rotational stages, which allow to align the crystal with respect to the beam in the $x - z$ plane (“rot” angle) and in the $y - z$ plane (“cradle” angle). Both stages feature an average accuracy of $1 \mu\text{m}$, a $1 \mu\text{m}$ repeatability and a $0.25 \mu\text{m}$ resolution. The rot state has a full rotation range of 360° .

All the stages are equipped with two-phase microstep motors. The control of the angular rotation of the goniometer is provided by an optical encoder and a closed loop mechanism. The positions of the motors are saved in the data files generated by the DAQ and in dedicated log files. The features of the goniometer are presented in [149].

3.2.7 THE MULTIPLICITY COUNTER

The interactions of the photons in the crystals produce a large number of electron-positron pairs. The measurement of the multiplicity of the charged particles exiting the crystal is thus one of the clearest way to characterize the Strong Field processes. This measurement was performed primarily by the Multiplicity Counter, which is a plastic scintillator coupled to a PMT, with a thickness of 4 cm and a transverse area of $10 \text{ cm} \times 10 \text{ cm}$ (figure 3.17). A measurement of this quantity was also performed by a beam chamber (C2), identical to C1 but which could not be used as tracking detector, due to the high multiplicity of charged particles crossing the silicon planes. In this case, the multiplicity of the charged particles was evaluated considering the number of detected clusters.

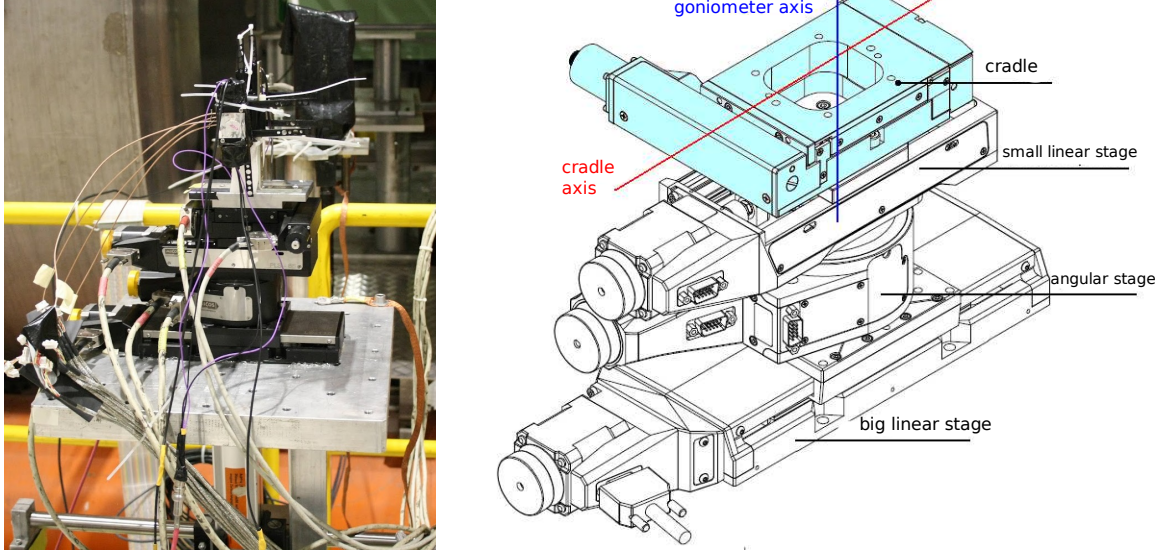


Figure 3.16: Left: photo of the goniometer, which was used to control the relative alignment of the photon beam and the crystal sample. Right: scheme of the translational and rotational stages of the goniometer [56].

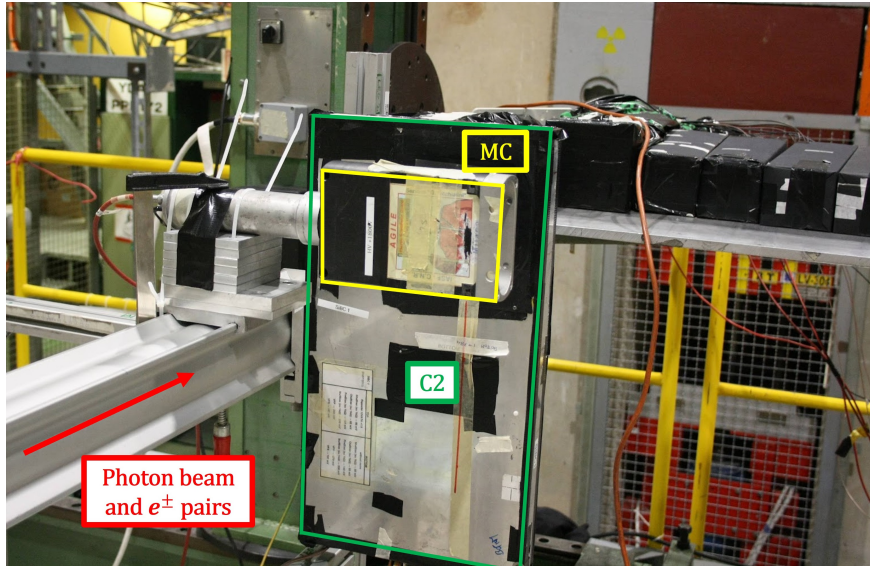


Figure 3.17: Photo of the Multiplicity Counter (MC, yellow) and a beam chamber (C2, green). On the back, a part of the electron spectrometer (eCAL) is visible.

3.2.8 THE PHOTON CALORIMETER

The energy of all the particles exiting the crystal was measured by a homogeneous calorimeter (γ CAL), which was placed on a movable frame ("Desy table"), located at the end of the beamline. The calorimeter is composed of a 3×3 matrix of trapezoidal 23 cm long BGO crystals ($\sim 20.5 X_0$), spare pieces of the PADME calorimeter [150], coupled to XP1912 PMTs (Photonis, [151]). Each crystal has a front area of $2.1 \text{ cm} \times 2.1 \text{ cm}$ and is coated with a white reflecting paint. The crystals and the PMTs are housed inside an aluminum light-tight structure. The PMTs were biased at 700 V for the equalization runs (which used

a muon beam) and at 500 V for the physics runs, to prevent the saturation effect induced by the larger energy deposit. More details about this calorimeter are given in [150, 152].

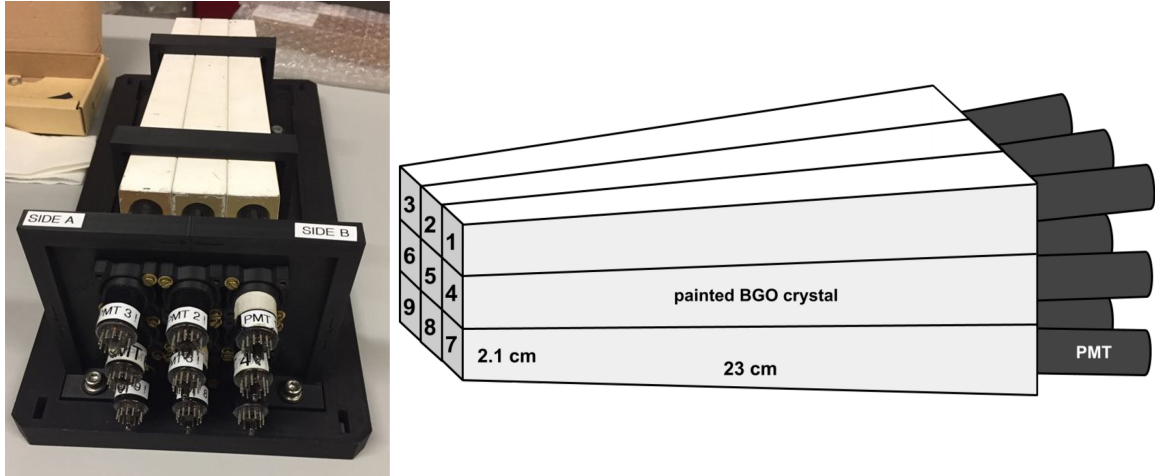


Figure 3.18: Left: photo of the BGO homogeneous calorimeter (γ CAL). Right: scheme of the calorimeter [152].

3.2.9 THE ELECTRON SPECTROMETER

The energy of the electrons deflected by the bending dipole magnet was measured by an electron spectrometer (figure 3.19), which is composed of:

- A shashlik sampling calorimeter, consisting in 70 tiles of 4 mm thick plastic scintillator, interleaved with 69 tiles of 1.5 mm thick zinc-coated lead (figure 3.21) [115, 153]. The total length of the calorimeter is $\sim 19 X_0$ and the transverse area is $11.5 \text{ cm} \times 11.5 \text{ cm}$. The readout is performed using 144 Wavelength Shifter (WLS) fibers with a diameter of 1.2 mm (Saint-Gobain BCF-92 [154]), which are coupled to a XP2262 PMT (Photonis [155]) and a R1828-01 PMT (Hamamatsu [156]). The sensitive part of the calorimeter is contained in a 1 cm thick aluminum vessel, which covers the top and bottom part of the tiles and the PMTs are covered with dark plastic. The PMTs were biased at 1400 V and 1100 V for the equalization runs and at 1350 V and 1100 V for the physics runs, to prevent the saturation effect induced by the larger energy deposit. A more detailed description of this calorimeter is given in [115, 153].
- 7 homogeneous Lead Glass calorimeters, spare modules of the OPAL electromagnetic calorimeter, each one with a thickness of 37 cm ($\sim 24.6 X_0$), a transverse area of $10 \text{ cm} \times 10 \text{ cm}$ at the front face and of $11 \text{ cm} \times 11 \text{ cm}$ at the back face (figure 3.20) [157, 158]. Each calorimeter is coupled to a high voltage PMT, biased in the 900 – 1000 V range, and covered with an aluminum foil and a cardboard layer.



Figure 3.19: Photo of the calorimeters employed on the H2 line. From left to right: the photon calorimeter (γ CAL), the shashlik calorimeter and the seven Lead Glass calorimeters (eCAL).

These calorimeters were placed on the Desy table, next to γ CAL. The measurement of the energy of the electrons (E_e) allowed to tag the energy of the photons which impinge on the crystal (E_γ), on an event-by-event basis:

$$E_\gamma = E_0 - E_e \quad (3.5)$$

where E_0 is the electron beam energy (i.e., 120 GeV).

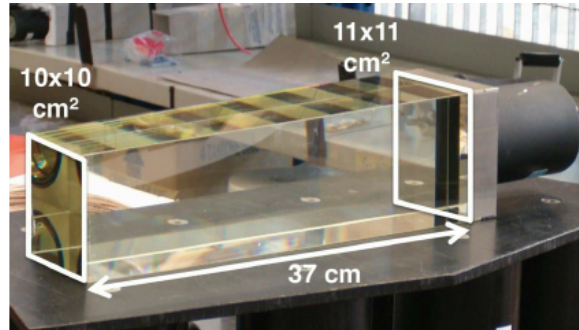


Figure 3.20: Photo of a Lead Glass calorimeter, without the cover layers.

3.2.10 THE DATA ACQUISITION SYSTEM

The DAQ system of the KLEVER 2021 beamtest is based on the Versa Module Eurocard (VME) standard [136]. The data taking procedure was the following (figure 3.22):

- The S1 and S2 trigger scintillators signals, once discriminated by a NIM discriminator, are combined with the SPS spill signal in a custom VME trigger board, to generate the trigger.
- The trigger is sent to a “master” VME Readout Board (VRB), connected to the first silicon telescope (T1). This board generates a “busy” signal that acts as trigger for

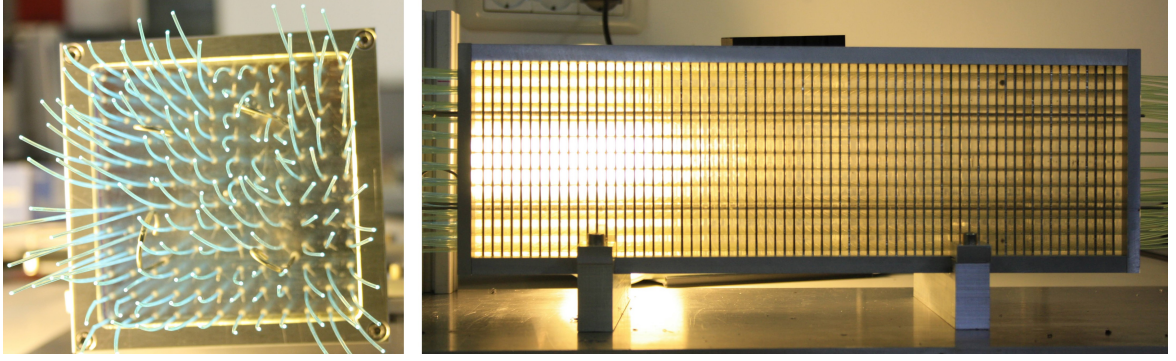


Figure 3.21: Left: front view of the back of the shashlik sampling calorimeter and the WLS fibers. Right: transverse profile of the shashlik sampling calorimeter.

the three other “slave” VRBs, each one connected to a different silicon module (T2, C1, C2). The signal is also sent to the four digitizers, that readout the signals of the other detectors (i.e., MCP, SiPMs, MC, eCAL, γ CAL).

- After the trigger, each VRB generates a “hold” signal, to store the silicon shaper output signals.
- In the readout phase, the silicon trackers output signals are digitized by dedicated two channel Analog to Digital Boards (ADCs) and sent to the corresponding VRB, where they are stored until the inter-spill period⁵. Each VRB can operate in two ways [136]:
 1. In “normal” mode, the digitized signals are de-multiplexed and the stream of data is temporarily stored, with a maximum of 4096 events, with 384×2 strips each. This mode was used in the preliminary measurements, to characterize the beam and measure the signal to noise ratio of each strip.
 2. In “zero-suppression” mode, only the strips with a signal over a given threshold are readout; the value of the threshold depends on the signal to noise ratio of each strip. In this way a maximum of 65536 events can be acquired, each one with 16×2 strips: the corresponding acquisition rate⁶ is ~ 6 kHz [136]. This mode was used in the physics and time resolution measurements.

Simultaneously, the signals coming from all the other detectors are sampled by the digitizers. An online algorithm determines the maximum value of each output signal (Pulse Height, PH) and the corresponding instant in time (signal time). These values, along with the baseline of the readout channels and the sampled waveforms, are stored into temporary memories and then readout in the inter-spill period.

- The readout of the angular and linear stages of the goniometric system is performed by optical encoders, which are controller by the DAQ.

⁵ The beam monitor instrumentation produces two digital signals: “warn of extraction” and “end of extraction”. The first is used to generate the trigger and the second to start the data transfer, from the VRBs and the digitizers to the PC.

⁶ The reported performances can be achieved only if there are no digitizers in the acquisition chain. Including the digitizers, the maximum acquisition rate is ~ 1 kHz [136].

- During the inter-spill period, the data are saved on the hard disk as HBOOK n-tuples.
- An online pre-processing procedure selects only the events with a single track in the silicon telescopes and produces ASCII files, in which each row corresponds to an event and each column to an information (e.g., the hit positions in the silicon tracker). A second online procedure merges all the ASCII files corresponding to a given run and saves a single Hierarcal Data Format 5 (HDF5) file as output, which is analyzed offline.

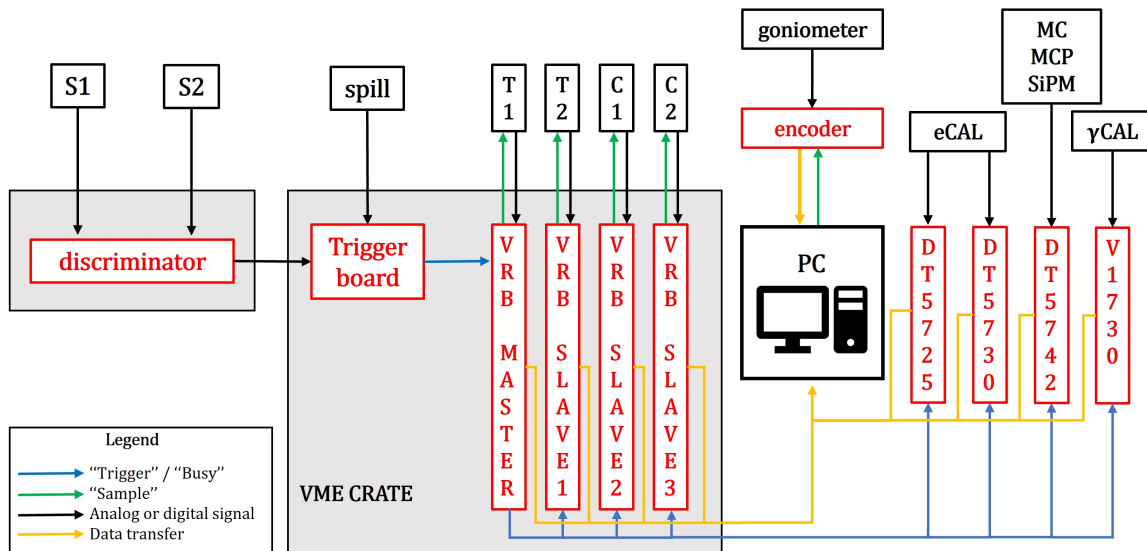


Figure 3.22: Scheme of the DAQ system.

Property	DT5725	DT5730	DT5742	V1730
Number of readout channels	8	8	16	8
Resolution [bits]	14	14	12	14
Maximum sampling frequency (f_{sample}) [MS/s]	250	500	5000	500
Full scale range [V]	2	2	2	2
Detectors readout by the digitizer	eCAL	eCAL γ CAL	SiPM MCP MC	γ CAL

Table 3.4: Features of the digitizers used in the KLEVER 2021 beamtest [159].

The digitizers used in the setup are presented in table 3.4. Several data taking runs were performed during the beamtest, each one with a different goal, trigger condition, DT5742 sampling frequency and electron beam energy. The run types were the following:

- Preliminary measurements with the crystal out of the beam, to characterize the electron beam and to calibrate the calorimeters (section 3.3). The beam energy was varied in the 20–120 GeV range.

- Measurements of the time resolution of the CRILIN photodetection system, coupled to the two non oriented PbF₂ samples (chapter 5). The beam energy was varied in the 100 – 120 GeV.
- Characterization of the Strong Field effects in the two oriented crystals (chapter 4). The beam energy was 120 GeV.

The sampling frequencies and trigger conditions used in these runs are reported in table 3.5. During all the runs, the DT5725, DT5730 and V1730 digitizers were always used at the maximum sampling frequency.

Crystal samples	Photodetection system	f_{sampl} (DT5742)	Trigger
None	None	2.5 GS/s	$S1 \wedge \text{spill}$
Non oriented PbF ₂	CRILIN	2.5 GS/s	$S1 \wedge \text{spill}$
Oriented PbF ₂	CRILIN	1 GS/s	$S1 \wedge \overline{S2} \wedge \text{spill}$
PbWO ₄	STORM	1 GS/s	$S1 \wedge \overline{S2} \wedge \text{spill}$

Table 3.5: Trigger condition and DT5742 sampling frequency used in the data taking runs. In ascending order, the rows describe: the preliminary measurements (first row), the qualification of the CRILIN photodetection system (second row) and the characterization of the oriented crystals (third and fourth row).

3.3 PRELIMINARY ANALYSIS

This section is dedicated to the description of the activities which were performed before the physics and timing measurements, namely the offline alignment of the silicon trackers, the characterization of the electron beam and the calibration of the calorimeters.

3.3.1 ALIGNMENT OF THE SILICON TRACKERS

The four silicon trackers located on the beamline were manually aligned in the plane perpendicular to the beam axis. However, small offsets still existed from module to module, thus requiring an offline compensation. In order to align all the detectors to the first telescope (T1), the incidence angles of the 120 GeV/c electrons were computed for each event, along both the x and y axis:

$$\begin{cases} \theta_x^j = \arctan\left(\frac{\Delta x_j}{\Delta z_j}\right) \\ \theta_y^j = \arctan\left(\frac{\Delta y_j}{\Delta z_j}\right) \end{cases} \quad (3.6)$$

where Δx_j and Δy_j are the differences between the hit positions measured by the j -th silicon tracker and T1, and Δz_j are the distances between the modules, along the z axis. The distributions of the incidence angles were fitted with a gaussian function (figure 3.23). The distribution along the x axis is asymmetrical, probably due to the collimators setting. The alignment was performed by subtracting the mean values of the gaussian functions

from the measured incidence angles. Equivalently, the alignment could be performed by subtracting the $b_{x,y}^i \cdot \Delta z_j$ products from the measured hit positions. The computed offsets are reported in table 3.6.

Detector	Offset (θ_x) [mrad]	Offset (θ_y) [mrad]	Offset (x) [cm]	Offset (y) [cm]
T2	-0.039	0.138	-0.053	0.189
C1	1.230	2.042	2.325	3.860
C2	1.197	0.331	3.904	1.079

Table 3.6: Silicon trackers alignment coefficients.

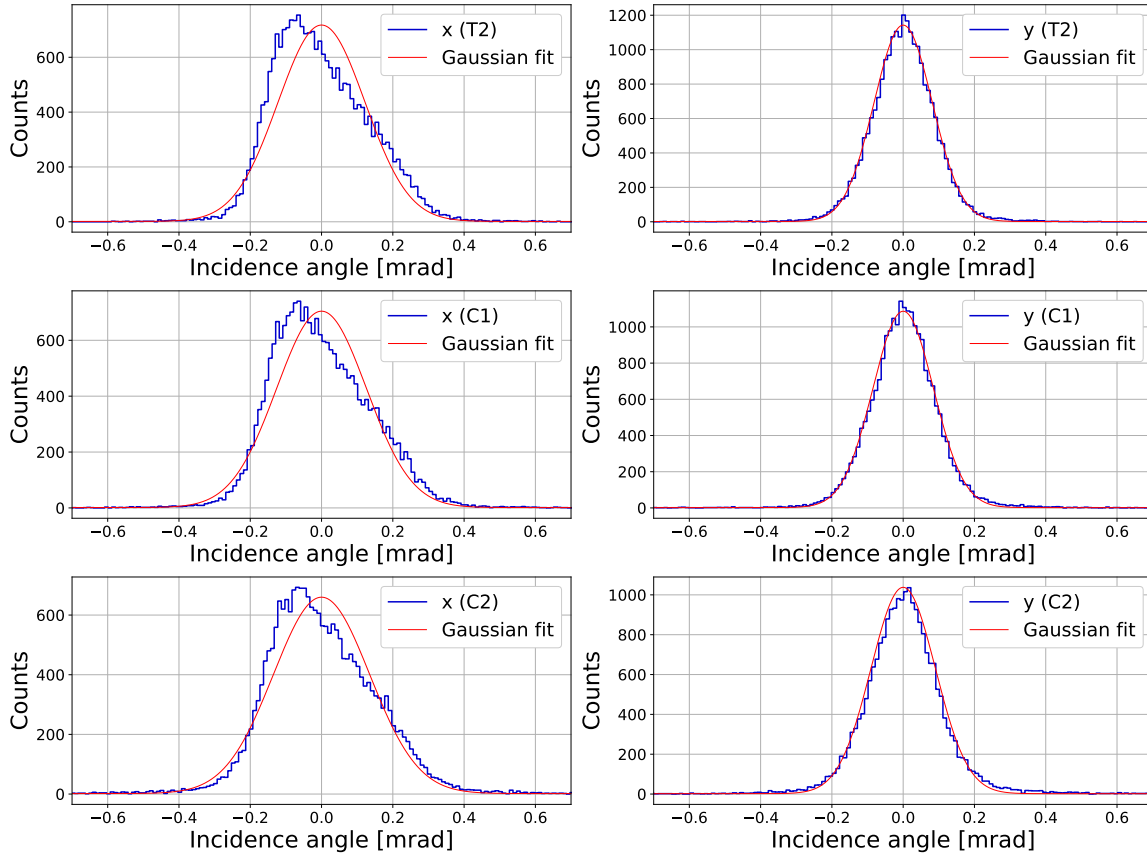


Figure 3.23: Frequency distributions of the electron incidence angles along the x (left) and y (right) axis, as determined by the silicon trackers, once aligned.

Trigger condition	FWHM _{x} [cm]	FWHM _{y} [cm]	σ_x [μ rad]	σ_y [μ rad]
S1 $\wedge$ spill	1.375	0.900	0.143 ± 0.001	0.100 ± 0.001
S1 $\wedge$ $\overline{S2}$ $\wedge$ spill	0.325	0.675	0.104 ± 0.001	0.078 ± 0.001

Table 3.7: Dependence of the electron beam width (FWHM _{x,y}) and divergence ($\sigma_{x,y}$) on the used trigger condition. The uncertainties on the divergences are the fitting errors.

3.3.2 CHARACTERIZATION OF THE ELECTRON BEAM

Once the silicon detectors were aligned, the 120 GeV/c electron beam was characterized. Figure 3.24 presents the beam profile in the $x - y$ plane, as reconstructed by T1, using both the trigger conditions previously described. It is evident that the $S1 \wedge \overline{S2} \wedge \text{spill}$ trigger performs a better collimation of the beam along both axes and, at the same time, maximizes the number of particles impinging on the crystal. The collimation improvement was evaluated considering the reduction of the Full-Width at Half Maximum (FWHM) of the beam and the divergence along the x and y axes. The divergence was computed as the standard deviation of the gaussian function fitted on the incidence angles distributions (figure 3.25).

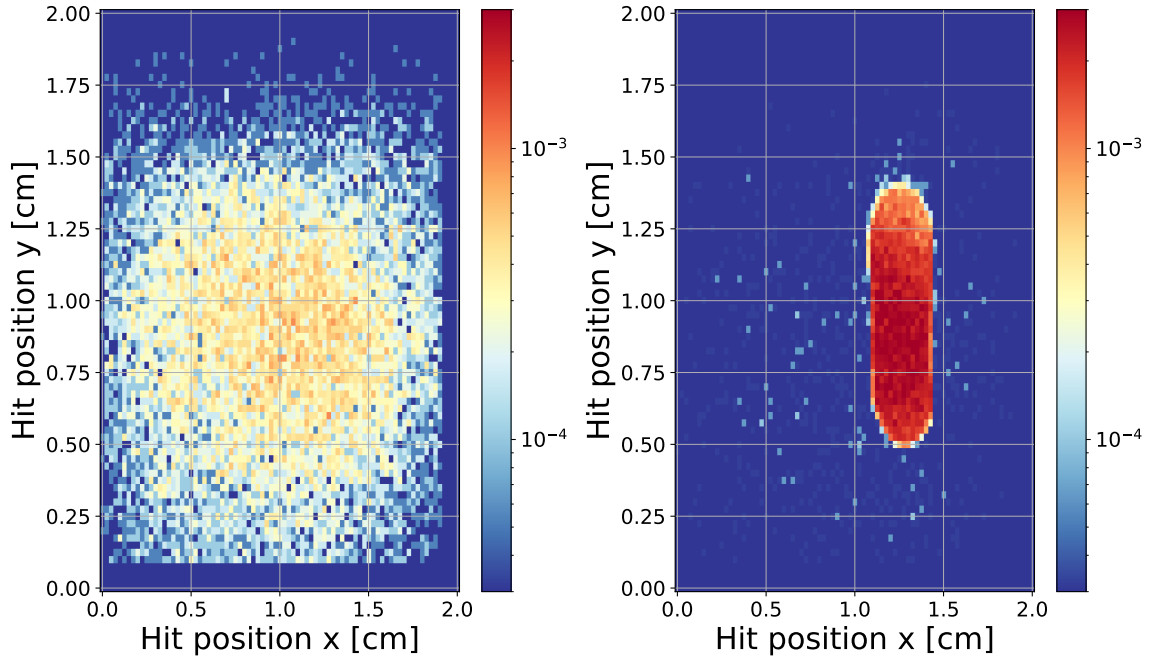


Figure 3.24: Left: transverse profile of the 120 GeV/c electron beam, obtained with the $S1 \wedge \text{spill}$ trigger condition. Right: transverse profile of the 120 GeV/c electron beam, obtained with the $S1 \wedge \overline{S2} \wedge \text{spill}$ trigger.

With the $S1 \wedge \overline{S2} \wedge \text{spill}$ trigger, the divergence of the 120 GeV/c beam along both axes is small enough to observe the Strong Field effects. As the energy of the electron beam decreases, the divergence along both axes becomes larger (figure 3.26): this is one of the reasons why the oriented crystals were characterized using the 120 GeV/c electron beam. The time resolution measurements did not require a narrowly collimated beam: on the contrary, a beam with a larger profile and angular spread allowed to distribute more homogeneously the particle tracks on the surface of the crystals and thus to characterize more SiPMs in a single run. For this reason, the time resolution measurements were performed using the $S1 \wedge \text{spill}$ trigger and different beam energies (section 5.3).

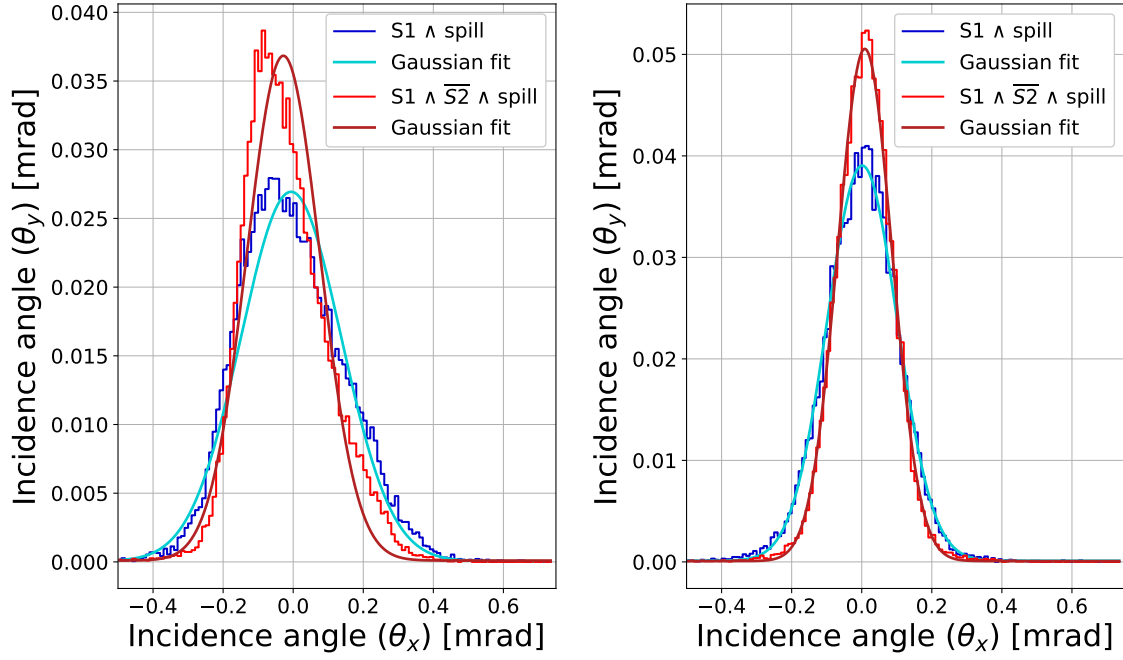


Figure 3.25: Distributions of the electron incidence angles on the x and y axis, obtained with two different trigger conditions. The beam energy is 120 GeV in both cases. Data are normalized.

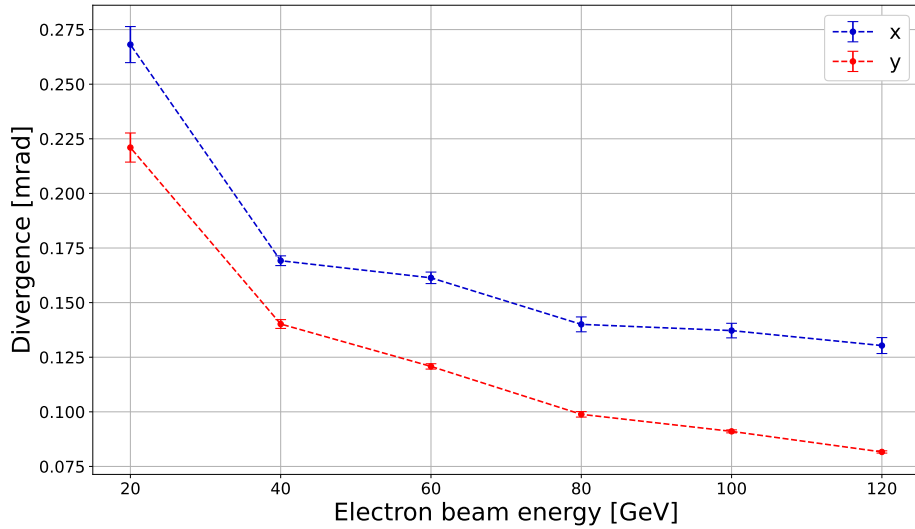


Figure 3.26: Beam divergence as a function of the energy. The $S1 \wedge \text{spill}$ trigger condition was used to take the data.

3.3.3 CALIBRATION OF THE CALORIMETERS

In order to find the correspondence between the PHs (in ADC counts) and the energy deposited in the calorimeters (in GeV) by the incoming particles, a calibration with monochromatic electron beams was required. The following procedure was adopted for each Lead Glass calorimeter:

1. An electron beam at a fixed energy E_{GeV} was aligned with the center of the calorimeter and events were acquired. The alignment was obtained by removing the crystal from the beamline and moving the Desy Table until the correct position was reached; however, due to a limitation in the movement range, the calibration of the last two LGs was performed with the bending magnet turned on, at different bias currents (i.e., 50 – 850 A, depending on the electron energy).
2. Cuts in Pulse Height and signal time were applied to the events, to remove spurious triggers (figure 3.27). For the calibration of LG n. 6 and n. 7, due to the non perpendicular incidence of the electron beam on the calorimeters themselves, an additional anti-coincidence cut was applied, selecting the events where the whole beam energy was deposited in only one of the two calorimeters.
3. The Pulse Height spectrum of the selected events was fitted with a gaussian function, obtaining a mean value $\bar{E}$ and a standard deviation σ_E (figure 3.27 on the right). The fit parameters allowed to compute the energy resolution:

$$R = \frac{\sigma_E}{\bar{E}} \quad (3.7)$$

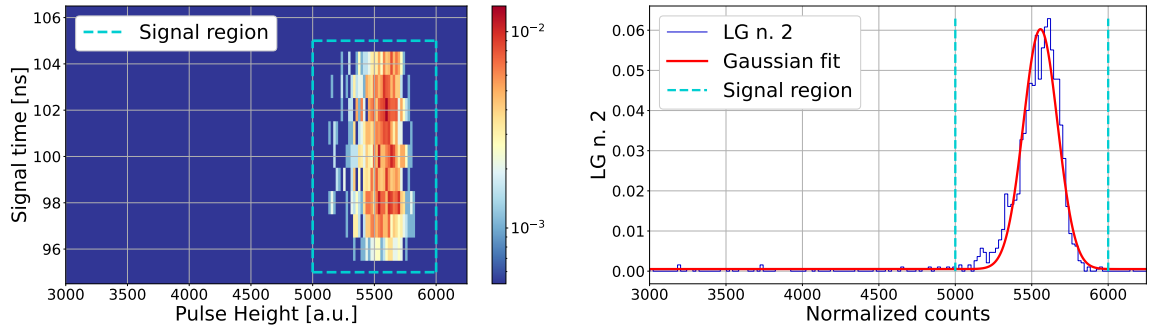


Figure 3.27: Left: correlation between the PH (expressed in arbitrary units, a.u.) and the signal time of the second Lead Glass calorimeter, showing the signal region cut. Right: PH spectrum of the second Lead Glass calorimeter.

4. A linear regression was performed on the $(E_{\text{GeV}}, \bar{E})$ pairs, thus obtaining the straight line parameters a_1, a_0 :

$$\bar{E} = a_1 \cdot E_{\text{GeV}} + a_0 \quad (3.8)$$

For some calorimeters, an additional $(0,0)$ point was considered in the fit. The calibration lines of all the calorimeters are shown in figure 3.28, on the left, and the calibration parameters are reported in table 3.8.

5. The residuals of each calibration curve were computed, as the relative difference between the data points and the straight lines. For all the calorimeters, these residuals were found to be smaller than 1.5%.

6. The dependence of the energy resolution on the beam energy (E_{GeV}) was modeled as [90]:

$$R = \frac{a}{\sqrt{E_{\text{GeV}}}} \oplus c \quad (3.9)$$

where $\oplus$ is the quadratic sum, a the stochastic term and c the constant term. The noise term was not considered here, since the calorimeters were readout by low-noise PMTs. The resolution curves are shown in figure 3.28, on the right, and the fit parameters are reported in table 3.9. The curves and parameters for LG n. 6 and LG n. 7 are not reported, since the non perpendicular incidence of the beam on the detectors caused a significant smearing in the PH spectra and prevented the correct estimation of the resolution.

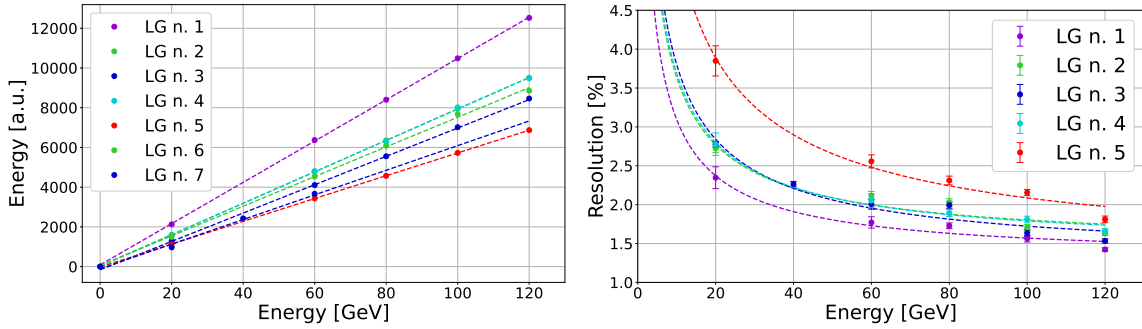


Figure 3.28: Left: calibration of the Lead Glass calorimeters. The uncertainties on the data point are the fitting errors and they are smaller than the points themselves. Right: resolution of the Lead Glass calorimeters. In both figures, the points are the experimental values and the dashed lines are the fitted curves.

Calorimeter	a_2 [a.u./GeV ²]	a_1 [a.u./GeV]	a_0 [a.u.]
LG n. 1	-	103.9 ± 0.5	86.0 ± 44.0
LG n. 2	-	79.1 ± 0.2	31.2 ± 18.9
LG n. 3	-	71.4 ± 1.4	-159.1 ± 98.0
LG n. 4	-	79.2 ± 0.9	17.6 ± 71.7
LG n. 5	-	57.4 ± 0.1	-16.6 ± 3.9
LG n. 6	-	74.7 ± 1.7	54.1 ± 145.4
LG n. 7	-	62.0 ± 4.7	-108.2 ± 171.0
Shashlik	-	69.8 ± 0.3	54.2 ± 27.6
γ CAL	-0.05 ± 0.01	35.8 ± 2.2	-52.6 ± 67.8

Table 3.8: Calorimeters calibration coefficients. γ CAL was calibrated using a quadratic function (eq. (3.16)) and the other detectors were calibrated using a linear function (eq. (3.8)). The reported uncertainties are the fit errors.

Since γ CAL and the shashlik calorimeter feature more readout channels, it was necessary to perform their equalization before the calibration. Two different procedures were adopted:

- The equalization of the γ CAL channels was performed using a beam of 80 GeV/c muons. The beam was aligned with the center of each tower and the Pulse Height

Calorimeter	a [% · $\sqrt{\text{GeV}}$]	c [%]
LG n. 1	8.9 ± 0.6	1.3 ± 0.1
LG n. 2	10.5 ± 1.0	1.5 ± 0.1
LG n. 3	11.3 ± 0.8	1.3 ± 0.1
LG n. 4	10.8 ± 0.4	1.4 ± 0.1
LG n. 5	16.4 ± 0.7	1.3 ± 0.2
Shashlik	12.4 ± 1.5	2.7 ± 0.1
γ CAL	19.0 ± 1.1	1.2 ± 0.2

Table 3.9: Calorimeters resolution terms. The reported uncertainties are the fit errors.

spectrum was recorded, applying the same cuts defined for the LGs calibration. Since high energy muons are Minimum Ionizing Particles (MIPs), the resulting PH spectra may be fitted with a Landau-like distribution (figure 3.29), which can be parametrized as [160]:

$$F(\lambda) = \frac{1}{\sqrt{2\pi}} e^{-0.5(\lambda + e^{-\lambda})} \quad (3.10)$$

where $F(\lambda)$ is the PH spectrum and λ is given by:

$$\lambda = 4.02 \frac{\text{PH} - \text{MPV}}{\text{FWHM}} \quad (3.11)$$

where MPV and FWHM are the Most Probable Value and the Full-Width at Half Maximum. The equalization coefficients are given by the ratio between the MPVs and the MPV of the central channel (MPV_{ref}), extracted from the fit:

$$eq_j = \frac{\text{MPV}_j}{\text{MPV}_{\text{ref}}} \quad (3.12)$$

where j is the channel index. The equalization factors are reported in table 3.10.

[Ch. 1] 0.278	[Ch. 2] 0.555	[Ch. 3] 0.450
[Ch. 4] 0.403	[Ch. 5] 1.000	[Ch. 6] 0.861
[Ch. 7] 0.324	[Ch. 8] 0.298	[Ch. 9] 0.759

Table 3.10: Equalization coefficients of the photon calorimeter readout channels. This table mirrors the spatial distribution of the channels in the $x - y$ plane.

- The equalization of the shashlik calorimeter was performed using two different approaches:
 1. The 120 GeV/c electron beam was aligned with the center of the calorimeter and the two channels PH distributions were produced and fitted with a gaussian function. The equalization factor was then computed as the ratio of the mean values extracted from the fit ($\bar{E}_{1,2}$):

$$k_{eq} = \frac{\bar{E}_1}{\bar{E}_2} = 1.566 \quad (3.13)$$

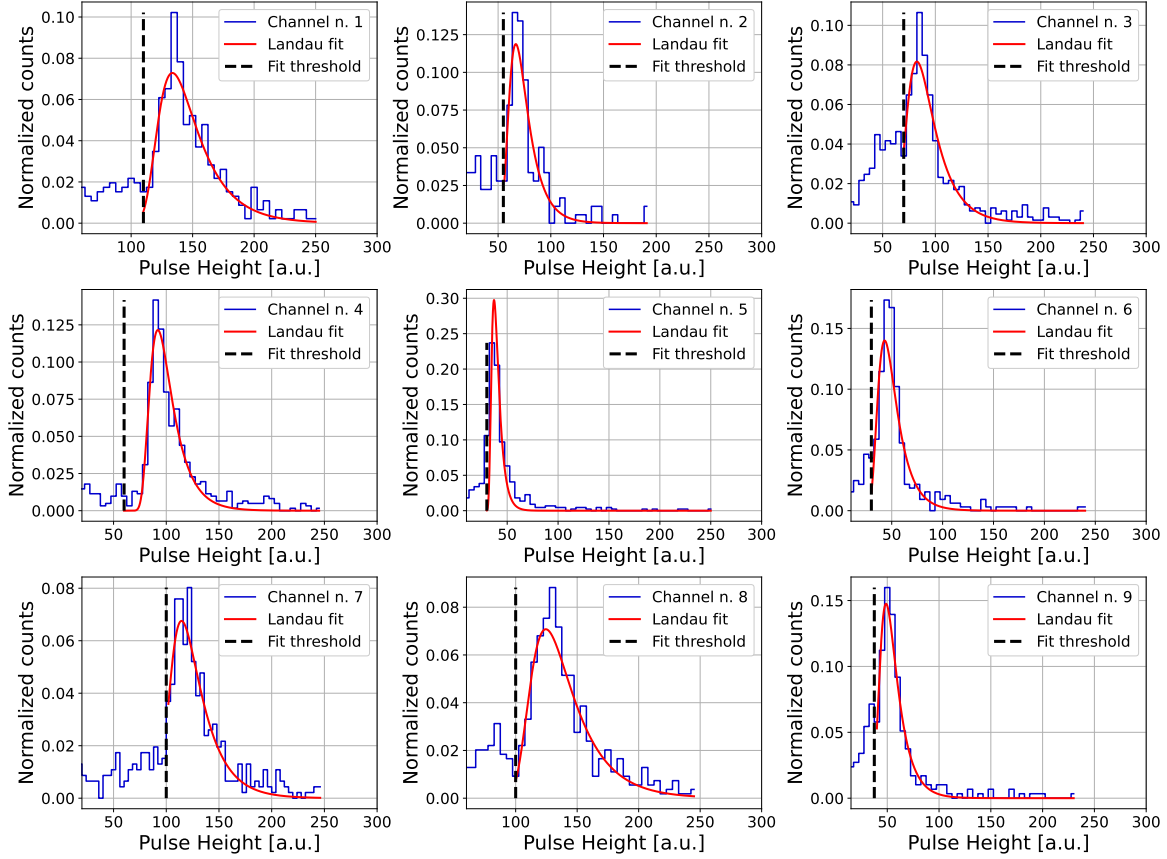


Figure 3.29: PH distributions of the γ CAL channels, obtained by aligning a 80 GeV/c muon beam with each tower. The fits were performed only on the Pulse Heights with values larger than the thresholds shown in black (dashed).

2. A scan with the electron beam along the x axis was performed, moving the Desy Table from run to run in a different position. For each alignment condition, the PH spectra of the channels were recorded and fitted with a gaussian function. The mean values extracted from the fit were plotted as a function of the horizontal coordinate (figure 3.30). The equalization factor was computed as the ratio of the peaks of these curves:

$$k_{eq} = \frac{\overline{E}_1^{\max}}{\overline{E}_2^{\max}} = 1.686 \quad (3.14)$$

The two coefficients have a relative discrepancy of 10.8 %, which suggests that both methods are acceptable for the equalization procedure. Nevertheless, given the fact that the bias voltages of the two PMTs were changed during the beamtest in order to avoid saturation effects (section 3.2.9), the equalization factor was finally computed by applying the first method to the data used also for the calibration, obtaining:

$$k_{eq} = \frac{\overline{E}_1}{\overline{E}_2} = 1.240 \quad (3.15)$$

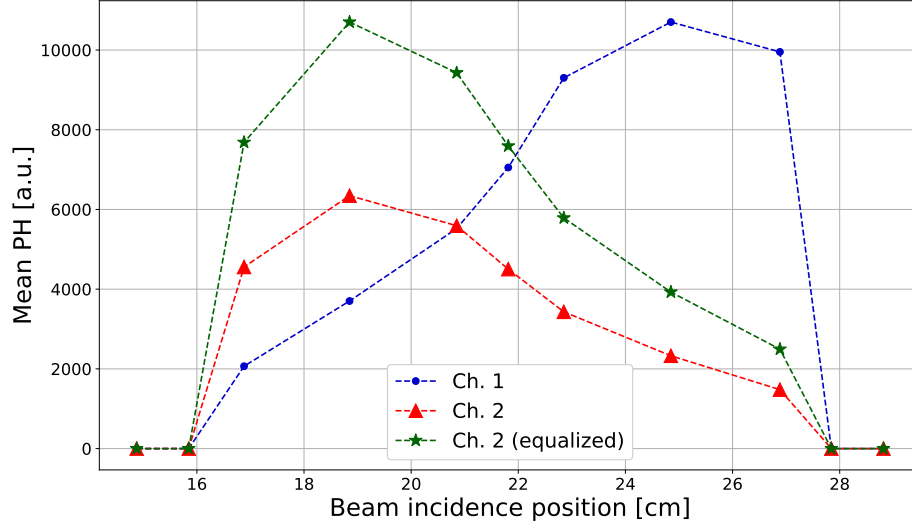


Figure 3.30: Dependence of the mean PH of the shashlik calorimeter channels on the beam hit position.

Once completed the equalization, the calorimeters were calibrated, with the same procedure described above for the Lead Glasses. In the γ CAL case, a quadratic function has been used:

$$\bar{E} = a_2 \cdot E_{\text{GeV}}^2 + a_1 \cdot E_{\text{GeV}} + a_0 \quad (3.16)$$

The calibration and resolution curves of these calorimeters are shown in figure 3.31 and the fit parameters are reported in tables 3.8 and 3.9. The residuals between the calibration curves and the experimental values were smaller than 1.5%. The γ CAL energy resolution was found to be larger than the value reported in previous studies [152]. This effect may be explained considering the small statistics acquired at each calibration point and the large divergence of the low energy electron beam. For this reason, the resolution terms reported in table 3.9 should be regarded as an upper limit on the calorimeters performance, rather than an accurate estimate of the a and c coefficients. It must be stressed that the choice of using the BGO calorimeter as γ CAL was not motivated by its energy resolution, but rather by its fine granularity in the transverse plane, which allowed to align the photon beam on the γ CAL central tower.

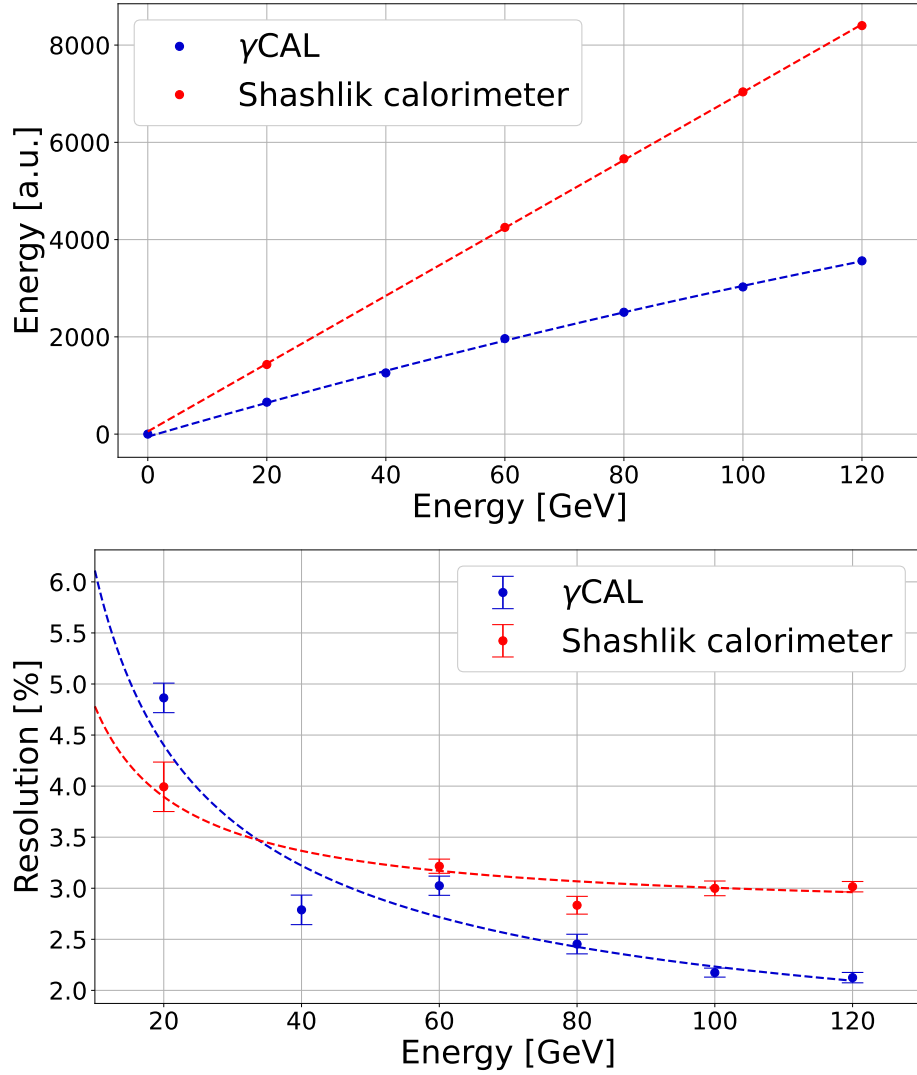


Figure 3.31: Top: calibration curves of the shashlik sampling calorimeter and γ CAL. The uncertainties on the data point, namely the fitting errors, are smaller than the points themselves. Bottom: resolution curves of the shashlik sampling calorimeter and γ CAL. In both figures, the points are the experimental values and the lines are the fitted curves.

CHARACTERIZATION OF THE ORIENTED CRYSTALS

The characterization of the Strong Field effects in an oriented crystal is a multi-step process. First, the sample must be placed on the beamline and the reference axis must be aligned with the incident photon beam. After the alignment, an angular scan is performed, from the condition where the beam is incident on the crystal axis (“axial alignment”) to a direction of random orientation: at each point, a long-statistics run is acquired, only a fraction of which is analyzed, since several cuts must be applied. The measurement of the energy deposited in the crystals and of the multiplicity of the exiting charged particles provides a complete characterization of the Strong Field processes occurring in the sample.

The goal of this chapter is to describe the alignment procedure (section 4.1) and to present the results of the characterization of the oriented PbF_2 and PbWO_4 samples (sections 4.2 and 4.3).

4.1 CRYSTAL ALIGNMENT

Before the characterization of the SF effects in an oriented crystal, it is necessary to align the axes of the sample with the incoming photon beam. This process is composed of two steps [56, 103]: the first is a pre-alignment and is performed without the beam, using a laser, a pentaprism and several mirrors, one of which is mounted on the crystal holder. The second is a more precise alignment and is performed using the goniometer and measuring the variation of the PH of a reference detector, as a function of the beam-crystal angle.

The goal of the first step is to determine the coordinates of the stages of the goniometer which allow to align as much as possible the axis of the crystal to the beam incidence direction. The procedure is the following:

- The crystal sample is placed on the goniometer.
- A laser source is located at the beginning of the beamline.
- Using two plummets and a straight line drawn on the ground, the laser beam is aligned with the z axis (i.e., with the electron beam).

- A pentaprism is placed in front of the goniometer, outside of the beam axis. The key feature of this instrument is that it always deflects a visible light beam by 90° (figure 4.1). Thus, if the mirror mounted on the surface of the crystal is not perfectly parallel to the z axis, the laser beam is reflected outside of the incident one (e.g., the magenta line in figure 4.1).
- By properly rotating the crystal sample in the $x - z$ and $y - z$ planes (section 3.2.6), the mirror is aligned along the z axis: in this condition, the incident and reflected laser beams are perfectly superimposed.
- The sample is rotated by 90° , thus aligning the mirror perpendicularly to the incident photon beam.
- The sample is rotated by a small angle, which is the displacement between the vector normal to the surface of the crystal and the reference axis of the sample. This angle is measured in the laboratory before the beamtest, with a High-Resolution X-Ray Diffractometer.

The pre-alignment allows to determine the position of the reference axis of the crystal with an uncertainty of a few mrad and needs to be followed by a more precise alignment, using the beam itself [56, 103].

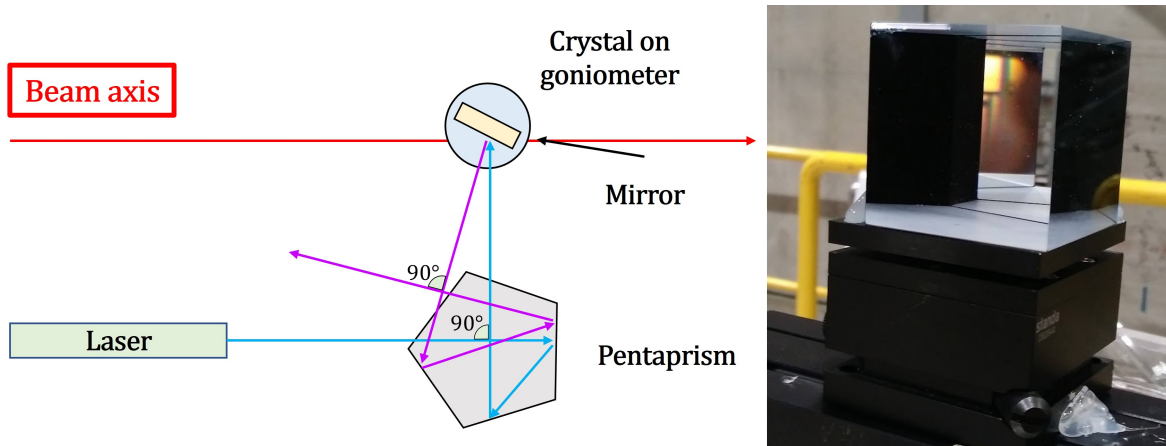


Figure 4.1: Left: scheme of the crystal pre-alignment process. The beam axis (z) is shown in red and the incident and reflected laser beam are shown, respectively, in cyan and magenta. In this condition, the crystal and the mirror are misaligned with respect to the z axis and thus the incident and reflected laser beams are not superimposed. Right: photo of the pentaprism.

In each run with the beam, the goniometer performs a scan along either the horizontal or the vertical axis, moving the rot angular stage (θ_{rot}) or the cradle angular stage (θ_{cradle}) in a predefined range. At each point of the scan, the average PH of a “reference” SiPM¹ is measured (figure 4.2): if the photon beam impinges far from the crystal axis, the Standard Pair Production process takes places and thus the measured energy deposit appears to be

¹ The reference SiPM used in these measurements was chosen between the two with the $1\times$ readout amplification gain (section 3.1.2).

constant and very small. As the reference axis of the crystal is approached, the photons interact with the enhanced crystalline field and undergo the Coherent Pair Production: thus, the average PH of the SiPM increases. By performing a large number of scans and following the directions along which the PH increases, it is possible to reconstruct the crystallographic stereogram (figure 4.3) and thus determine the coordinates of the axis.

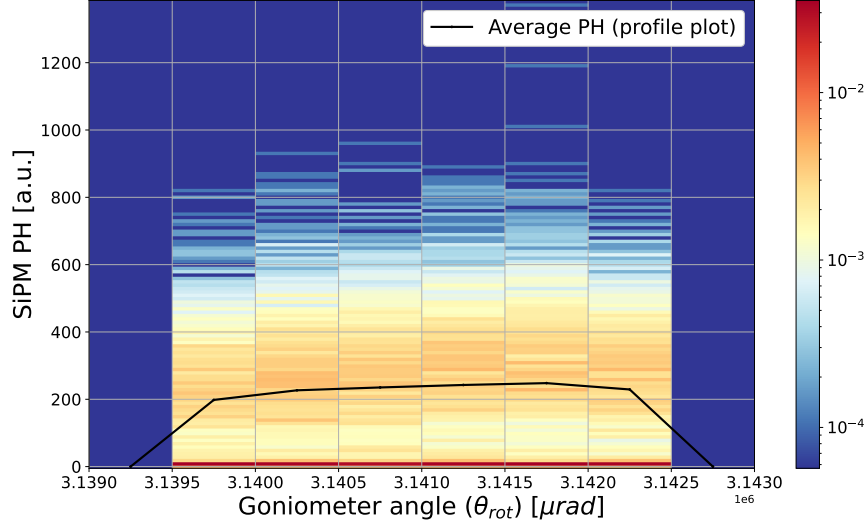


Figure 4.2: Correlation between the PH of one of the SiPMs coupled to the oriented PbF_2 crystal and the θ_{rot} coordinate of the goniometer, during a pre-alignment angular scan.

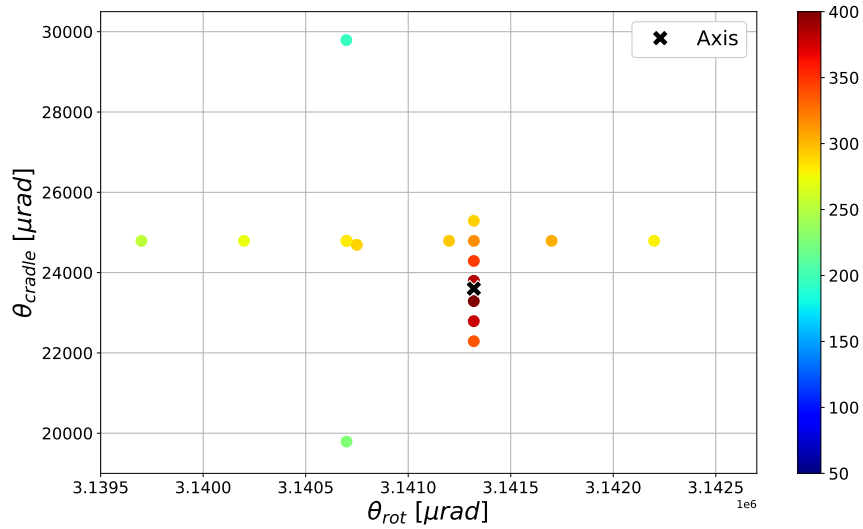


Figure 4.3: Reconstructed crystallographic stereogram of the oriented PbF_2 sample.

The performance of a complete scan in the $\theta_{rot} - \theta_{cradle}$ plane requires a large amount of time, due to the displacement between the position reached after the pre-alignment and the coordinates of the reference axis. However, it is not necessary to perform such a scan, due to the symmetry of the stereogram and the properties of the lattice axes. In fact, an axis is the intersection of several crystalline planes: if two planes have been located, the following scans should be performed in the direction where the inter-plane distance decreases. The

positions of the planes can be determined by studying the correlation between the PH of the SiPM and the angle between the axes of the goniometer and the incident photon beam ($\theta_{\text{rel},x}, \theta_{\text{rel},y}$):

$$\begin{cases} \theta_{\text{rel},x} = \theta_{\text{rot}} + \theta_{\text{in},x} \\ \theta_{\text{rel},y} = \theta_{\text{cradle}} + \theta_{\text{in},y} \end{cases} \quad (4.1)$$

where $\theta_{\text{in},x}$ and $\theta_{\text{in},y}$ are the electron incidence angles² along the x and y axis. The dependence of the average SiPM PH on $\theta_{\text{rel},x}$ in a horizontal angular scan is shown in figure 4.4: the multi-peaked shape of the histogram projection indicates that the photons have crossed a large number of planes along their path. A similar curve is found if the average PH of the Multiplicity Counter is considered (figure 4.5). Performing the fine alignment of the crystal sample using the SiPM or the Multiplicity Counter is in fact perfectly equivalent, as it has already been demonstrated in [56, 103].

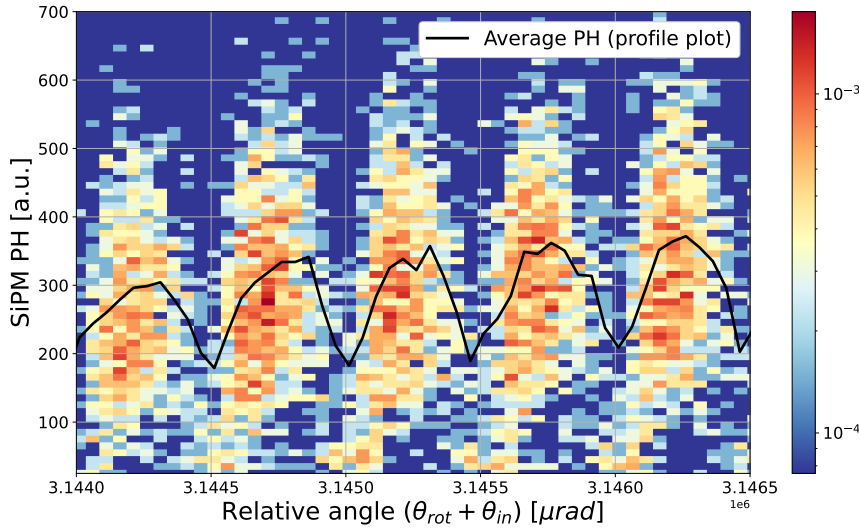


Figure 4.4: Correlation between the PH of the reference SiPM, coupled to the oriented PbF_2 sample, and the angle between the goniometer axis and the photon incidence direction, computed using eq. (4.1). The periodic increase of the PH is due to the incidence of the photons on the crystallographic planes.

4.2 PbF_2 CHARACTERIZATION

This section presents the characterization of the oriented PbF_2 crystal (section 3.1.1), which was coupled to the CRILIN photodetection system. The goal of this study was to measure the enhancement of the pair production cross-section and the reduction of the radiation length, which occur when the beam impinges on the crystal axis. Moreover, the angular

² Since the photon emission angle is $\sim 1/\gamma \sim 5 \mu\text{rad}$, it is assumed that the photon and electron incidence angles are equal.

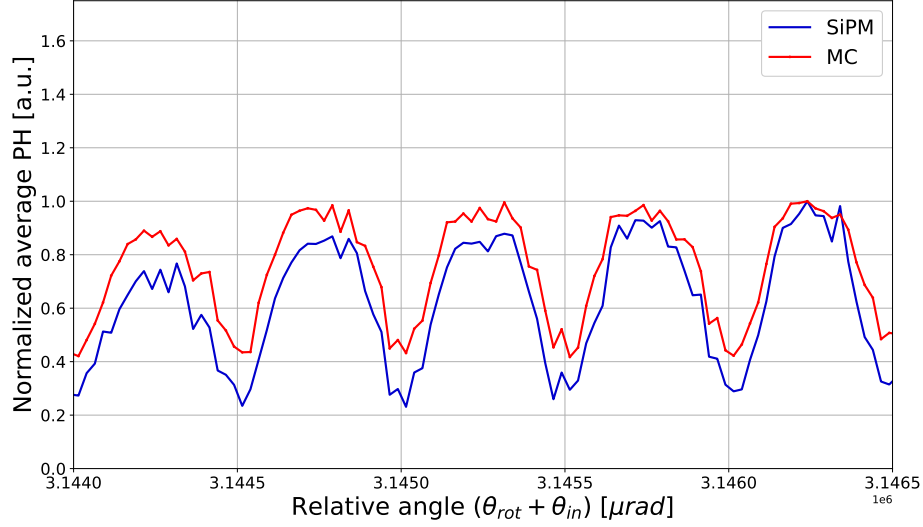


Figure 4.5: Comparison of the average PH of the reference SiPM and the Multiplicity Counter, during a pre-alignment scan performed with the PbF₂ crystal. The curves are normalized.

dependence of these effects has been compared with the predicted acceptance of the Strong Field regime (Θ_0).

4.2.1 THE EVENTS SELECTION CRITERIA

After the alignment, the PbF₂ sample was characterized by means of dedicated long-statistics runs, using the 120 GeV electron beam and setting the bending magnet at the maximum current (850 A); each run corresponded to a different angle between the photon beam and the $\langle 110 \rangle$ axis of the crystal (table 4.1). Only a fraction of the events was analyzed, since the reconstruction of a single electron track in the upstream silicon trackers (T1, T2, C1) and an electron incidence angle within the $[-200 \mu\text{rad}, +200 \mu\text{rad}]$ range were required. Moreover, the electrons trajectories reconstructed by T2 and C1 had to cross a fiducial region inside a plane located at the center of the crystal. This region was defined by studying the efficiency map of the crystal, namely the spatial distribution of the fraction of the events where the reference SiPM detected a signal with a large PH (figure 4.6, on the left). Such region could also be defined on a similar map, obtained using the number of tracks detected in the C2 tracker (figure 4.6, on the right).

4.2.2 THE PRELIMINARY MEASUREMENTS

The enhancement of the pair production cross-section of the PbF₂ crystal, in the angular transition from the random orientation to the axial alignment, was measured in several ways:

- By computing the energy spectra of γCAL for each incidence angle (figure 4.7, on the left). In fact, the high energy tail of the spectrum is smaller when the beam is

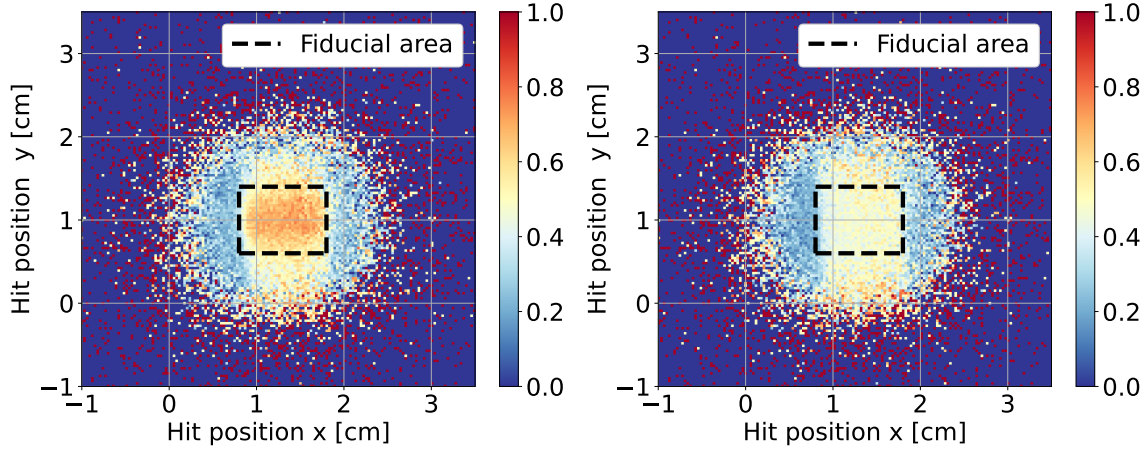


Figure 4.6: Left: efficiency map of the PbF_2 crystal, defined as the distribution of the fraction of the events where the PH of the reference SiPM was larger than 50 a.u.. Right: efficiency map of the PbF_2 crystal, obtained by requiring the detection of at least 5 tracks (clusters) in at least one side of the C2 module.

Angle [mrad]	Alignment condition	Analyzed events
0	Axial alignment	138405
0.625	Transition	33072
1.250	Transition	79785
4.093	Transition	70225
5.236	Transition	69344
8.313	Transition	14342
50.000	Random orientation	84201

Table 4.1: Angular scan performed with the oriented PbF_2 sample. The reported statistics were computed after applying the cuts described in the text.

aligned with the axis of the crystal. This effect cannot be attributed to a variation of the energy spectrum of the incident photons, since the eCAL spectra were found to be constant during the whole angular scan (figure 4.7, on the right). Thus, any difference observed in the γ CAL spectrum and in the PH spectrum of any other detector must be due to the SF enhancement of the pair production process.

- By computing the PH spectra of the reference SiPM (figure 4.8). In fact, it can be observed that the maximum energy deposit in the axial alignment is more than twice as large as the one in the random orientation. Moreover, the similarity between the spectra recorded in axial alignment and at 0.625 mrad confirm that the Strong Field processes are angle-independent, within the acceptance defined by Θ_0 (which is ~ 0.650 mrad for the PbF_2 $\langle 110 \rangle$ axis, table 3.2). The spectra recorded at the larger incidence angles, namely in the transition from 1.250 mrad to 8.313 mrad, were found to be less intense than the axial alignment but anyway more than the random orientation. This observation confirmed that the CB and CPP processes feature an angular acceptance significantly broader than the SF regime.

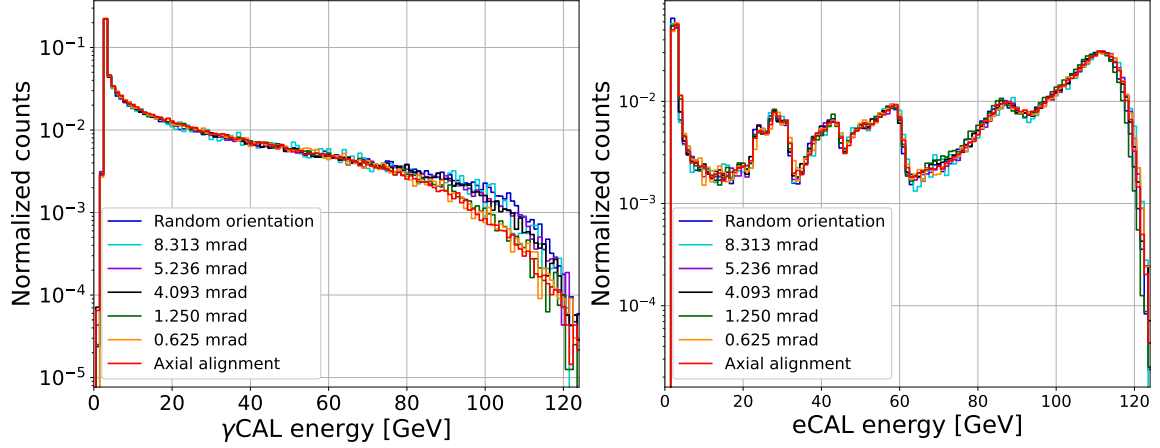


Figure 4.7: Left: γ CAL energy spectra, shown for different angles between the photon beam and the PbF₂ crystal. Right: eCAL energy spectra, shown in the same conditions. The discontinuities which can be observed in the eCAL spectra are due to the presence of small gaps between the electromagnetic calorimeters. In both figures, the histograms are normalized.

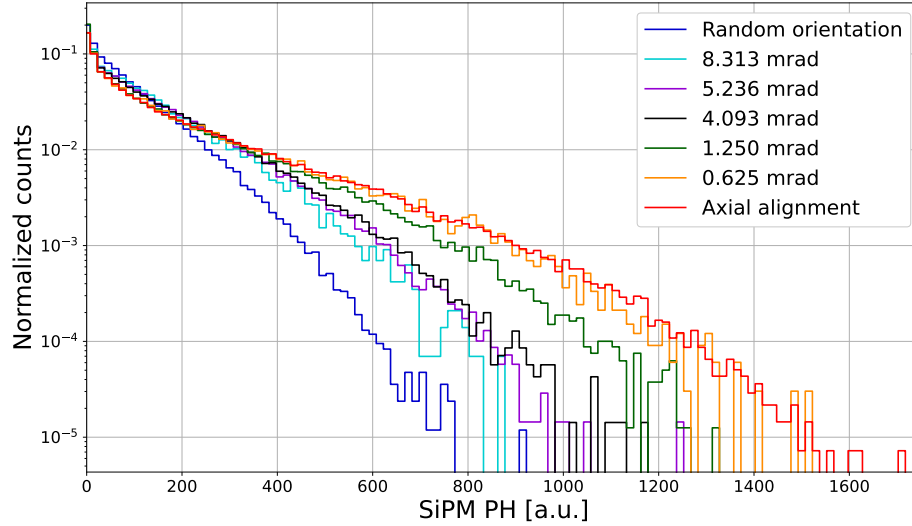


Figure 4.8: Comparison of the PH spectra of the reference SiPM, for different angles between the photon beam and the PbF₂ crystal. The entries are normalized.

- By computing the PH spectra³ of the Multiplicity Counter (figure 4.9). The results obtained in this case are coherent with the ones shown for the SiPM. In fact, for an incidence angle smaller than 0.625 mrad, a large increase of the fraction of the events with a PH of at least ~ 3000 a.u. is observed.

These results were confirmed by considering the dependence of the average PH of these detectors on the beam incidence angle (figure 4.10).

The relative increase of the SiPM and MC PHs shown in figure 4.10 does not describe accurately the Strong Field processes occurring in the oriented crystal, since they are averaged

³ Due to the limited input range of the DT5742 digitizer and the output range of the PMT, the MC signals with an amplitude larger than ~ 3500 a.u. were saturated. In such cases, the PHs were reconstructed by analyzing the MC waveforms and applying the Time Over Threshold (TOT) method (section A.1).

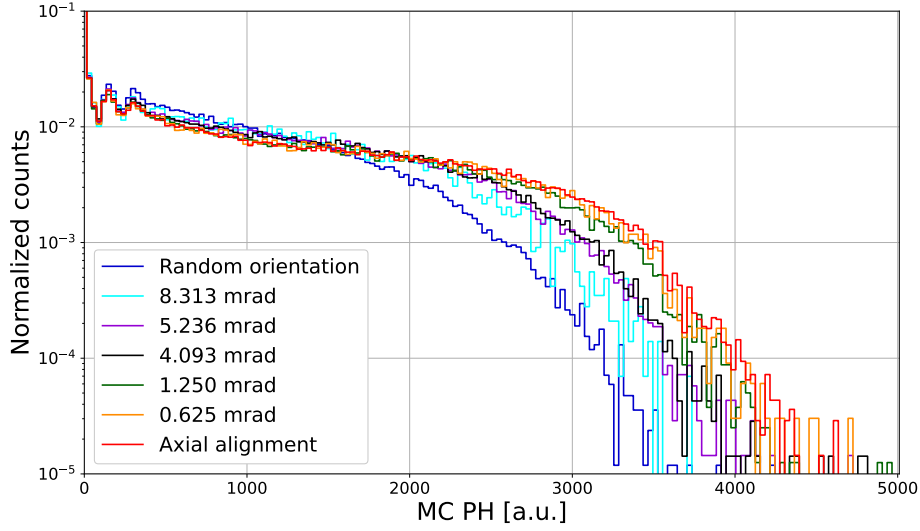


Figure 4.9: Comparison of the PH spectra of the Multiplicity Counter, for different angles between the photon beam and the PbF₂ crystal. The entries are normalized.

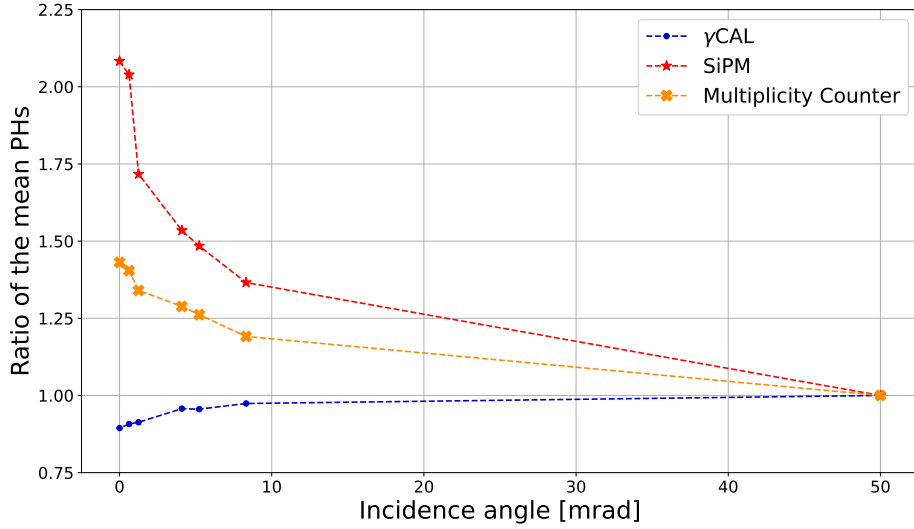


Figure 4.10: Dependence of the mean PH of the different detectors on the angle between the photon beam and the PbF₂ crystal. The values were normalized to the random orientation (i.e., an angle of 50 mrad).

over the energy spectrum of the incident photons. To perform a more accurate evaluation, it was necessary to compute the energy of the photons (E_γ^0) on an event-by-event basis, for instance through the following relation:

$$E_\gamma^0 = 120 \text{ GeV} - E_e \quad (4.2)$$

where E_e is the energy measured by the electron spectrometer. During the data analysis, it was noted that eCAL features a limited angular acceptance and a number of blind spots: in fact, several gaps are visible in the eCAL spectrum (figure 4.7, on the right) and in the correlation of the energy measured respectively by γ CAL and eCAL (figure 4.11). For

instance, one of such holes lies in the $E_e = 60 - 70$ GeV interval. Since γ CAL does not feature any gap, it was decided to compute the incident photon energy as:

$$E_\gamma^0 = E_\gamma + E_{\text{crystal}} \quad (4.3)$$

where E_γ is the energy measured by γ CAL and E_{crystal} is the energy deposited in the crystal. The latter was computed by calibrating the SiPM, assuming a direct proportionality between the PH and the energy deposit:

$$E_{\text{crystal}} = m \cdot \text{PH}_{\text{SiPM}} \quad (4.4)$$

The validity of eq. (4.3) and (4.4) is based on the assumption that the energy of the incident photon is fully absorbed in the crystal and in γ CAL, without losses. This is an approximation, since γ CAL features a limited angular acceptance and shower containment, and could be a source of a small systematic error.

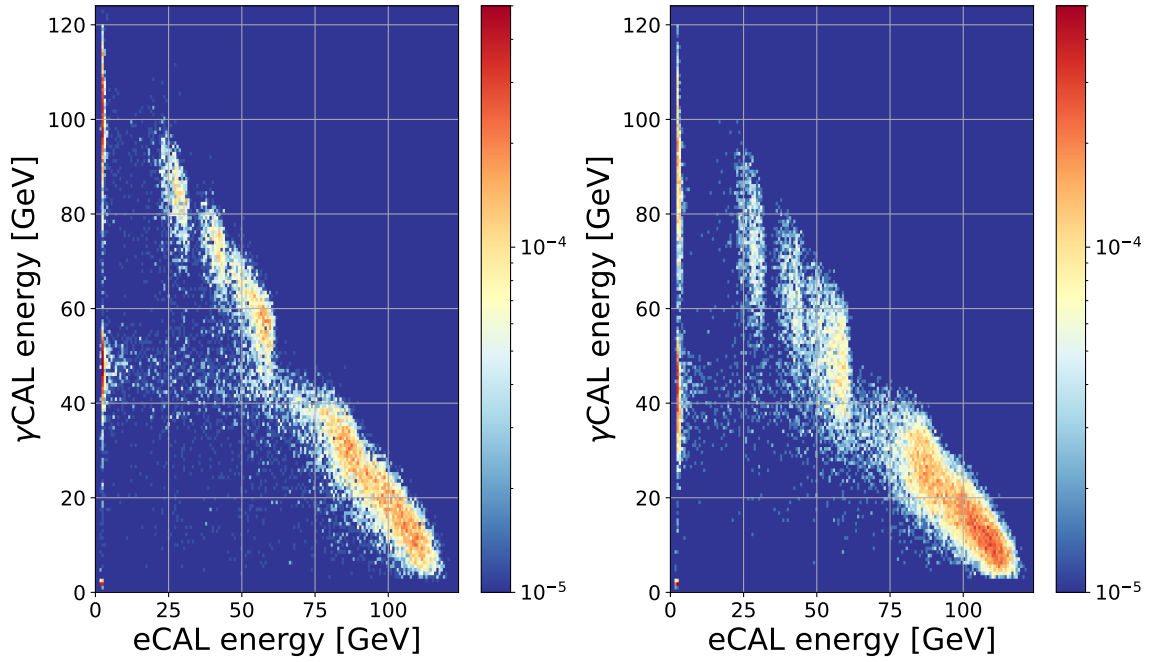


Figure 4.11: Left: correlation between the energy deposits in eCAL and γ CAL, for an incidence angle of the photon beam on the PbF₂ crystal axis of 50 mrad (random orientation). Right: same correlation histogram, computed for an incidence angle of 0 mrad (axial alignment). In both cases, only the events where at least 5 clusters were detected in at least one side of C2 were considered. The entries are normalized.

4.2.3 THE SIPM CALIBRATION

In principle, there are several ways to compute the SiPM calibration coefficient (m). For instance, one could consider a small range of electron energies, within the acceptance of eCAL. In this condition, the energy deposited in the crystal is:

$$E_{\text{crystal}} = 120 \text{ GeV} - E_e - E_\gamma \quad (4.5)$$

If the considered E_e range is small enough, E_{crystal} follows a gaussian distribution, whose mean is equal to the product of m and the average PH of the SiPM. However, the calorimeters used in the setup featured an energy resolution larger than 2% at 120 GeV (section 3.3.3): since the energy deposit in the crystal is expected to be smaller than ~ 1 GeV, the intrinsic fluctuations of E_{crystal} did not allow to reliably estimate m . For this reason, two other calibration methods were evaluated:

1. **The MIP peak approach.** This method was based on the acquisition of a run where the non oriented $4.3 X_0$ PbF_2 sample was coupled to the CRILIN SiPMs and exposed to a 80 GeV muon beam. Since high energy muons are MIPs, the resulting energy deposit distribution has a Landau shape [35], whose Most Probable Value (MPV) is given by:

$$E_{\text{MPV}} = L \cdot \varepsilon_{\text{MIP}} \quad (4.6)$$

where L is the crystal thickness and ε_{MIP} is the MIP energy loss per unit length. For the non oriented PbF_2 crystals, $L = 4$ cm and $\varepsilon_{\text{MIP}} = 9.373$ MeV/cm (table 3.2) and thus $E_{\text{MPV}} = 37.492$ MeV.

The events were selected applying dedicated cuts on the signal time and the hit position of the muons on the plane of the crystal. The resulting reference spectrum was fitted with a Landau-like distribution, whose analytical form is given in eq. (3.10) (figure 4.12). The MPV extracted from the fit (PH_{MPV}) was used to compute the calibration coefficient of the reference SiPM:

$$m = \frac{\text{PH}_{\text{MPV}}}{L \cdot \varepsilon_{\text{MIP}}} \quad (4.7)$$

A value of 723.66 ± 20.66 a.u./GeV was obtained. The error on m was determined by propagating the uncertainty on PH_{MPV} , extracted from the fit.

2. **The simulation approach.** This method was based on a full Geant4 simulation of the experimental setup, which allowed to predict the frequency distribution of the energy deposited in the randomly oriented crystal by the photon beam⁴. Figure 4.13 compares the PH spectrum of the reference SiPM with the energy distribution com-

⁴ It was not possible to predict the energy deposited in the crystal in the axial alignment, since the physics of the oriented crystals is not implemented in the Geant4 standard Physics List [104, 161].

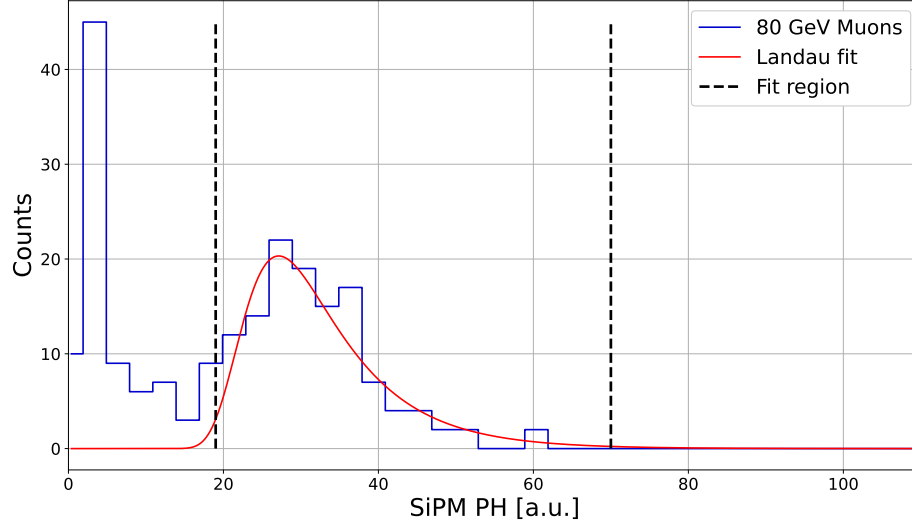


Figure 4.12: PH spectrum of the reference SiPM, coupled to the $4.3 X_0$ PbF₂ crystal, exposed to a 80 GeV muon beam. Cuts on the signal time and the hit position in the plane of the crystals were applied, before computing the histogram.

puted with a 100,000 events simulation. To determine the calibration coefficient, an exponential distribution was fitted on both histograms, with the following equation:

$$y = a \cdot e^{-bx} \quad (4.8)$$

where the b coefficient is inversely proportional to the average value of the spectrum and thus can be used to calibrate the SiPM:

$$m = \frac{b_{G4}}{b_{\text{SiPM}}} \propto \frac{\langle \text{PH}_{\text{SiPM}} \rangle}{\langle E_{\text{crystal}} \rangle} \quad (4.9)$$

where b_{G4} and b_{SiPM} are the coefficients extracted from the fit of the simulated energy distribution (E_{crystal}) and the SiPM PH spectrum (PH_{SiPM}), and $\langle \text{PH}_{\text{SiPM}} \rangle$ and $\langle E_{\text{crystal}} \rangle$ are the numerical averages of the respective spectra. Using this method, a value of 725.55 ± 5.43 a.u./GeV was obtained.

Eq. (4.9) was considered to be more reliable than computing the numerical averages of the two spectra. In fact, such observables depend on the fraction of the events in which a signal with a null PH, or a null energy deposit in the crystal, was observed. However, the simulation did not model the production of the Cherenkov light in the crystal nor the efficiency of the SiPMs⁵. Moreover, no selection criterion was applied to the simulated data (e.g., the cut on the hit positions of the incident particles): thus, the pedestal of the E_{crystal} spectrum was found to be ~ 3 times larger than the one of PH_{SiPM} (figure 4.13). Correspondingly, the ratio of the numerical averages of the spectra was found to be 1451.65 ± 81.07 a.u./GeV, which is twice as large as the values obtained using eq. (4.9) and with the MIP peak approach. This difference confirmed the unreliability of directly computing the numerical averages of the spectra.

⁵ More details on the Geant4 simulation are given in section A.2.

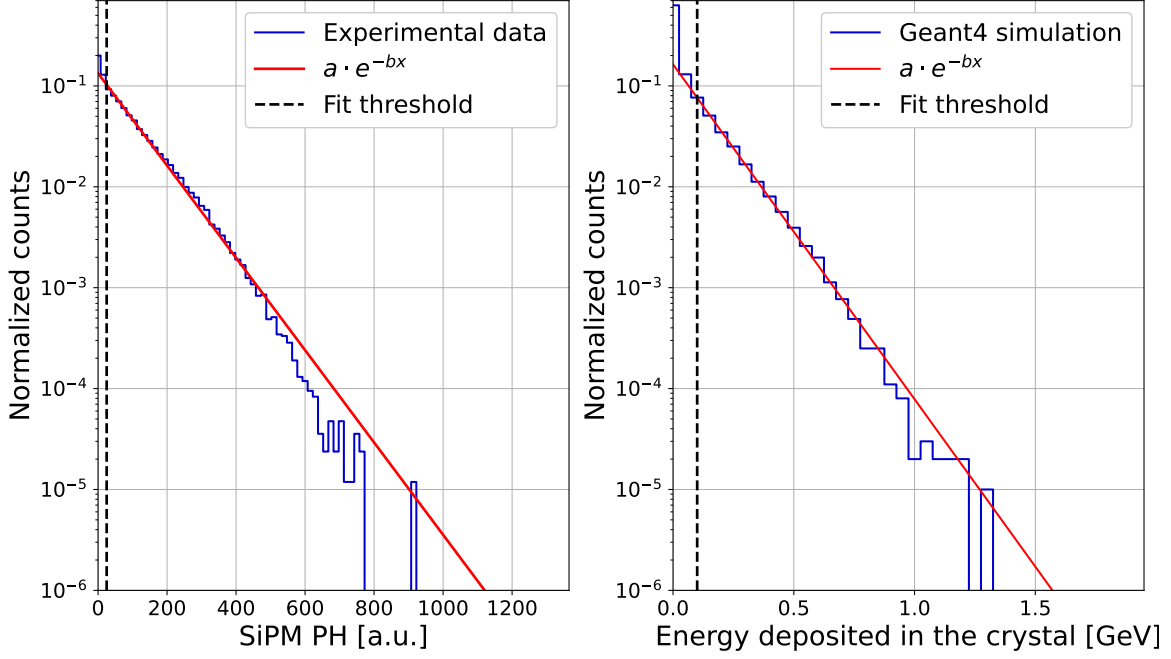


Figure 4.13: Left: PH distribution of the reference SiPM, measured with the oriented PbF_2 crystal in the condition of random orientation. Right: distribution of the energy deposited in the crystal, computed with a full Geant4 simulation of the experimental setup. In both figures, the histograms are normalized.

Table 4.2 compares the calibration coefficients obtained with the two approaches. The relative discrepancy between the two values is $\sim 0.25\%$, which means that these calibration strategies are in excellent agreement. In the following analyses, m was computed as the weighted average of the obtained values (i.e., $m = 725.43$ a.u./GeV). Figure 4.14 presents the energy deposit spectra, computed by calibrating the SiPM PH spectra, for the different alignment conditions. As previously noted, when the beam impinges on the axis of the crystal, a maximum energy deposit of ~ 2 GeV is observed, while the corresponding value in random orientation is ~ 1 GeV. Thus, the Strong Field effects caused a net increase of the energy deposit of a factor ~ 2 .

Calibration method	Coefficient [a.u./GeV]
Muon run	723.66 ± 20.66
Geant4 simulation	725.55 ± 5.43
Weighted average	725.43 ± 5.25

Table 4.2: Calibration coefficients of the reference SiPM, coupled to the PbF_2 crystal. The relative discrepancy between the two coefficients is $\sim 0.2\%$.

After calibrating the SiPM, the energy of the incident photons could be computed by means of eq. (4.3), allowing to measure the correlation between the energy deposited in the crystal and the energy of the incident photons, when a high multiplicity of charged particles is detected (figure 4.15). In particular, it was found that the axial-to-random enhancement of the energy deposited in the crystal increases with the energy of the incident particles, as

expected from the theory of the Strong Field regime. A similar effect was also observed for the multiplicity of the charged particles produced in the crystal, as measured by MC (figure 4.16).

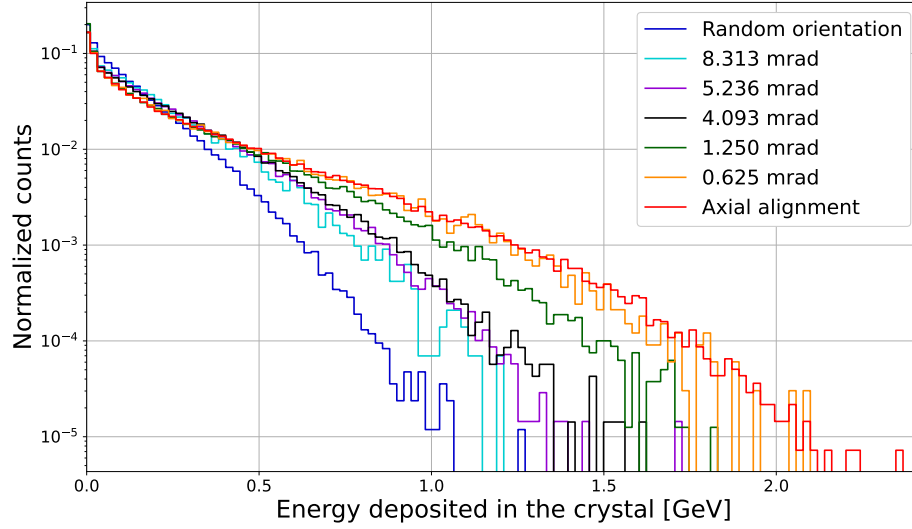


Figure 4.14: Comparison of the crystal energy deposit distributions, for different incidence angles of the photon beam on the PbF_2 sample. The spectra were computed by rescaling the SiPM PH spectra, using the calibration coefficient reported in table 4.2.

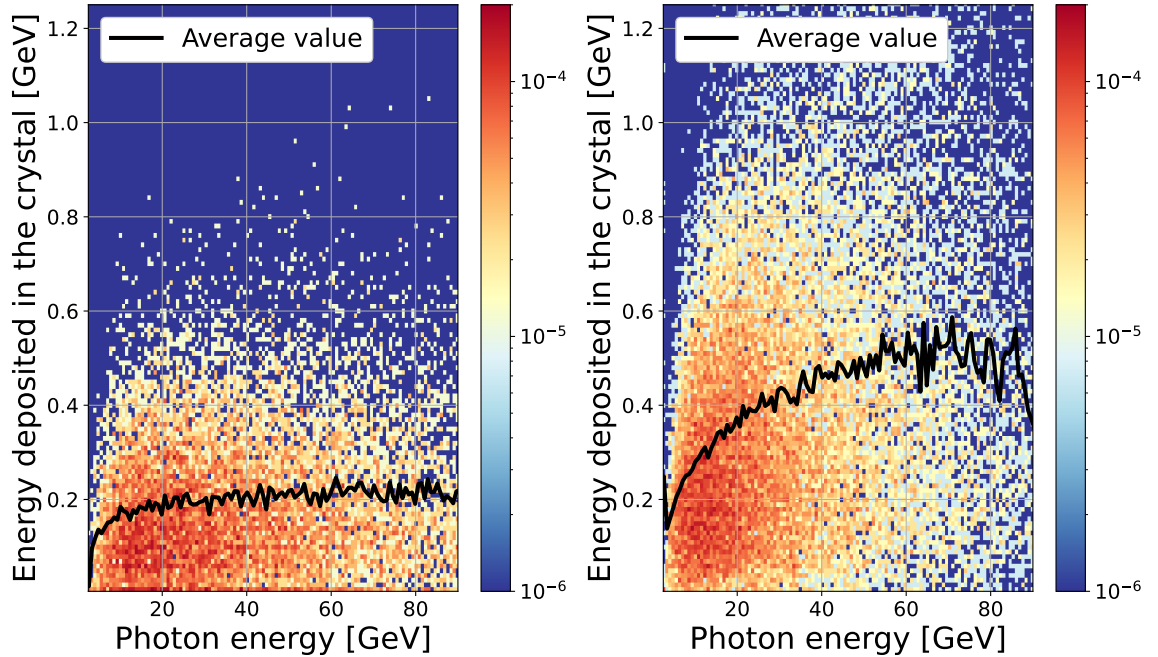


Figure 4.15: Correlation between the energy deposited in the PbF_2 crystal and the energy of the incident photons, when a high multiplicity of charged particles is observed (i.e., when more than 5 tracks are reconstructed in both planes of the C2 module). Left: random orientation. Right: axial alignment.

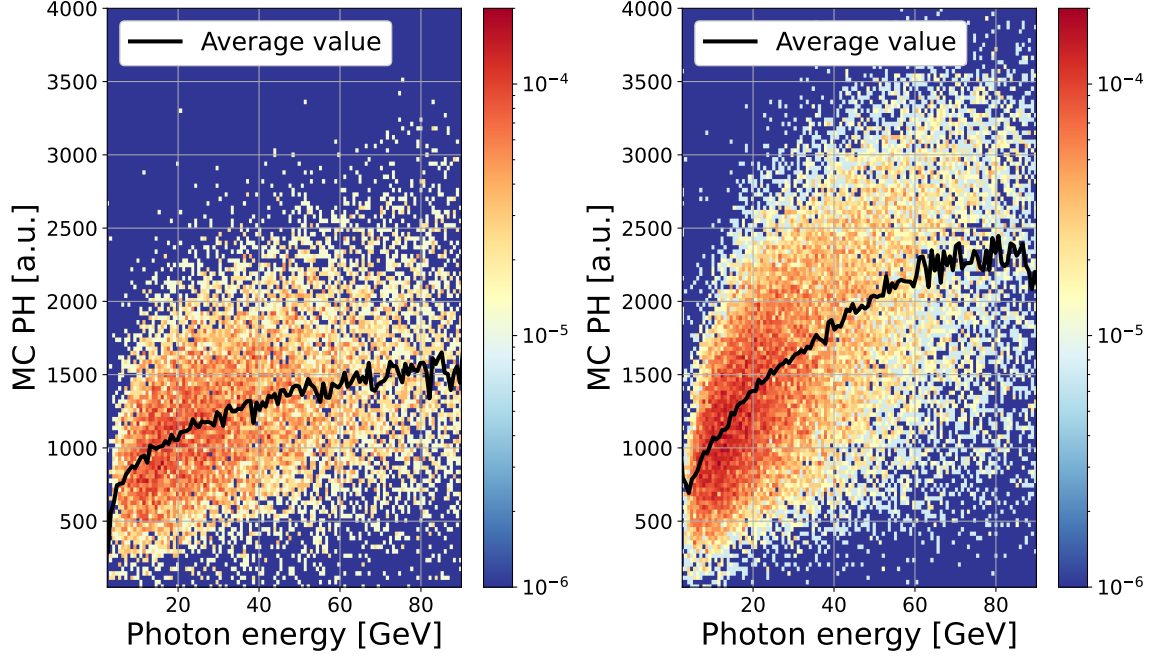


Figure 4.16: Correlation between the multiplicity of the MC PH and the energy of the incident photons, when a high multiplicity of charged particles is observed (i.e., when more than 5 tracks are reconstructed in both planes of the C2 module). Left: PbF₂ crystal in random orientation. Right: crystal in axial alignment.

4.2.4 THE ENHANCEMENT OF THE PAIR PRODUCTION CROSS-SECTION

In order to compute the enhancement of the energy deposited in the crystal as a function of the angle between the lattice axis and the incident photon beam, the following procedure was adopted:

- For every alignment condition, the correlation between E_{crystal} and the energy of the incident photons was computed, as shown in figure 4.15, without applying any selection criterion to the acquired data.
- The projection of the correlation histogram on the horizontal axis, namely the average energy deposited in the crystal as a function of E_{γ}^0 , was found.
- The ratios of the projections obtained at the different incidence angles and the projection corresponding to the random orientation were computed.

This procedure allowed to measure the energy deposit enhancement factor (e.f.) as a function of E_{γ}^0 , for all the points in the angular scan (figure 4.17). In particular, a e.f. value of $\sim 2.5 - 2.75$ was observed for incident photons with an energy larger than ~ 40 GeV, namely when the Strong Field regime condition is fully satisfied (i.e., when $\chi \sim 1$, table 3.2). Moreover, the curves corresponding to incidence angles smaller than 0.625 mrad were found to be almost identical, as predicted by the theory of the Strong

Field regime. Finally, a e.f. larger than 1.50 was obtained even at the largest incidence angles (i.e., 8.313 mrad).

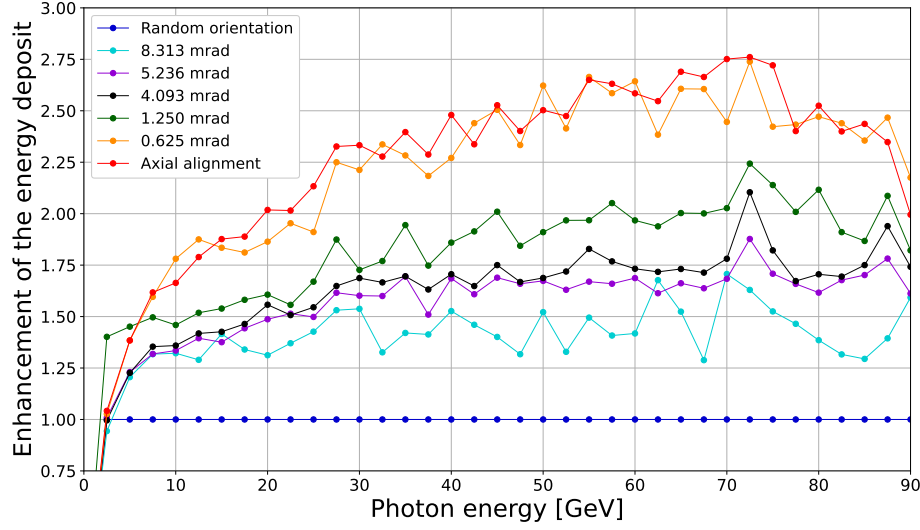


Figure 4.17: Enhancement of the energy deposited in the PbF₂ crystal (e.f.), for different photon incidence angles. The relative errors on the points are $\sim 25\%$ (figure 4.18) and are not shown for readability reasons.

The axial e.f. curve was fitted, in the 0 – 75 GeV energy range, with a logarithmic function, to empirically model the slow increase of e.f. as a function of the photon energy⁶. The fit function was the following:

$$y = a \cdot \log(bx + c) \quad (4.10)$$

where y is the e.f. and x is the photon energy. The data corresponding to a photon energy larger than 75 GeV were not considered in the fit, since the corresponding statistics was small enough to observe unphysical fluctuations of the enhancement factors. The fitted curve is presented in figure 4.18: the logarithmic model was found to be in excellent agreement with the experimental data, since a reduced chi-square⁷ of 0.012 was obtained. The fitted curve allowed to predict the e.f. value at an energy of 120 GeV to be 2.97 ± 0.19 . This value is in excellent agreement with the results reported in [56], where the characterization of an oriented 2 X₀ PbWO₄ sample exposed to a 120 GeV/c electron beam is described and an e.f. of ~ 3 was found.

The procedure described above was applied also to the PH spectra of the MC, in order to measure the enhancement of the multiplicity of the charged particles produced in an

⁶ An empirical reason behind the choice of this model is given by the consideration that, in a randomly oriented crystal, the peak of the e.m. shower is $t_{\max} \sim \log(E/E_c)$, where E is the incident particle energy and E_c the critical energy [35, 90]. Since in an oriented crystal the shower peak was found to be approximately energy-independent (section 2.5), the e.f. should scale as $\sim \log(E)$.

⁷ The reduced chi-square (χ^2) was defined as [35]:

$$\overline{\chi^2} = \frac{1}{N} \sum_{i=1}^N \frac{(y_{i,exp} - y_{i,fit})^2}{\sigma_i^2}$$

where N is the number of points composing the e.f. curves, $y_{i,exp}$ the experimentally measured e.f., $y_{i,fit}$ the fit points and σ_i the uncertainties on $y_{i,exp}$.

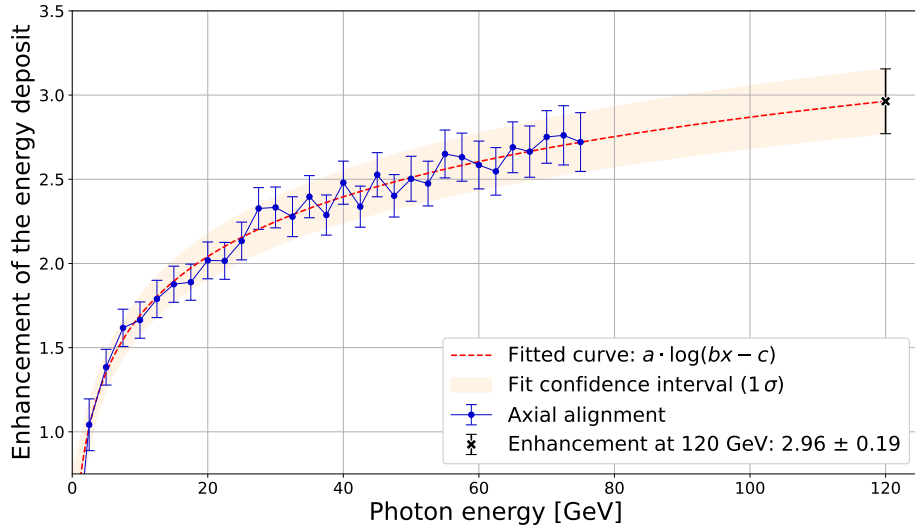


Figure 4.18: Enhancement of the energy deposited in the axially aligned PbF_2 crystal, with respect to a non oriented lattice. The experimental data have been fitted with a logarithmic function, in order to predict the enhancement factor at 120 GeV, to compare the results with the ones documented in [56].

oriented and a randomly oriented crystal. The e.f. curve is shown in figure 4.19. In this case, a smaller increase was observed, with respect to the e.f. curve of the energy deposit; this effect could be due to the limited angular acceptance of MC, which prevents an accurate estimation of the multiplicity of the charged particles produced in the crystal. However, the two curves present the same angular dependence, thus confirming the predictions of the theory of the Strong Field regime.

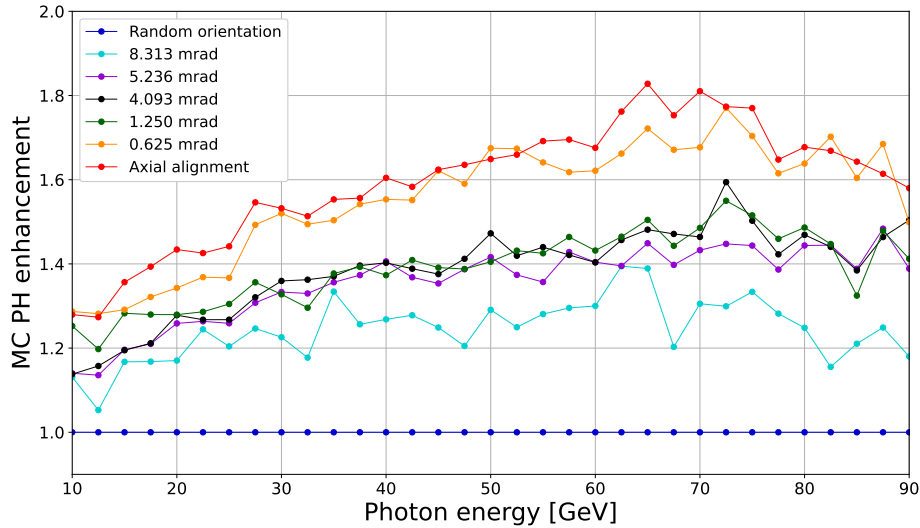


Figure 4.19: Enhancement of the multiplicity of the charged particles produced in the PbF_2 crystal (e.f.), for different photon incidence angles. The relative errors on the points are $\sim 10\%$ and are not shown for readability reasons.

4.2.5 THE RADIATION LENGTH REDUCTION

Once defined an energy deposit e.f., it is possible to compute the equivalent thickness of the randomly oriented crystal (L_{axial}) seen by the photons impinging on the axis of an oriented lattice. To perform this calculation, it is necessary to either measure or model the energy deposit curve in the randomly oriented material (figure 4.20). The equivalent reduction of the radiation length is then given by:

$$\chi_0^{red} [\%] = 100 \cdot \left(1 - \frac{L_{axial}}{L_{random}} \right) \quad (4.11)$$

where L_{random} is the physical length of the crystal. This is a rough approximation of the actual reduction of the radiation length, which can be estimated accurately only by numerically integrating the motion equations of the particles in the oriented lattice, as described in [104].

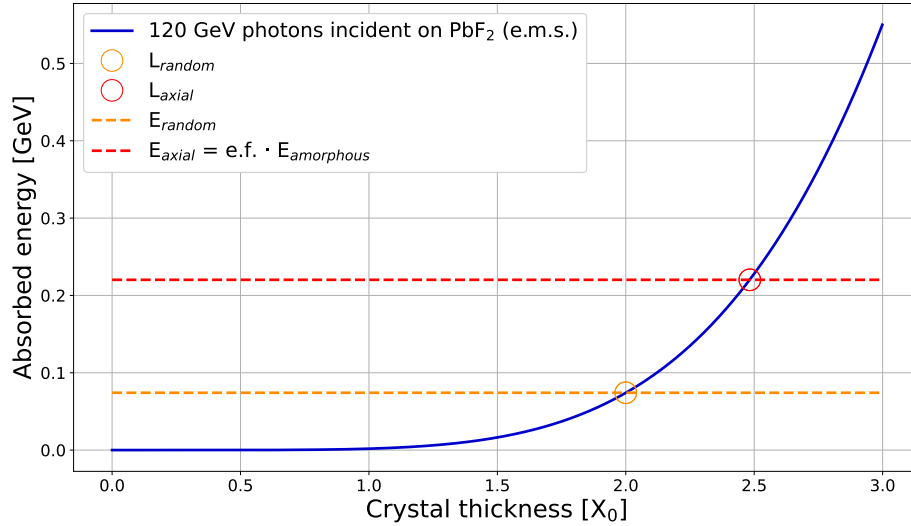


Figure 4.20: Dependence of the energy deposited in a randomly oriented PbF₂ crystal by a 120 GeV photon on the thickness of the material. The curve was obtained by integrating the electromagnetic shower model (e.m.s.) based on eq. (4.12) and described in [90]. To compute the equivalent thickness of the axially aligned crystal (L_{axial}), it is first necessary to evaluate the predicted energy deposit (E_{random}) at the physical length of the material (L_{random}). L_{axial} is given by the thickness where the predicted energy deposit is the product of the enhancement factor and E_{random} , namely E_{axial} .

Two different methods were employed to predict the energy deposit curves in a randomly oriented PbF₂ crystal:

- The shower development was described using the semi-empirical model (i.e., the e.m.s. model) presented in [35, 90]:

$$\frac{dE}{dt}(t) = E_0 b^a \frac{t^{a-1} e^{-b \cdot t}}{\Gamma(a)} \quad (4.12)$$

where dE is the mean energy deposited in a crystal of thickness dt (expressed in units of radiation length, t), E_0 the energy of the incident particle, Γ the generalized factorial function⁸ and a and b the model parameters. For photons incident on a high- Z material, the parameters may be computed as [90]:

$$a = \frac{5}{4} + \frac{1}{2} \log \left(\frac{E_0}{E_c} \right) \quad (4.13)$$

$$b = 0.5 \quad (4.14)$$

where E_c is the critical energy of the material. The energy deposit curve is computed as the definite integral of eq. (4.12):

$$E(t) = \int_0^t dt' \frac{dE}{dt'} = \frac{E_0}{\Gamma(a)} \gamma(a, b \cdot t) \quad (4.15)$$

where γ is the lower incomplete gamma function. The equivalent thickness of the crystal is then computed from this curve either using the method described above (e.g., figure 4.20), or defining $L_{\text{axial}} = k \cdot L_{\text{random}}$ and numerically solving the equation:

$$\text{e.f.}(k) = \frac{E(L_{\text{axial}})}{E(k \cdot L_{\text{random}})} = \frac{\gamma(a, b \cdot k \cdot L_{\text{random}})}{\gamma(a, b \cdot L_{\text{random}})} \quad (4.16)$$

where $L_{\text{random}} = 2 X_0$.

- The shower development was simulated using the Geant4 toolkit [161]. Each point of the energy absorption curve, corresponding to a thickness t and an initial photon energy⁹ E_0 , was determined by performing a 10000 events simulation of the energy deposited in a PbF₂ crystal, with a transverse area of 40 cm $\times$ 40 cm.

These methods allowed to compute L_{axial} and X_0^{red} as a function of the energy of the incident photons, given the previously determined e.f. (figure 4.18): the results are presented in figure 4.21. Both methods allowed to estimate a reduction of the radiation length of the oriented PbF₂ crystal larger than 15%, for incident photons with an energy larger than 20 GeV. However, the computed curves differ by $\sim 5\%$ in the high energy tail. In general, the Geant4 simulation should be regarded as the more accurate method, since it is known that the e.m.s. model underestimates the energy deposit in the first radiation lengths, as reported in [90] and visible in figure 4.22. Thus, the Geant4 approach was used to predict the radiation length reduction at 120 GeV, assuming an e.f. of 2.97 ± 0.19 and obtaining:

$$X_0^{\text{red}} = (30.56 \pm 1.95)\% \quad (4.17)$$

which is in perfect agreement with the result reported in [56] (i.e., $X_0^{\text{red}} \sim 30\%$).

⁸ The generalized factorial, namely the Gamma function, is defined as:

$$\Gamma(z) = \int_0^\infty dt t^{z-1} e^{-t}$$

⁹ In this simulation, the incident photon beam used was a pencil-beam, meaning that it features a null extension in the transverse plane and a null divergence.

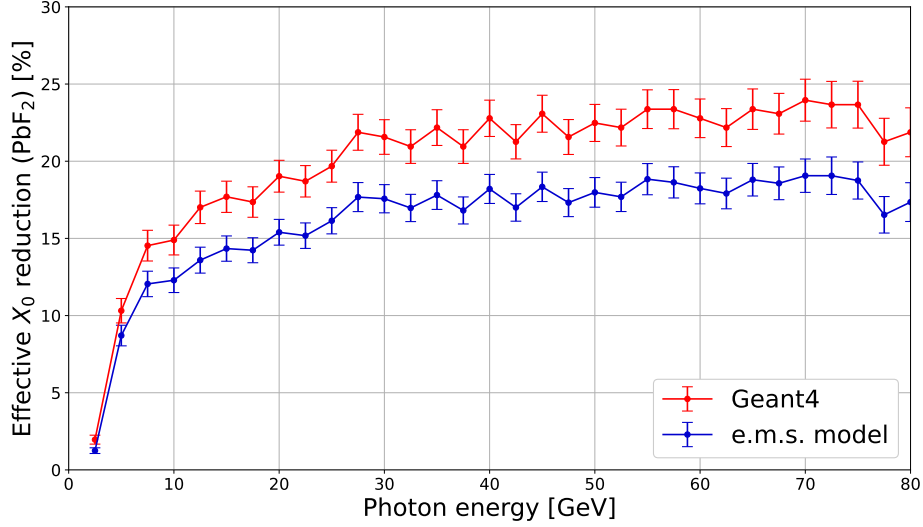


Figure 4.21: Reduction of the equivalent radiation length of an axially oriented PbF₂ crystal, with respect to the randomly oriented material.

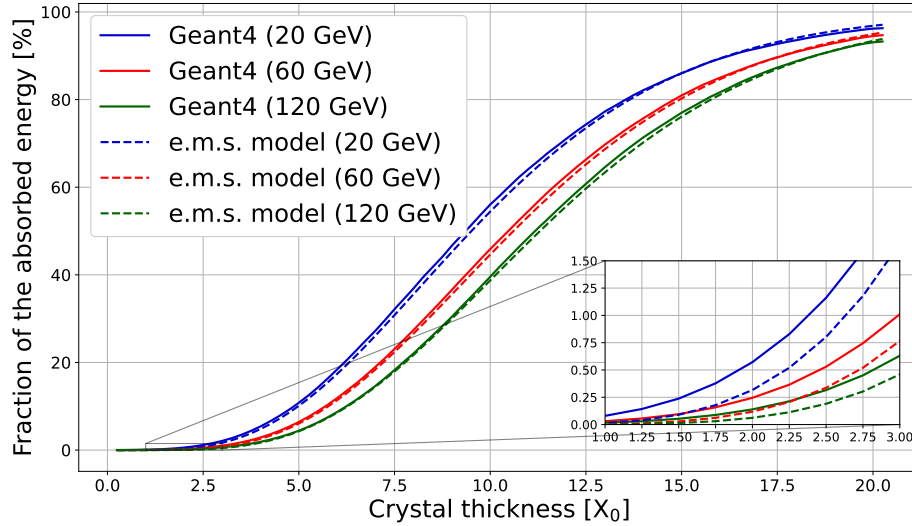


Figure 4.22: Comparison of the energy absorption curves in a PbF₂ crystal, computed with the e.m.s. model described by eq. (4.15) (dashed lines) and simulated with Geant4 (continuous lines). The inset plot is a zoom on the $1 - 3 X_0$ region.

4.3 PBWO₄ CHARACTERIZATION

This section presents the characterization of the oriented PbWO₄ crystal (section 3.1.1), which was coupled to the STORM photodetection system. The goal of this study was, once again, to measure the enhancement of the pair production cross-section and the reduction of the radiation length, which occur when the beam impinges on the crystal axis. Moreover, the measurement of the angular dependence of these effects was compared with the predicted acceptance of the Strong Field regime (Θ_0).

The alignment of the $1 X_0$ PbWO₄ crystal on the beamline was performed following the procedure described for PbF₂. The stereogram of the PbWO₄ crystal, showing the coordin-

ates of the $\langle 100 \rangle$ axis, is presented in figure 4.23. After the alignment, the crystal was characterized by means of dedicated long-statistics runs, using the 120 GeV electron beam and setting the bending magnet at the maximum current (850 A). The events selection criteria used to select the data to be analyzed were the ones already defined for PbF₂. Since the beam spot was smaller than the transverse area of the crystal, the fiducial region was defined in this case as a small rectangle in the center of the PbWO₄ efficiency map (figure 4.24). The reference SiPM used in the reconstruction of the efficiency map and in the other measurements was the one with the largest PHs.

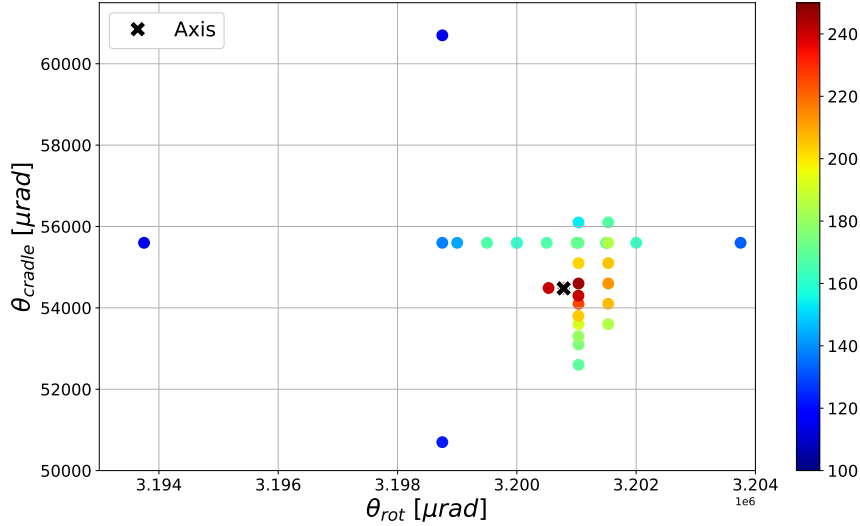


Figure 4.23: Crystallographic stereogram of the oriented PbWO₄ sample, reconstructed by measuring the average PH of the SiPMs in each point of the preliminary angular scans.

Angle [mrad]	Alignment condition	Analyzed events
0	Axial alignment	156840
1.000	Transition	160521
4.000	Transition	78047
50.000	Random orientation	41153

Table 4.3: Angular scan performed with the oriented PbWO₄ sample. The reported statistics were computed after applying the cuts described in the text.

4.3.1 THE PRELIMINARY MEASUREMENTS

The characterization of the Strong Field effects occurring in the PbWO₄ crystal was performed following the procedure described for the PbF₂ crystal, namely by measuring:

- The energy deposited in γ CAL and eCAL (figure 4.25). A small reduction of the tail of the γ CAL spectrum was observed: in this case, the variation of the spectrum intensity is smaller than the one measured with PbF₂, due to the difference between the two crystal thicknesses. The independence of the eCAL spectrum on the beam inci-

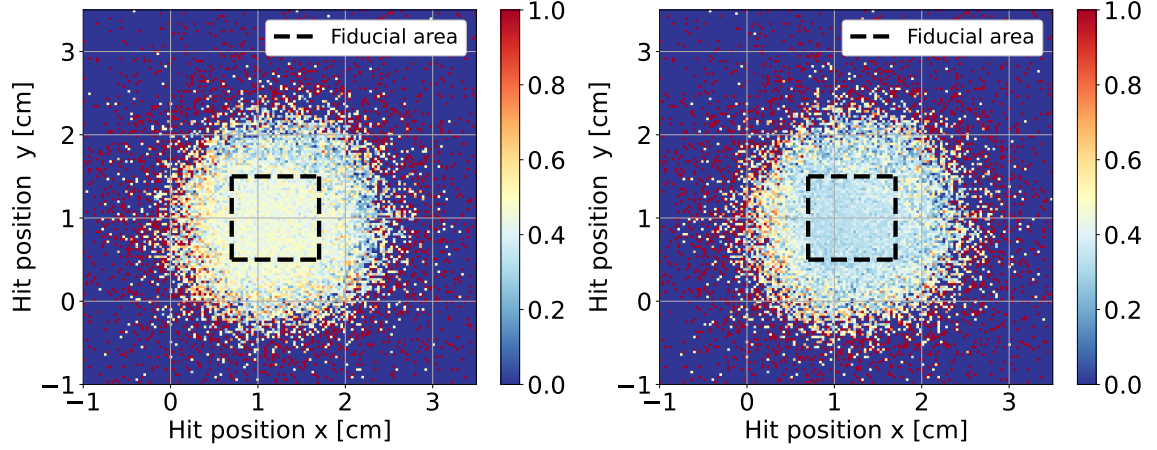


Figure 4.24: Left: efficiency map of the PbWO₄ crystal, defined as the distribution of the fraction of the events where the PH of the reference SiPM was larger than 50 a.u.. Right: efficiency map of the PbWO₄ crystal, reconstructed by requiring the detection of at least 5 tracks (clusters) in at least one side of the C2 module.

ence angle confirmed that the variation of the PH of any detector must be attributed to the Strong Field effects and not to a fluctuation of the photon energy spectrum.

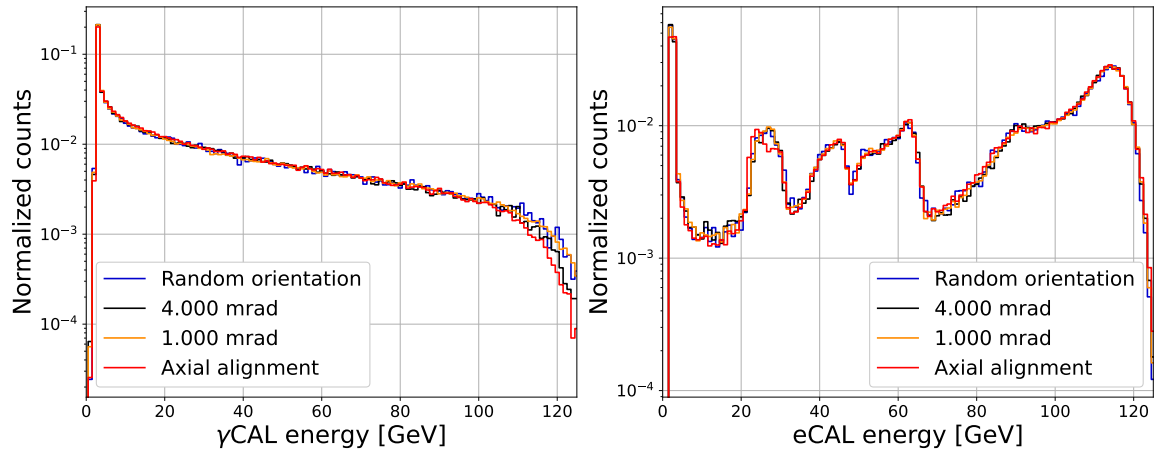


Figure 4.25: Left: γ CAL energy spectra, shown for different angles between the photon beam and the PbWO₄ crystal. Right: eCAL energy spectra, shown in the same conditions. The discontinuities which can be observed in the eCAL spectra are due to the presence of small gaps between the electromagnetic calorimeters. In both figures, the histograms are normalized.

- The energy deposited in the crystal (figure 4.26), computed by rescaling the SiPM PH with the calibration coefficient (m). In this case, it was not possible to measure the energy deposited in the crystal by a MIP, due to the small thickness of the active material and the lower gain of the SiPMs. However, the characterization of the PbF₂ crystal demonstrated the reliability of the simulation approach. Thus, the full Geant4 simulation of the experimental setup was used to determine the following calibration coefficient (figure 4.27):

$$m = (1649.63 \pm 15.72) \text{ a.u./GeV} \quad (4.18)$$

The rescaled spectra show that the Strong Field regime causes an enhancement of the maximum energy deposited in the crystal of a factor ~ 2 .

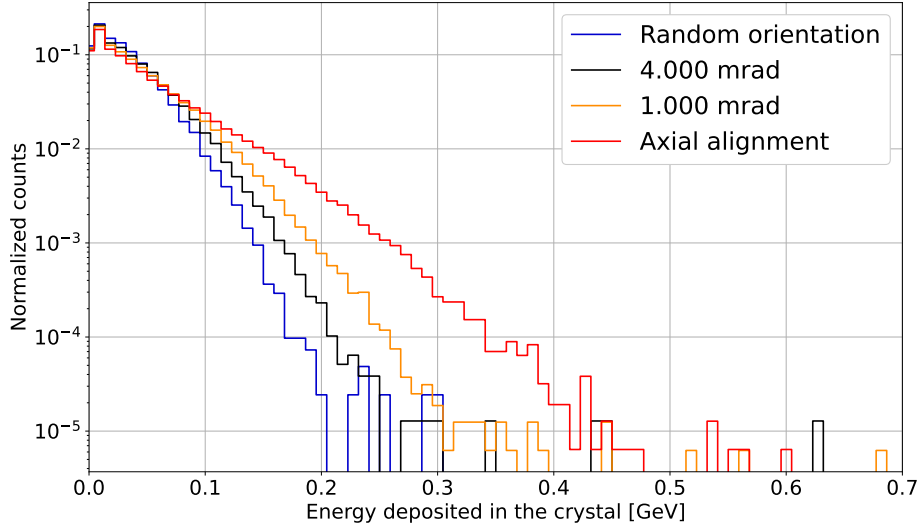


Figure 4.26: Comparison of the energy deposit distributions, for different incidence angles of the photon beam on the PbWO_4 sample. The spectra were computed by rescaling the SiPM PH spectra, using the calibration coefficient reported in eq. 4.18.

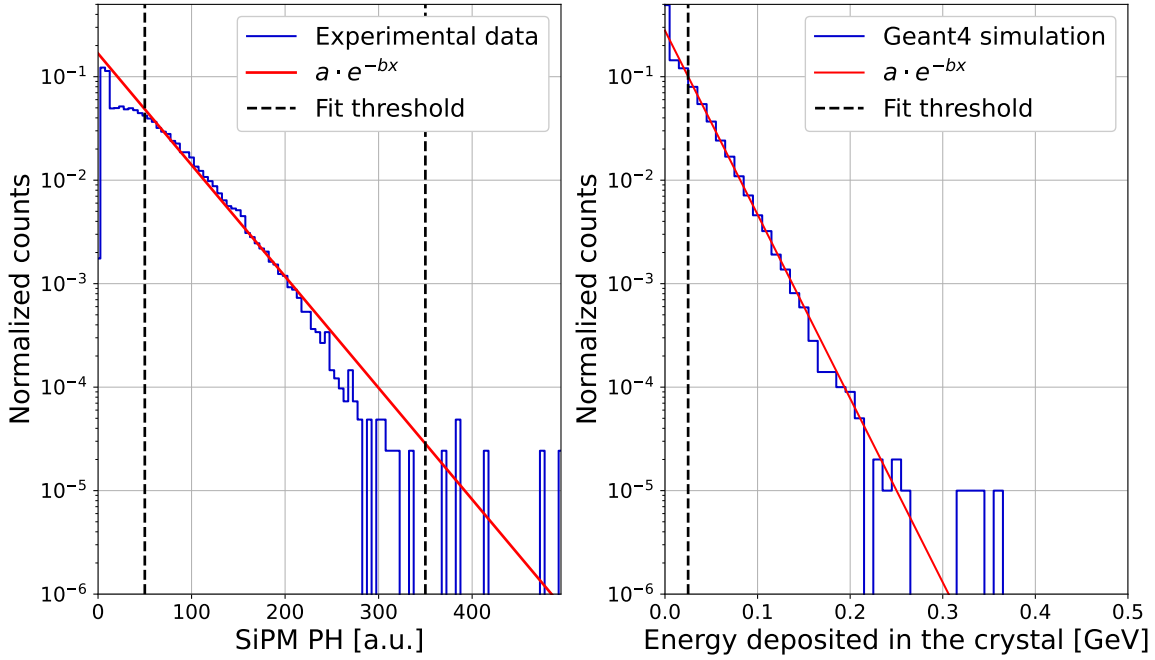


Figure 4.27: Left: PH distribution of the reference SiPM, measured with the oriented PbWO_4 crystal in random orientation. Right: distribution of the energy deposited in the crystal, computed with a full Geant4 simulation of the experimental setup. In both figures, the histograms are normalized.

- The MC PH (figure 4.28). The results obtained in this case are coherent with the ones shown for the SiPM: the maximum multiplicity of the produced charged particles increases of a factor ~ 1.5 , when the photon beam impinges on the crystal axis. Moreover, the acceptance of the CPP and CB phenomena is larger than the threshold

of the Strong Field regime, since even at 4 mrad the MC PH spectrum is different from the one recorded in the random orientation.

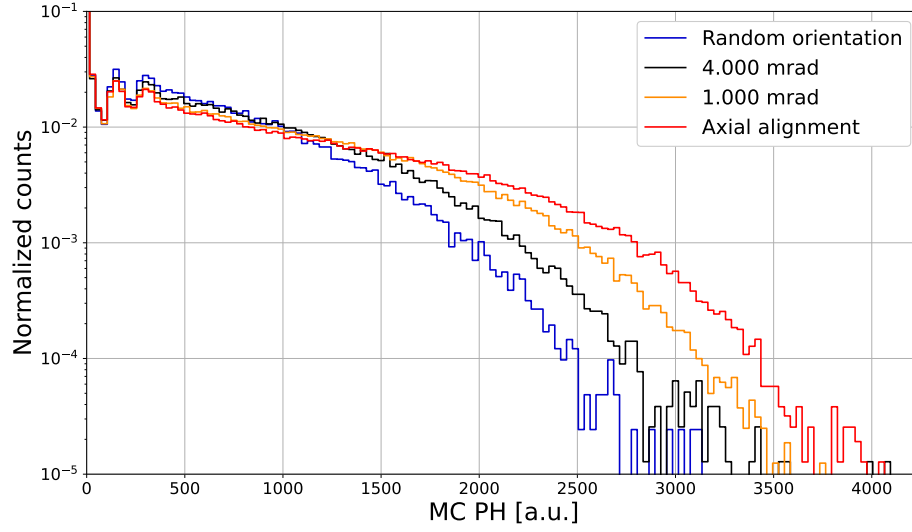


Figure 4.28: Comparison of the PH spectra of the Multiplicity Counter, for different incidence angles of the photon beam on the PbWO₄ crystal. The entries are normalized.

These results were confirmed by considering the dependence of the average PH of these detectors on the beam incidence angle (figure 4.29).

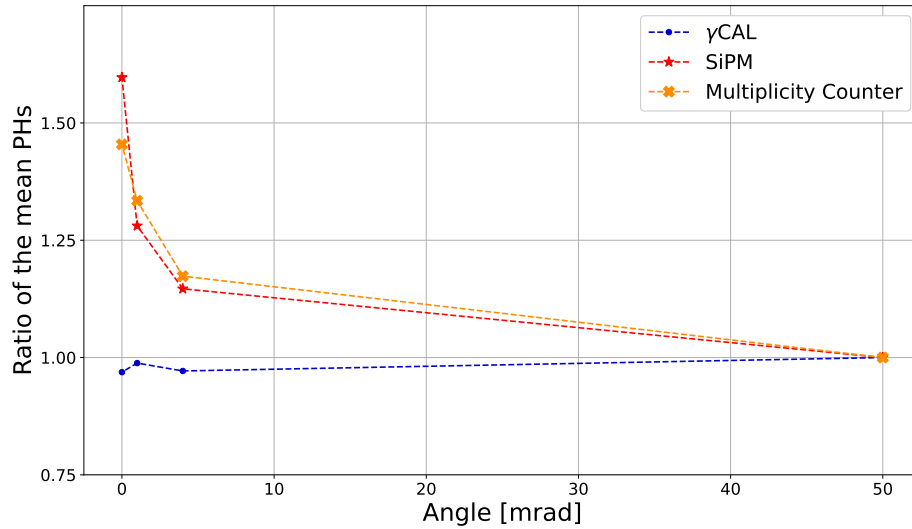


Figure 4.29: Dependence of the mean PH of the different detectors on the angle between the photon beam and the PbWO₄ crystal. The values were normalized to the random orientation (i.e., an angle of 50 mrad).

The calibration of the SiPM allowed to overcome the limits of the electron spectrometer and compute the energy of the incident photons as:

$$E_{\gamma}^0 = E_{\gamma} + m \cdot \text{PH}_{\text{SiPM}} \quad (4.19)$$

where, once again, it is assumed that all the energy of the incident photon is absorbed either in the crystal or in γ CAL. Figure 4.30 presents the correlation between the energy deposited in the crystal, when a high multiplicity of charged particles is detected. Figure 4.31 presents the same correlation histogram, computed using the MC PH, rather than the deposited energy in the crystal. In both cases it is evident that the Strong Field regime induces an increase of the pair production cross-section which is proportional to the energy of the incident particles, with a maximum e.f. of 2 – 2.5.

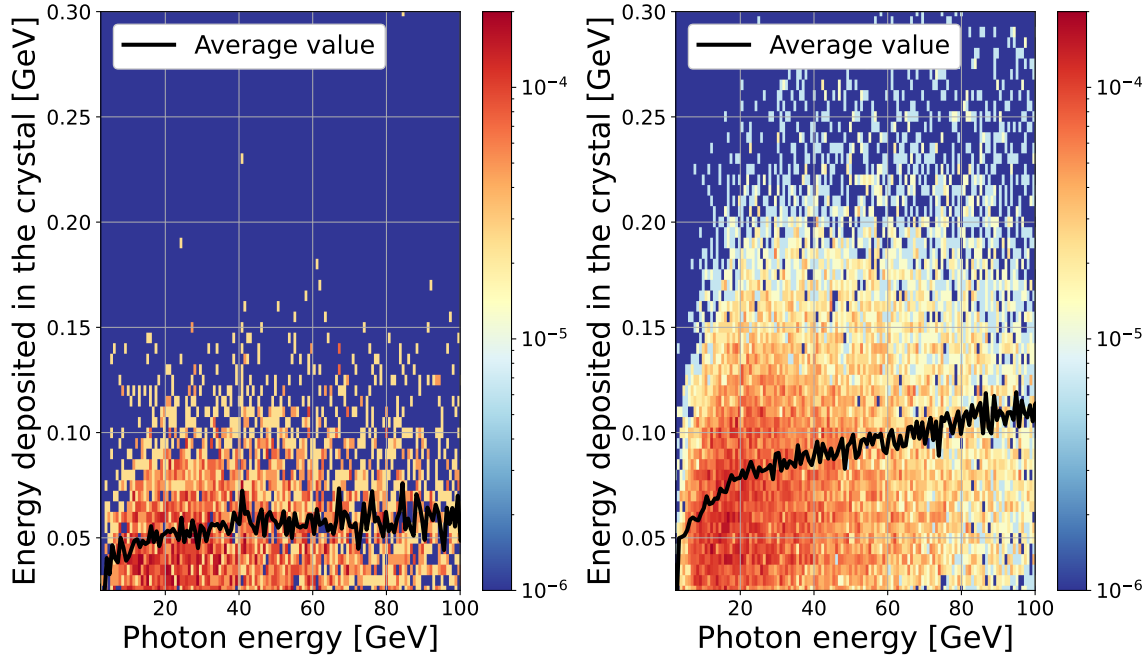


Figure 4.30: Correlation between the energy deposited in the PbWO_4 crystal and the energy of the incident photons, when a high multiplicity of charged particles is observed (i.e., when more than 5 tracks are reconstructed in both planes of the C2 module). Left: random orientation. Right: axial alignment.

4.3.2 THE ENHANCEMENT OF THE PAIR PRODUCTION CROSS-SECTION

The energy deposit enhancement factor (e.f.) was computed for the PbWO_4 crystal as a function of the photon energy, following the procedure described in section 4.2.4. Figure 4.32 presents the e.f. curves, measured for each beam-axis angle: the reported values are smaller than the ones obtained with PbF_2 , as it could be expected, due to the different crystal thicknesses. The e.f. curve measured in axial alignment was fitted by means of eq. (4.10): the results are presented in figure 4.33. In this case, a reduced chi-square of 0.027 was obtained, confirming the excellent agreement between the experimental data and the logarithmic model. The fit parameters allowed to predict the e.f. value at an energy of 120 GeV:

$$\text{e.f.}(120 \text{ GeV}) = 2.09 \pm 0.37 \quad (4.20)$$

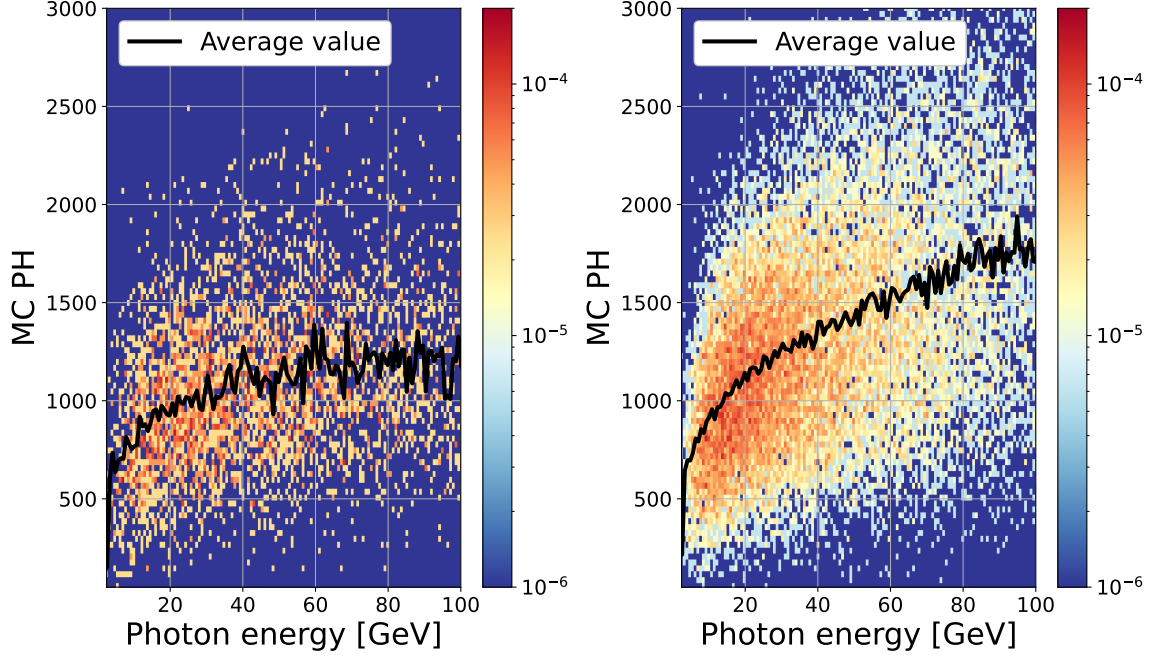


Figure 4.31: Correlation between the multiplicity of the charged particles exiting from the PbWO₄ crystal, evaluated as the MC PH, and the energy of the incident photons, when a high multiplicity of charged particles is observed (i.e., when more than 5 tracks are reconstructed in both planes of the C2 module). Left: random orientation alignment. Right: axial alignment.

This value is consistent with the results reported in [56]. In fact, by exposing the 1 X₀ PbWO₄ crystal to an incident electron beam with an energy of 120 GeV, an enhancement of the energy deposit of a factor ~ 2 was found.

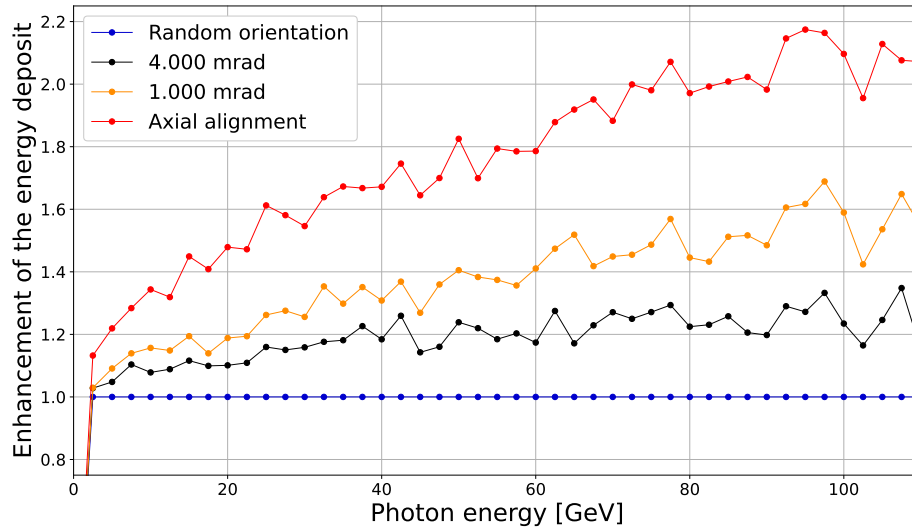


Figure 4.32: Enhancement of the energy deposited in the PbWO₄ crystal (e.f.), for different photon incidence angles. The relative errors on the points are $\sim 18\%$ (figure 4.33) and are not shown for readability reasons.

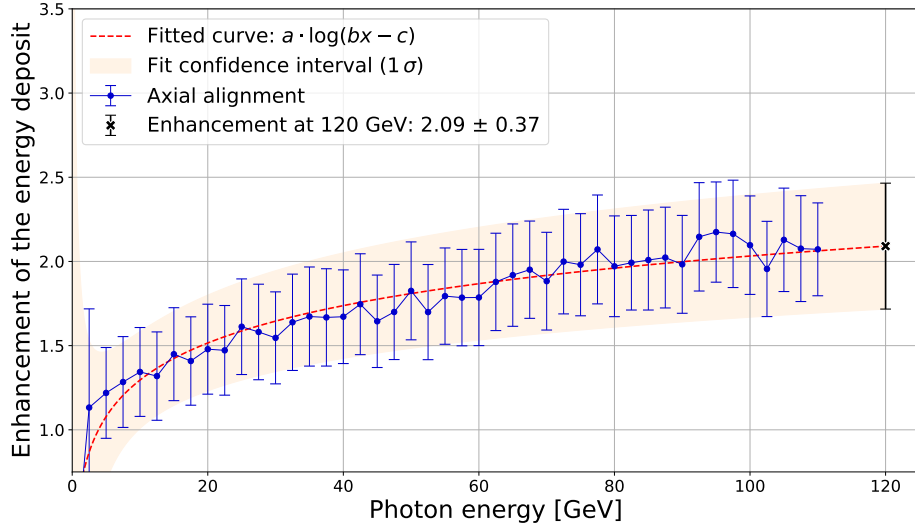


Figure 4.33: Enhancement of the energy deposited in the axially aligned PbWO_4 crystal, with respect to a randomly oriented lattice. The experimental data have been fitted with a logarithmic function, in order to predict the enhancement factor at 120 GeV, to compare the results with the ones reported in [56].

Figure 4.34 presents the enhancement factors computed using the MC PH: the reported values are comparable to the ones obtained with the SiPM and with the PbF_2 sample. All these results confirm the fundamental predictions of the Strong Field regime, namely that:

1. The enhancement of the pair production cross-section is the same for incident electrons and photons and increases with the energy of the incident particle.
2. For incidence angles larger than the SF acceptance, there is still an enhancement of the pair production cross-section, due to the CPP and CB phenomena.

A quantitative measurement of the agreement between the experimental data and the theory will be given by simulating the interactions occurring in the oriented PbWO_4 crystal and comparing the results with the ones reported here.

4.3.3 THE RADIATION LENGTH REDUCTION

The energy deposit e.f. allowed to compute the equivalent reduction of the radiation length, which occurs in an oriented PbWO_4 crystal. Both the methods described in section 4.2.5 were applied, obtaining the results shown in figure 4.35. Similarly to the PbF_2 case, it was found that the e.m.s. model of the shower development underestimates the reduction of the PbWO_4 radiation length by 5% – 10%, due to the limited description accuracy in the first part of the energy loss curve. The Geant4 approach allowed to predict a reduction of the radiation length, at an incident energy of 120 GeV, of:

$$\chi_0^{\text{red}} = (23.08 \pm 4.09)\% \quad (4.21)$$

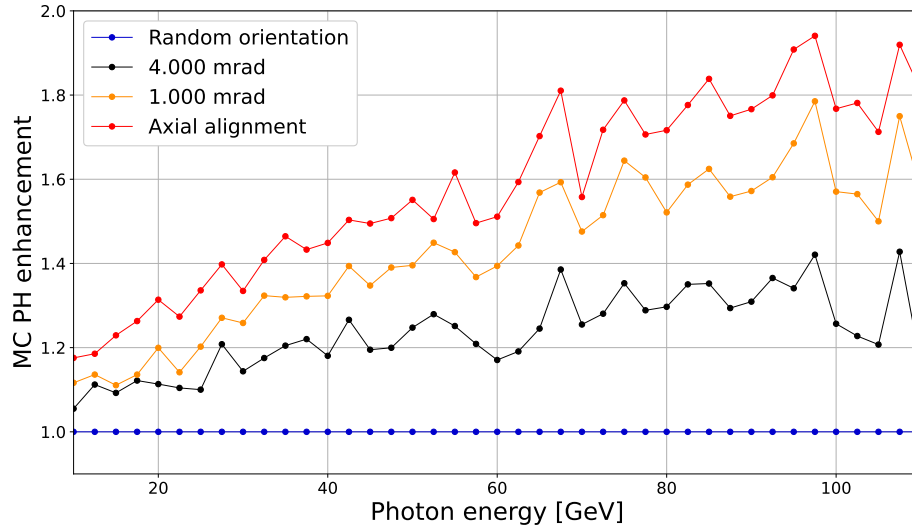


Figure 4.34: Enhancement of the multiplicity of the charged particles produced in the PbWO₄ crystal (e.f.), for different photon incidence angles. The relative errors on the points are $\sim 10\%$ and are not shown for readability reasons.

This result completes the characterization of the Strong Field interactions in the studied oriented crystals.

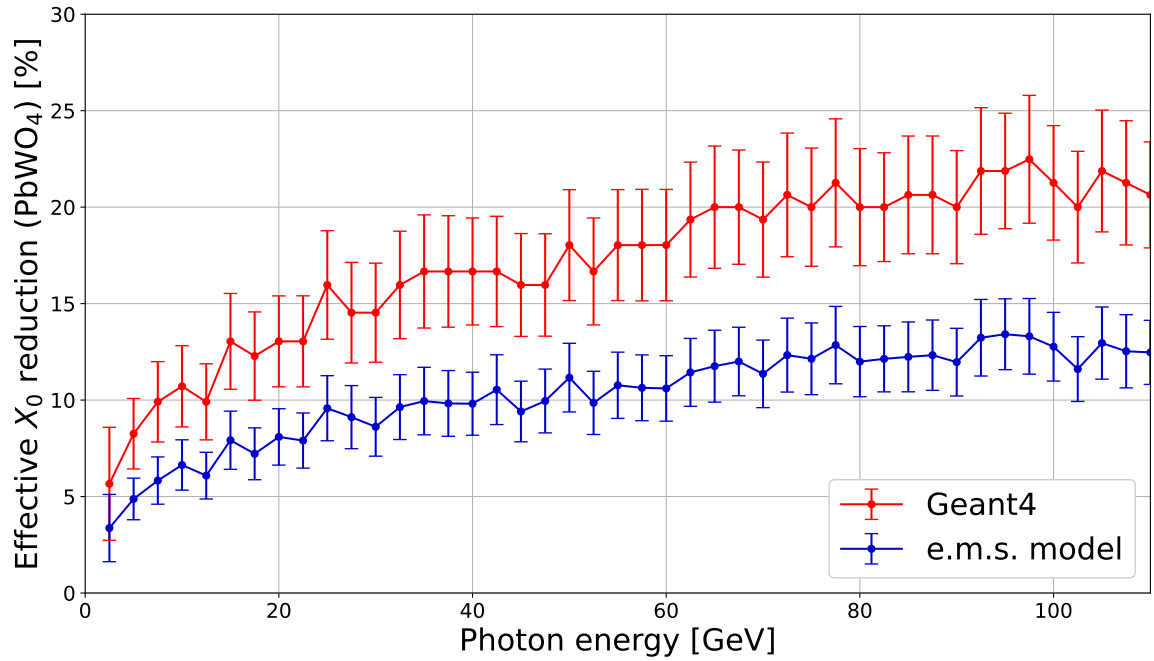


Figure 4.35: Reduction of the equivalent radiation length of an axially oriented PbWO₄ crystal, with respect to the randomly oriented material.

TIME RESOLUTION MEASUREMENTS

The time resolution of a photodetector is the spread of the time residual, namely the interval occurring between a reference signal and the detector response to a light pulse. One of the goals of the KLEVER 2021 beamtest was the measurement of the time resolution of several SiPMs, coupled to scintillating crystals and Cherenkov radiators and readout by custom FEE systems. In these measurements, the trigger signal was provided by the MCP detector, which determined the time of arrival of the incident beam with a nominal time resolution better than 35 ps [146]. The timestamps associated to the events were determined by analyzing the detectors analog signals and applying the “zero-crossing” extrapolation algorithm. The study of the variation of the time resolution of the SiPMs as a function of the energy deposited in the crystals provided a complete characterization of both the photodetection systems and the tested materials.

This chapter presents the time resolution measurements, describing the zero-crossing algorithm and its application to the measurement of the MCP time resolution, together with the results obtained analyzing the output signals of the CRILIN and STORM photodetection systems.

5.1 THE ZERO-CROSSING ALGORITHM

The method used to measure the instant in time corresponding to the trigger of any channel of a given particle detector is the “zero-crossing” extrapolation algorithm. This method is based on the analysis of the analog signals produced by the detector under study (i.e., the waveforms). Each signal is independently analyzed, with the following procedure:

1. The waveform is inverted, if it has a negative polarity.
2. The signal baseline, computed over the first 100 points of the acquisition window, is subtracted from the waveform (figure 5.1).
3. The rising edge of the waveform is fitted with a linear function. The fit region extends from t_{15} to t_{70} , that is, between the first point in time corresponding to a signal value larger than 15% of the event PH and the one corresponding to 70%.

4. The timestamp of the event (t_0) is computed by extrapolating to zero the linear function fitted on the rising edge:

$$t_0 = -\frac{q}{m} \quad (5.1)$$

where m is the angular coefficient of the linear function and q the constant term.

Figure 5.1 presents the application of this method to the output signal of the MCP detector. In the analysis of the SiPMs signals, an additional pre-processing step was added, before the interpolation of the rising edge: a smoothing of the waveform, through a 5-tick wide moving average filter (figure 5.2). This procedure reduced the amplitude of the noise oscillations of the signals, without altering the coefficients of the interpolated rising edges.

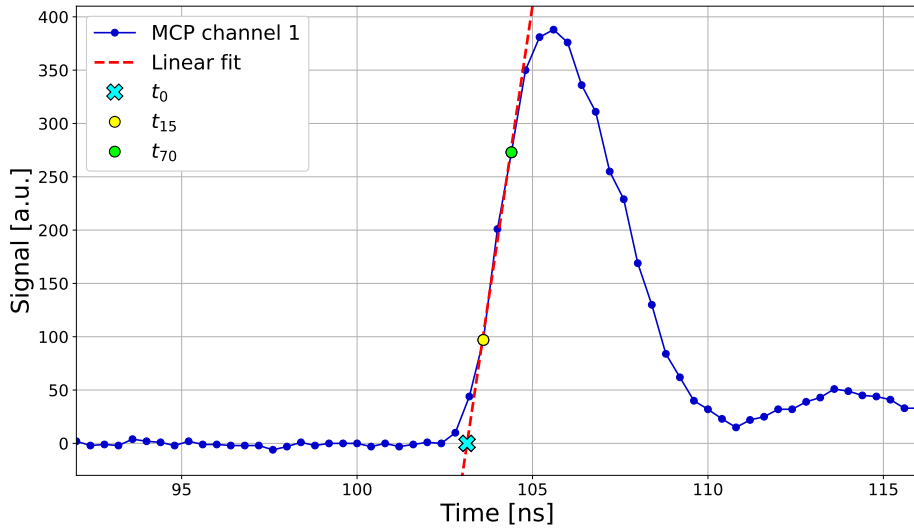


Figure 5.1: Application of the zero-crossing extrapolation algorithm to an analog signal produced by the MCP detector, sampled at a frequency of 2.5 GS/s. The cyan marker (X) represents the timestamp of the event (t_0).

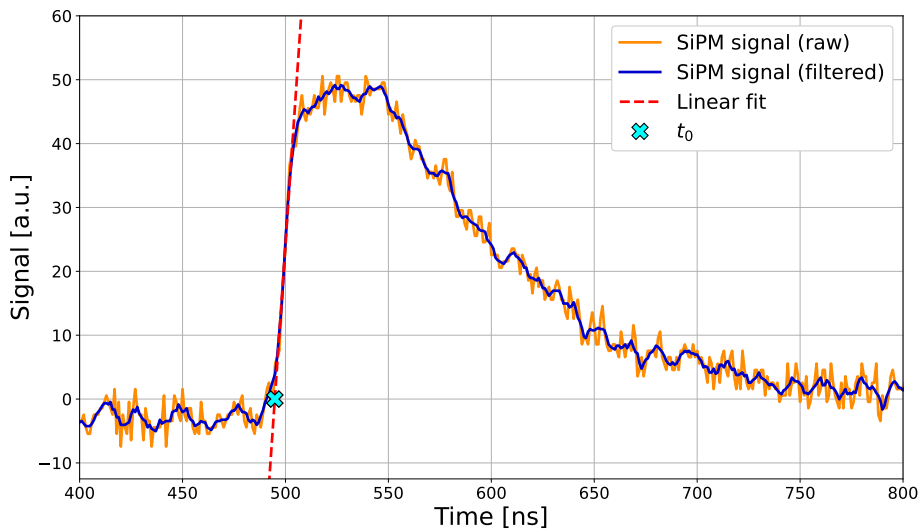


Figure 5.2: Comparison of the waveforms produced by a SiPM (CRILIN), before and after applying a 5-tick wide moving average filter.

5.2 THE MICRO-CHANNEL PLATE TIME RESOLUTION

Before the characterization of the SiPMs, the performance of the detector used to determine the times of arrival of the incident beam, namely the MCP, had to be evaluated. The MCP time resolution was estimated by studying the distribution of the difference of the particle detection times of the two MCP channels (t_1 and t_2), namely the time residual:

$$\Delta t = t_1 - t_2 \quad (5.2)$$

where t_1 and t_2 were computed applying the zero-crossing algorithm to the MCP waveforms. Since t_1 and t_2 are independent variables, Δt follows a gaussian distribution, whose standard deviation ($\sigma_{\Delta t}$) is given by the squared sum of the resolutions of the two channels ($\sigma_{\text{MCP, ch}}$). If the two contributions are assumed to be equal, the following relation is obtained:

$$\sigma_{\Delta t} = \sigma_{\text{MCP, ch}} \sqrt{2} \quad (5.3)$$

If the reference time used for the measurement of the SiPMs time resolution ($\bar{t}$) is given by the average of t_1 and t_2 , the uncertainty on the trigger signal is given by:

$$\sigma_{\bar{t}} = \frac{\sigma_{\text{MCP, ch}}}{\sqrt{2}} = \frac{\sigma_{\Delta t}}{2} \quad (5.4)$$

Two sets of data were used to measure $\sigma_{\Delta t}$ and extract the value of $\sigma_{\bar{t}}$:

- The first set was composed of dedicated runs, where the CRILIN photodetection system was coupled to the two non oriented PbF₂ samples (sections 3.1.1-3.1.2). In these measurements, the MCP signals were sampled at 2.5 GS/s. Cuts on the signal times were applied, in order to exclude random triggers from the analysis. Figure 5.3 presents the distribution of the time residual: the standard deviation of the fitted gaussian function is 30.23 ± 0.05 ps.
- The second set was composed of the data runs acquired either with the CRILIN photodetection system coupled to the oriented PbF₂ crystal, or with the STORM system coupled to the PbWO₄ crystal (sections 3.1.1-3.1.2). In these measurements, the MCP signals were sampled at 1 GS/s and the data were processed following the same procedure applied in the previous case. Thus, it was possible to measure once again the standard deviation of the gaussian function fitted on the MCP channels residual distribution, obtaining a value of 39.97 ± 0.04 ps.

Figure 5.4 compares the distributions obtained in the two cases: it can be seen that the one measured at 2.5 GS/s features a smaller width, with respect to the other (table 5.1). This difference is due to the fact that a digitization frequency of 2.5 GS/s corresponds to a sampling period of 0.4 ns and thus it allows to increase the number of points in the rising edge of each signal. This effect improves the resolution on the measurement of the residuals. Nevertheless, the difference between the two results is relatively small

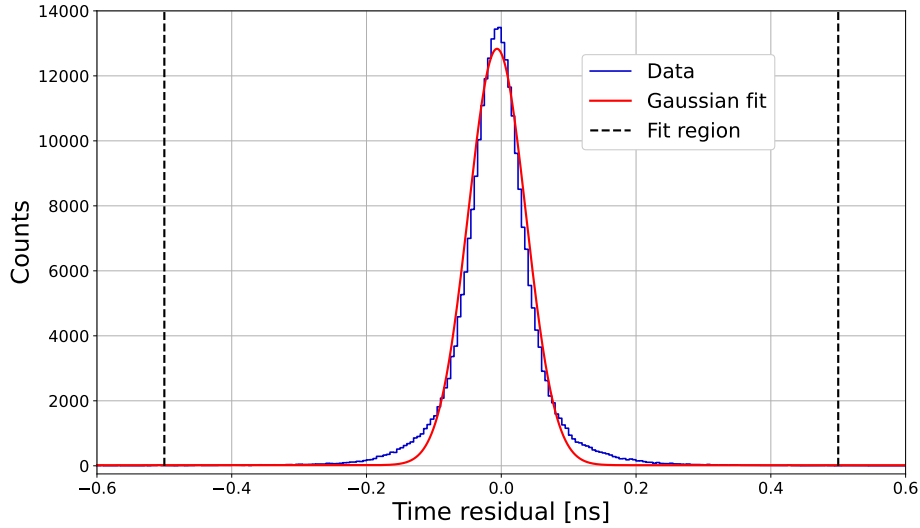


Figure 5.3: Distribution of the residuals between the zero-crossing times of the two MCP channels, obtained acquiring the data at a sampling frequency of 2.5 GS/s.

and confirms that the MCP detector is able to provide a stable reference in time, with a resolution on the measurement of $\bar{t}$ of 20 – 25 ps (eq. (5.4)).

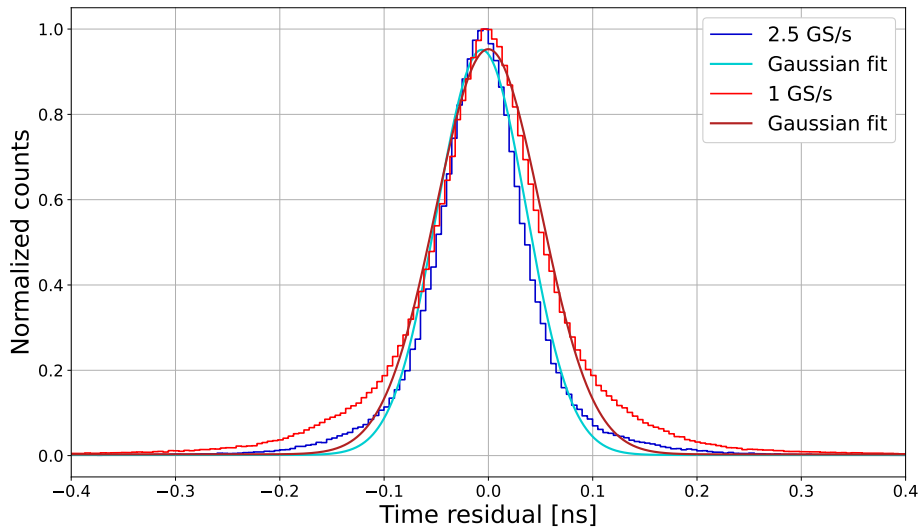


Figure 5.4: Comparison of the distributions of the residuals between the zero-crossing times of the two MCP channels, obtained acquiring the data at a sampling frequency of 2.5 GS/s (blue) and 1 GS/s (red). The histograms were normalized.

Sampling frequency [GS/s]	$\sigma_{\text{MCP,ch}}$ [ps]	$\sigma_{\bar{t}}$ [ps]
1	39.97 ± 0.04	28.27 ± 0.03
2.5	30.23 ± 0.05	21.38 ± 0.03

Table 5.1: Time resolution of the MCP channels ($\sigma_{\text{MCP,ch}}$) and of the average timestamp ($\sigma_{\bar{t}}$), computed analyzing the data acquired with two different sampling frequencies. The uncertainties on the resolutions are the fitting errors.

5.3 THE CRILIN PHOTODETECTION SYSTEM

This section presents the measurement of the time resolution of the CRILIN photodetection system (section 3.1.2). Two sets of data were used for this goal: the first set was composed of dedicated runs, where CRILIN was coupled to the two non oriented PbF_2 samples; in these measurements, the SiPMs signals were sampled at 2.5 GS/s. The second set was composed of all the runs where CRILIN was coupled to the oriented PbF_2 sample, namely the runs which were used to characterize the Strong Field effects occurring in the crystal (section 4.2). In these measurements, the SiPMs signals were sampled at 1 GS/s.

5.3.1 MEASUREMENTS WITH THE NON ORIENTED PbF_2 CRYSTALS

The first dataset used for the characterization of the CRILIN photodetection system was acquired coupling CRILIN to the two $4\text{ cm} \times 1\text{ cm} \times 1\text{ cm}$ non oriented PbF_2 crystals (figure 5.5). In these runs, the amplification gain of all the channels was set to 1x. The samples were exposed to an electron beam with an energy of 100 – 120 GeV and then to the tagged photon beam, produced by the interaction of the 120 GeV/c electron beam with the copper target.

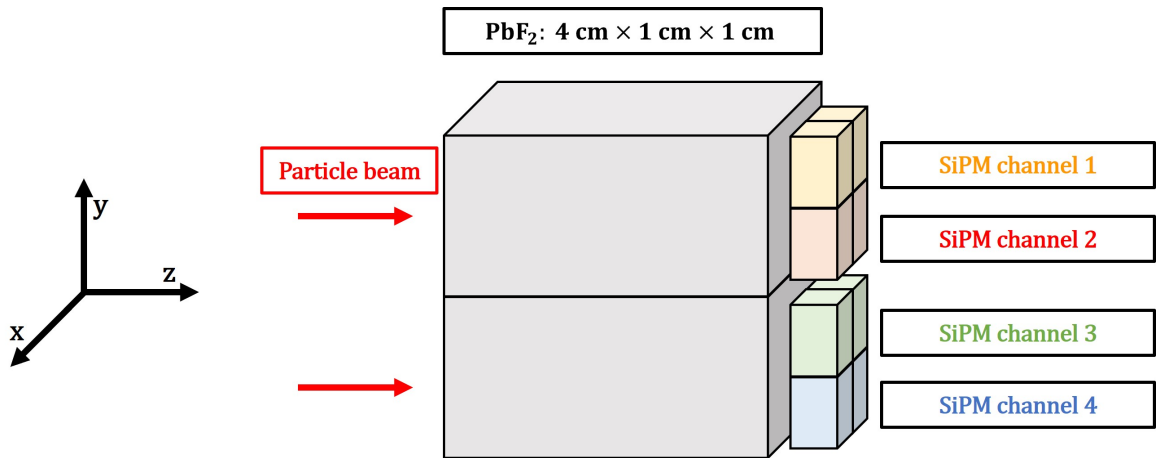


Figure 5.5: Experimental layout of the CRILIN photodetection system coupled to the non oriented PbF_2 crystals. The gray boxes are the crystals and each colored cube represents a $4\text{ mm} \times 4\text{ mm}$ SiPM matrix. As it was described in section 3.1.2, each readout channel was composed of two SiPM matrices connected in series and readout by a custom FEE system. The SiPMs belonging to the same channel are identically colored.

Only a part of the dataset was analyzed, since the detection of a single electron track in the upstream silicon trackers (T1, T2, C1) was required. Cuts on the signal time and PH of the SiPMs were applied, in order to remove the spurious triggers and the saturated events¹ (figure 5.6). Moreover, a fiducial region was defined by studying the correlation between

¹ The saturation mentioned in the text was caused by the limited input range of the DT5742 digitizer and the large output range of the CRILIN FEE system. In this case, the incomplete sampling of the rising edges of the signals prevented an accurate reconstruction of t_0 .

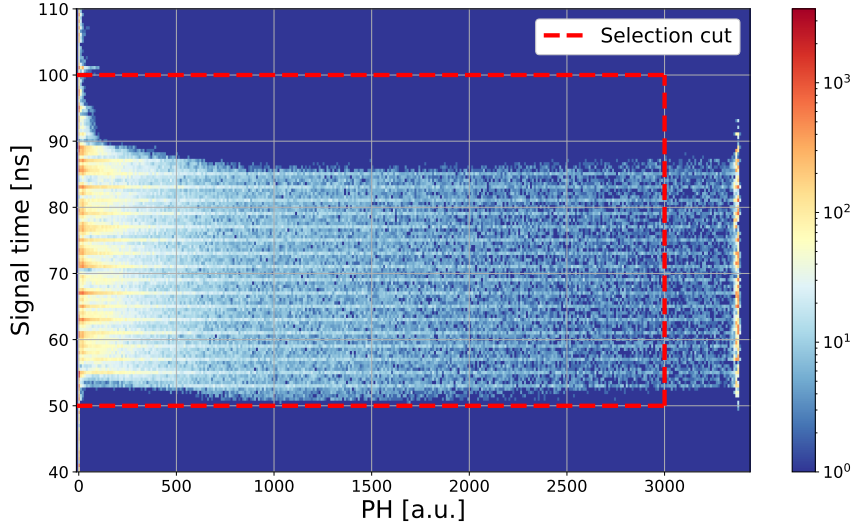


Figure 5.6: Correlation between the PH and the signal time, computed on the waveforms of a SiPM (CRILIN). The selection cut applied to avoid the saturated events and the spurious triggers is shown in red.

the PH of the SiPMs and the projections of the particles trajectories on the face of the crystal (figure 5.7). It was observed that the energy deposited in the crystals is not correlated with the hit position along the x axis, as long as the incident particle crosses the crystal volume. On the contrary, a strong correlation was observed between the PHs and the hit coordinates along the y axis (figure 5.7): this effect is due to the fact that the Cherenkov light is emitted in a narrow cone centered on the incident particle direction. Thus, the visible photons produced in the crystals reach only the SiPMs which are the closest to the interaction point, while the other SiPMs measure only a fraction of the light pulse. Such an effect was not visible along the x axis, since each readout channel was coupled to two SiPM matrices connected in series and placed in different points along the axis. Thus, they responded as if they were a single large-area SiPM, covering the whole crystal thickness along the x axis (figure 5.5). On the contrary, the different SiPMs placed along the y axis were completely separate one from each other. In order to avoid systematical errors, a narrow cut on the hit coordinates along the y axis was applied.

After applying the selection cuts, all the events were analyzed with the following procedure:

1. The signals were smoothed with a 5-tick wide moving average filter, in order to reduce the noise fluctuations without altering the shape of the rising edges.
2. The timestamp (t_0) of each signal with a PH larger than ~ 1600 a.u. was computed using the zero-crossing method described in section 5.1. This procedure could not be applied directly on the events with a PH smaller than ~ 1600 a.u., since they present a two-peaked shape, with the second peak being the highest (figure 5.8). In such cases, both t_{15} and t_{70} must be determined using as a reference the height of the first peak (h_0) and not the PH. The h_0 values were estimated with a custom resampling

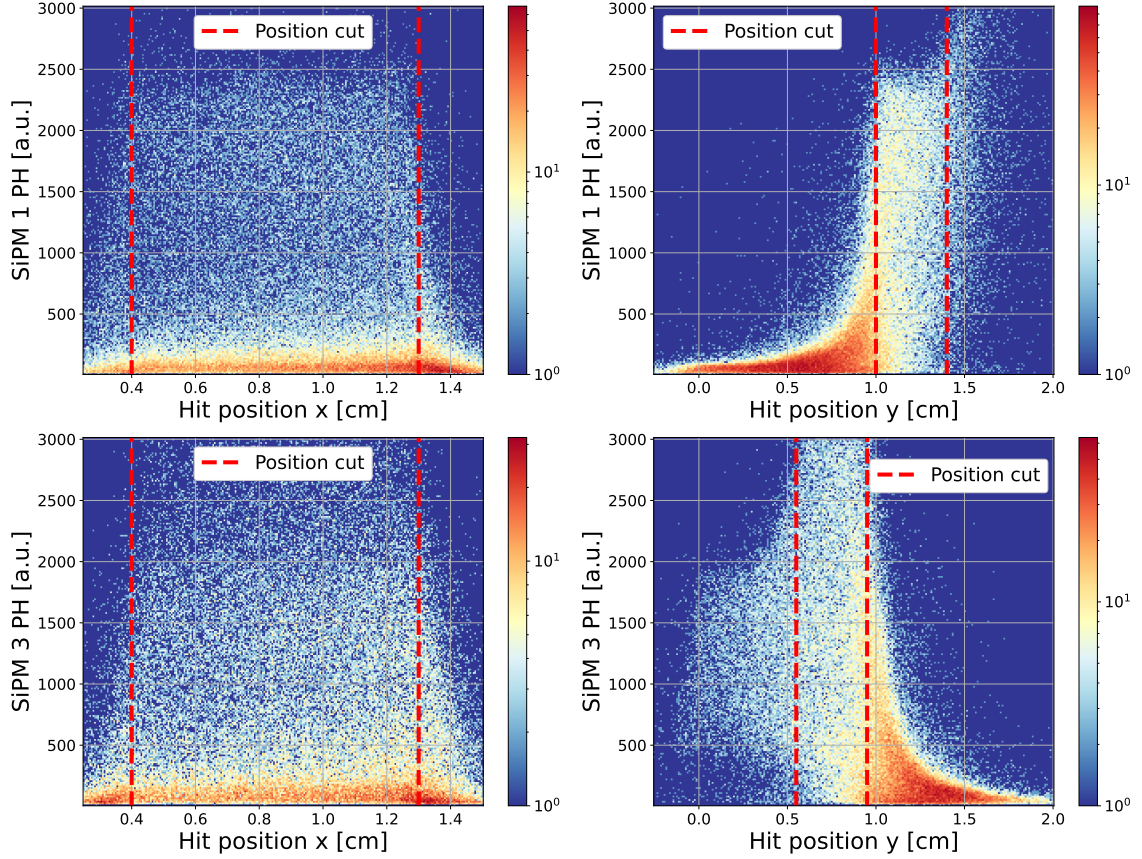


Figure 5.7: Correlation between the PH of the CRILIN SiPMs and the hit coordinates of the incident particles along the x (left) and y axis (right). Top: channel n. 1, corresponding to the two SiPM matrices connected in series and coupled to the upper PbF_2 crystal (figure 5.5). Bottom: channel n. 3, corresponding to the two SiPM matrices connected in series and coupled to the other crystal. The different positions of the matrices along the y axis caused the asymmetries visible in the histograms, which are due to the features of the Cherenkov light emission process, as described in the text.

algorithm (section A.3) and were used to evaluate the events timestamps (t_0), again with the zero-crossing method.

3. The residuals of the SiPM timestamps (t_0^j , $j = 1, 2, 3, 4$) and the average timestamp of the MCP channels ($\bar{t}_{\text{MCP}}$) were computed in the following way:

$$\Delta t^j = \bar{t}_{\text{MCP}} - t_0^j \quad (5.5)$$

4. The correlation between the time residual and the PH of the SiPMs was studied (figure 5.9, on the left) and a non linear dependence of the average residual on the PH was observed. This is known as “slew effect” and is due to the dependence of the shape of the rising edge of the output signal on the event PH. To avoid a systematical error on the estimation of the time resolution, a slew correction was applied, by fitting the dependence of the average time residual on the SiPMs PH with an exponential function (figure 5.10):

$$y = a + b \cdot e^{-cx} \quad (5.6)$$

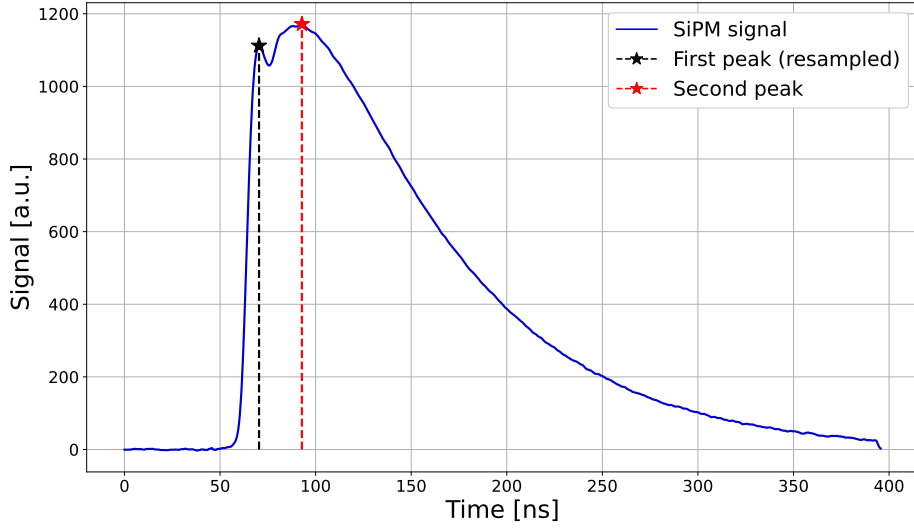


Figure 5.8: Waveform produced by one of the CRILIN SiPMs, coupled to one of the non oriented 4 mm PbF₂ crystals.

where x is the PH and y the average time residual. The slew effect was corrected subtracting from all the residuals the corresponding y value (figure 5.9, on the right).

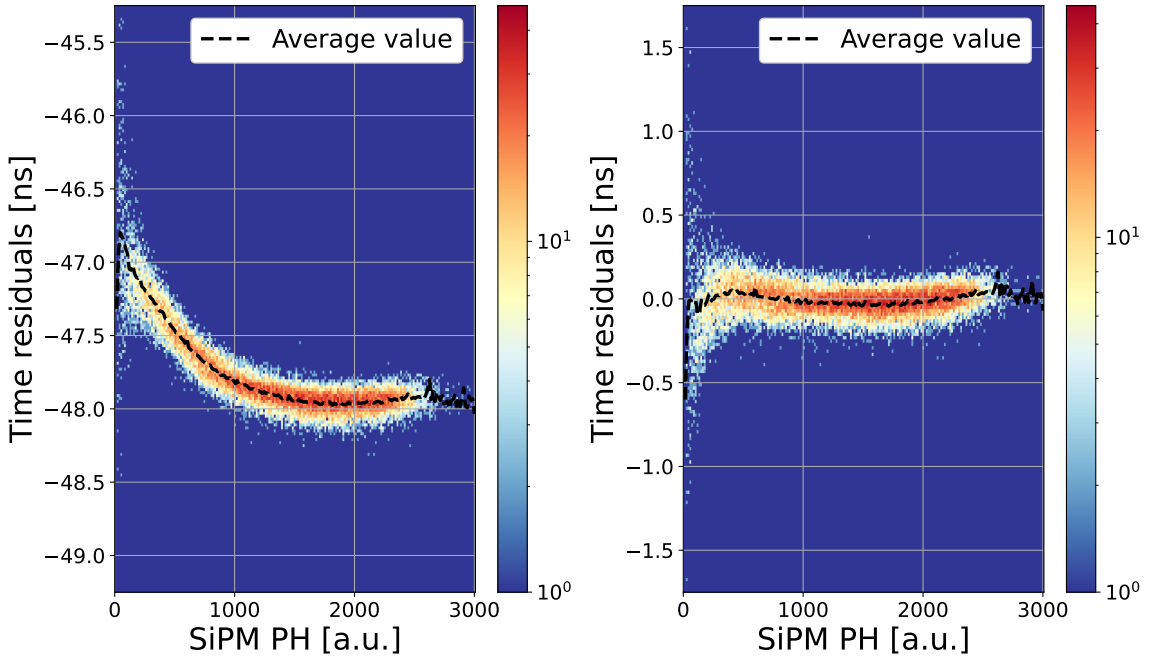


Figure 5.9: Correlation between the PH of the CRILIN SiPMs and the time residual, computed with eq. (5.5), before (left) and after (right) the slew correction.

5. The data were divided in PH bins, each one with a 60 a.u. width. The distribution of the time residuals measured in each bin was fitted with a gaussian function. This procedure allowed to estimate the SiPMs time resolutions as a function of the PH, using the following relation:

$$\sigma_{\text{SiPM}} = \sqrt{\sigma_{\Delta t}^2 - \sigma_t^2} \quad (5.7)$$

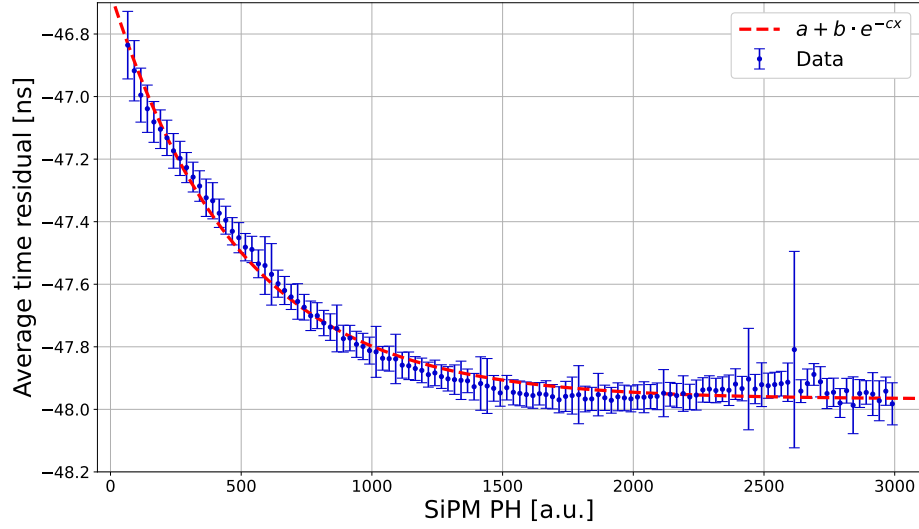


Figure 5.10: Slew correction of the CRILIN SiPMs time residuals: an exponential function was fitted on the average PH-residual dependence.

where $\sigma_{\Delta t}$ is the standard deviation of the fitted gaussian function and $\sigma_{\bar{t}}$ the MCP resolution measured at a sampling frequency of 2.5 GS/s (i.e., 21.38 ± 0.03 ps).

6. The energy deposits in the crystals were estimated by rescaling the PHs with the calibration coefficients obtained with the procedure described in section 4.2.3 (figure 5.11).
7. Each resolution curve was fitted with the following function (section 3.1.2):

$$\sigma_{\text{SiPM}}(E) = \frac{a}{\sqrt{E}} \oplus c \quad (5.8)$$

The fitted curves are presented in figure 5.11 and the values of the parameters extracted from the fit are reported in table 5.2.

Channel	a [ps · GeV ^{1/2}]	c [ps]	$\sigma_{\text{SiPM}}(1 \text{ GeV})$ [ps]
1	76.31 ± 1.18	46.42 ± 1.12	89.32 ± 1.16
2	76.70 ± 1.31	55.14 ± 1.03	94.46 ± 1.22
3	72.79 ± 1.17	52.95 ± 0.95	90.01 ± 1.10
4	74.13 ± 1.19	58.09 ± 1.04	94.17 ± 1.14

Table 5.2: Time resolution terms of the CRILIN SiPMs, obtained by analyzing the signals sampled at a frequency of 2.5 GS/s. The last column on the right reports the predicted time resolution of the SiPMs, for an energy deposit of 1 GeV in the crystals.

The results obtained in this analysis satisfy the desired requirements: in fact, every tested SiPM features a time resolution smaller than 100 ps for an energy deposit of 1 GeV (table 5.2). As required, the a factors of the resolution curves have been always found to be smaller than $100 \text{ ps} \cdot \text{GeV}^{1/2}$ and the c factors are as small as possible. These results confirmed the feasibility of using the CRILIN photodetection system for the readout of the KLEVER SAC.

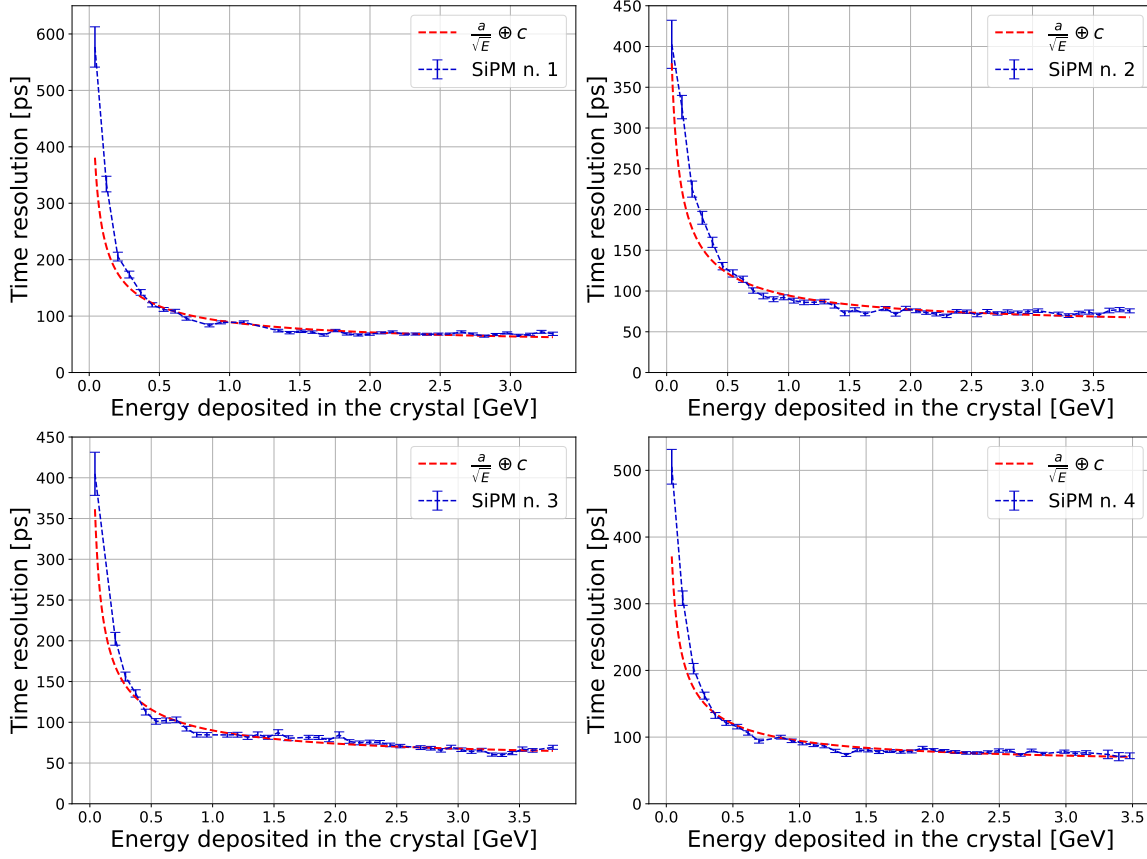


Figure 5.11: Time resolution of the CRILIN SiPMs as a function of the energy deposit in the non oriented PbF_2 crystals. The curves were obtained by analyzing the SiPMs signals sampled at a frequency of 2.5 GS/s.

5.3.2 MEASUREMENTS WITH THE ORIENTED PbF_2 CRYSTAL

The second set of data used for the characterization of the CRILIN photodetection system was the one acquired to study the Strong Field effects occurring when a high energy photon beam impinges on an oriented PbF_2 crystal. In these runs, the amplification gains of the readout channels n. 1 and n. 3 were set to 1x and all the others were set to 9x. The sampling frequency of the DT5742 digitizer was 1 GS/s.

The waveforms acquired in these runs were processed following the same procedure described in the previous section. Figure 5.12 presents the final time resolution curves and table 5.3 reports the a and c parameters extracted from the fits. These curves and parameters are incompatible with the ones measured with the non oriented PbF_2 crystals: for instance, the average time resolution predicted at an energy deposit of 1 GeV is larger than 200 ps in the first case and smaller than 100 ps in the other. Three are the possible causes of this discrepancy:

1. For each SiPM, the two resolution curves were measured digitizing the waveforms with a different sampling frequency. As it was already noticed in the measurement of the MCP time resolution (section 5.2), a higher frequency leads to the acquisition of

a larger number of points in the rising edges and thus to a more accurate evaluation of the time resolution of the detector.

2. The different energy range accessible in the two cases, which depends on the thickness of the crystal coupled to the SiPMs, respectively of $\sim 4.3 X_0$ and $2 X_0$. In fact, the larger the energy range is, the more accurate the evaluation of the a and c parameters.

In conclusion, the results which provide the more accurate evaluation of the SiPMs time resolutions are the ones obtained at a sampling frequency of 2.5 GS/s.

Channel	a [ps $\cdot$ GeV $^{1/2}$]	c [ps]	$\sigma_{\text{SiPM}}(1 \text{ GeV})$ [ps]
1	173.87 ± 0.80	—	173.87 ± 0.80
2	101.87 ± 1.06	213.95 ± 2.99	236.97 ± 2.74
3	159.94 ± 0.65	103.77 ± 3.68	190.65 ± 2.08
4	81.35 ± 1.30	265.25 ± 2.57	277.44 ± 2.49

Table 5.3: Time resolution terms of the CRILIN SiPMs, obtained by analyzing the signals sampled at a frequency of 1 GS/s. The c parameter of the first SiPM could not be estimated with the fit and was forced to zero. The last column on the right reports the predicted time resolution of the SiPMs, for an energy deposit of 1 GeV in the crystals.

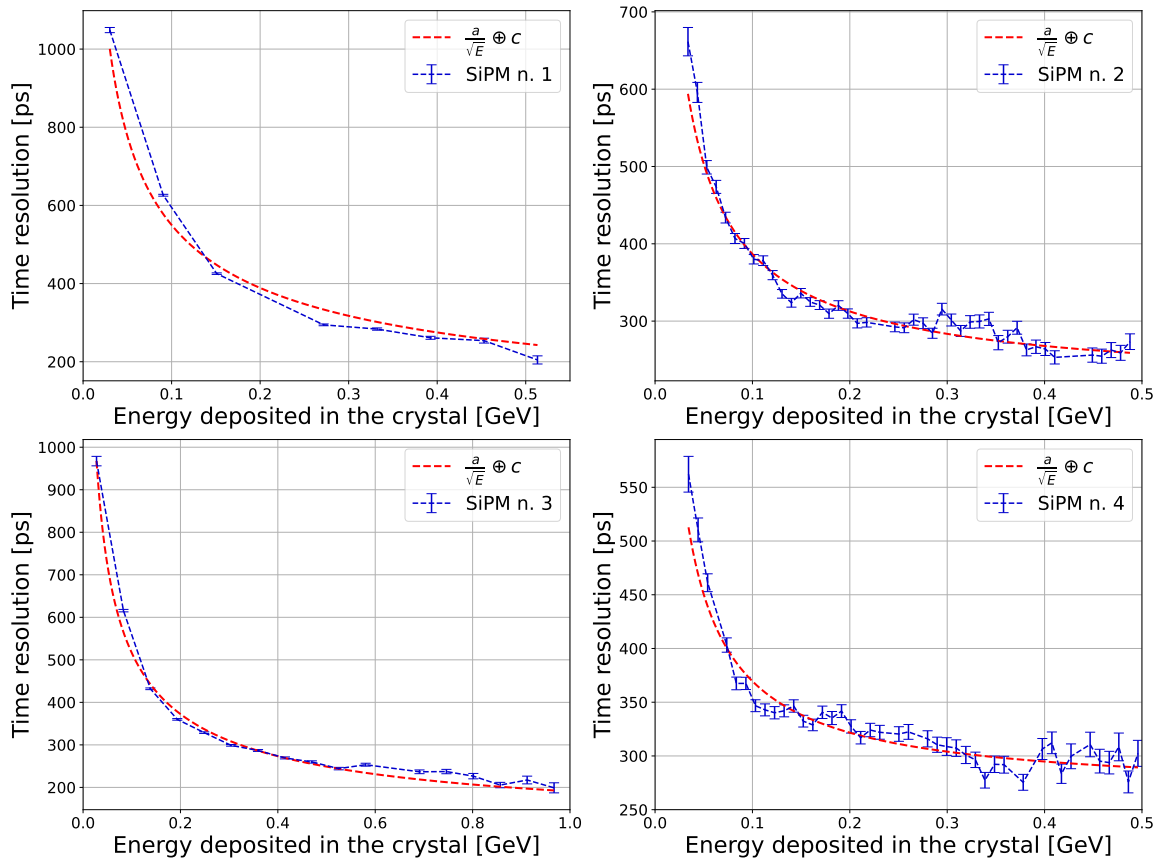


Figure 5.12: Time resolution of the CRILIN SiPMs as a function of the energy deposit in the oriented PbF_2 crystal. This curve was obtained by analyzing the SiPMs signals sampled at a frequency of 1 GS/s.

5.4 THE STORM PHOTODETECTION SYSTEM

This section presents the measurement of the time resolution of the STORM photodetection system (section 3.1.2). The dataset used for this goal was the one acquired to study the Strong Field effects occurring when a high energy photon beam impinges on an oriented PbWO_4 crystal. In these runs, the sampling frequency of the DT5742 digitizer was 1 GS/s.

Only a part of the dataset was analyzed. As described in section 5.3, cuts on the number of electron tracks detected in the upstream silicon detectors (T1, T2, C1) and the signal times were applied. The PH cut was not necessary in this case, due to the smaller amplitude of the STORM SiPMs signals. Moreover, no directional effects were observed in the correlations between the SiPMs PH and the hit coordinates of the incident particles (figure 5.13): thus, only a broad cut on the hit coordinates was applied.

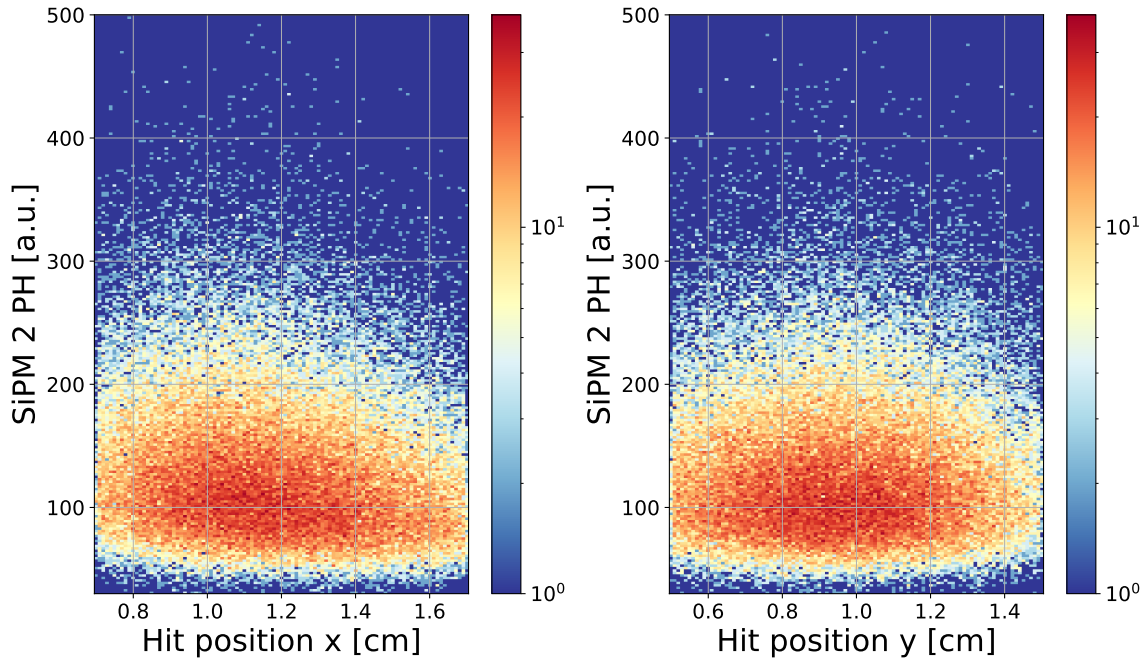


Figure 5.13: Correlation between the SiPMs PH and the hit coordinates of the incident particles along the x (left) and y axis (right). No directional effects are evident.

After applying the selection cuts, all the events were analyzed following a procedure similar to the one described in the previous sections:

1. All the signals were smoothed with the 5-tick wide moving average filter (figure 5.14).
2. The timestamp of each signal (t_0) and the residual, with respect to the average timestamp of the MCP channels, were computed.
3. The correlation between the time residual and the PH of the SiPMs was studied (figure 5.15). Due to the symmetrical shape of the correlation histogram, the slew correction was not necessary.

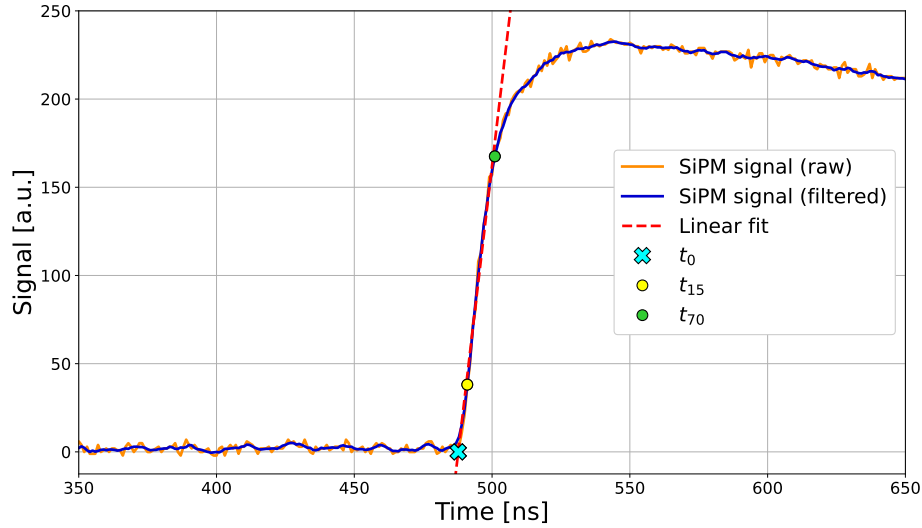


Figure 5.14: Comparison of the waveforms produced by a SiPM (STORM), before and after applying a 5-tick wide moving average filter.

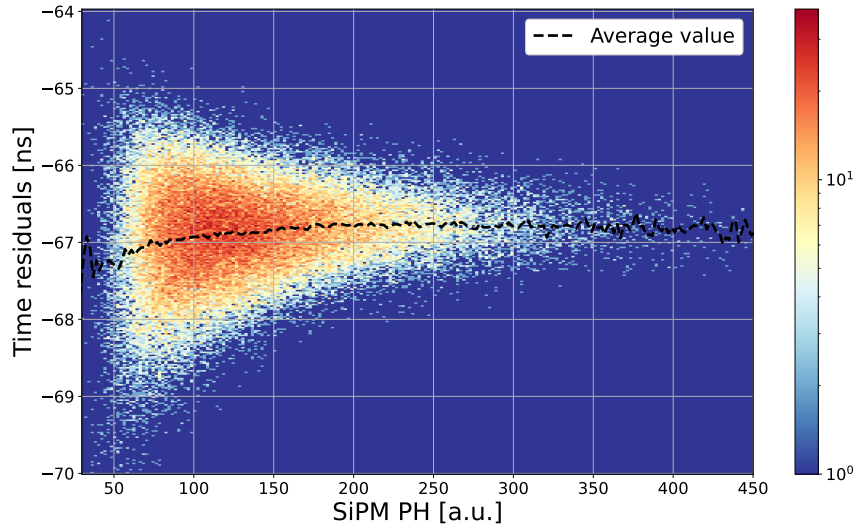


Figure 5.15: Correlation between the PH of the STORM SiPMs and the time residuals.

4. The data were divided in PH bins, each one with a width of 10 a.u., in order to reconstruct the average time resolution curves (figure 5.16).
5. The resolution curves were fitted using eq. (5.8). The parameters extracted from the fit are reported in table 5.4.

The results obtained in this analysis confirmed that the STORM photodetection system does not feature an optimal time resolution, if compared with CRILIN. In fact, the best STORM SiPM has a predicted time resolution of 233.97 ± 16.74 ps, for an energy deposit in the crystal of 1 GeV. The resolution of the best CRILIN SiPM is predicted to be 89.32 ± 1.16 ps, in the same conditions. This difference was expected, since the STORM photodetection system is not optimized specifically for timing measurements and the PbWO_4 crystal features longer light emission times, with respect to PbF_2 . However, due to the small energy range evaluated, the results obtained in this study do not rule out

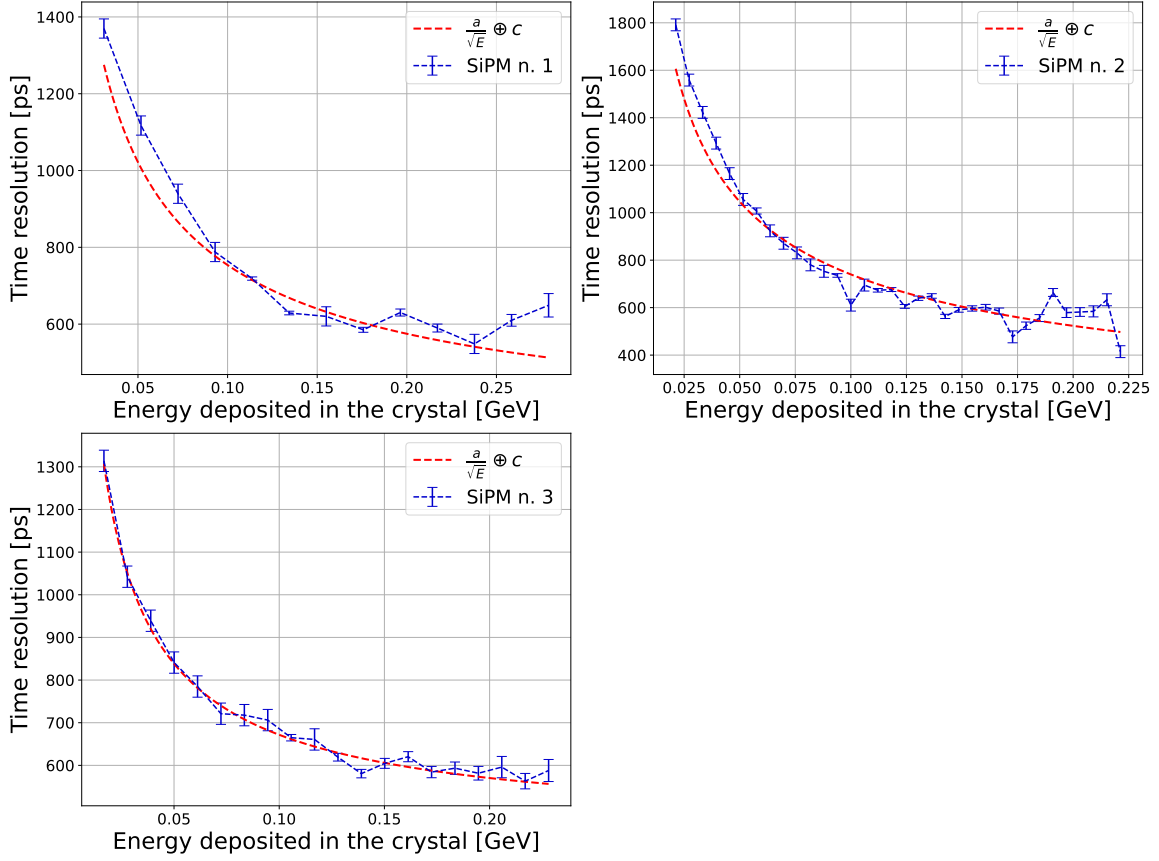


Figure 5.16: Time resolution of the STORM SiPMs as a function of the energy deposit in the PbWO_4 crystal.

Channel	a [$\text{ps} \cdot \text{GeV}^{1/2}$]	c [ps]	$\sigma_{\text{SiPM}}(1 \text{ GeV})$ [ps]
1	218.09 ± 3.23	304.27 ± 17.02	374.36 ± 13.96
2	233.41 ± 1.91	—	233.97 ± 16.74
3	158.68 ± 2.66	446.42 ± 8.95	473.78 ± 8.48

Table 5.4: Time resolution terms of the STORM SiPMs, obtained by analyzing the signals sampled at a frequency of 1 GS/s. The c parameter of the second SiPM could not be estimated with the fit and was forced to zero. The last column on the right reports the predicted time resolution of the SiPMs, for an energy deposit of 1 GeV in the crystals.

completely the possibility of using PbWO_4 (either of the normal type or PWO-UF) for the construction of the KLEVER SAC.

CONCLUSIONS

This thesis work has been performed in the framework of the HIKE project, the planned multi-phase evolution of the NA62 experiment. The most critical and ambitious phase of the HIKE physics programme is the KLEVER experiment, whose main goal is the first-time ever measurement of $\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})$ with a 20% precision. The study of such decay will allow to simultaneously test the validity of the Standard Model and search for a sign of new physics. Since this process is extremely rare and difficult to observe, mainly due to its signature (i.e., the detection of two photons with a large missing momentum), the KLEVER experimental apparatus must be composed of high-performance particle detectors.

One of the most important elements of the KLEVER setup will be the Small Angle Calorimeter (SAC), which will be located directly in the neutral beamline and has to detect the photons produced by the π^0 decays with a small opening angle ($\lesssim 2$ mrad). To comply with the environment of the KLEVER beamline and to achieve the HIKE physics goals, the SAC must satisfy several requirements, such as:

- A time resolution better than 100 ps on the detection of 1 GeV photons.
- A photon detection inefficiency smaller than 10^{-4} for incident photons with an energy larger than 30 GeV.
- A transparency as large as possible to neutral hadrons, whose flux in the beamline has been estimated to be ~ 500 MHz.

The current SAC layout is based on four layers of high-Z Cherenkov or scintillating crystals, such as PbF_2 or PbWO_4 -Ultra Fast (PWO-UF), readout by compact and fast photodetectors, for an overall length of $\sim 17 X_0$ along the beam direction. The first goal of this thesis was to evaluate the feasibility of using oriented crystals for the SAC active layers. This choice would allow to exploit the Strong Field (SF) enhancement of the pair production cross-section, to induce a reduction of the photon detection inefficiency without affecting the sensitivity to the neutral hadrons. The second goal was to evaluate the performance of the photodetection systems which are being developed for the SAC readout.

To reach these goals, the STORM and KLEVER collaborations performed a beamtest on the H2 line at the CERN SPS in August 2021. In this beamtest, a $2 X_0$ oriented PbF_2 crystal and a $1 X_0$ oriented PbWO_4 were exposed to a tagged beam of high energy photons. The visible light emitted inside the crystals was measured with Silicon PhotoMultipliers (SiPMs), readout by a custom Front-End Electronics (FEE). The experimental setup employed in this test was composed of a high resolution tracking system, a Micro-Channel Plate (MCP) detector, a copper target, a dipole magnet, a high-precision goniometer, a Multiplicity Counter (MC), a photon calorimeter (γCAL) and an electron spectrometer (eCAL).

After the preliminary calibration measurements, the crystals were placed on the beamline and exposed to the tagged photon beam. The energy of the incident photons (E_γ^0) could not be computed using as reference the energy measured by eCAL, due to the poor spatial coverage of the spectrometer. Thus, E_γ^0 was computed by summing the γ CAL energy and the calibrated response of the SiPMs. Two SiPM calibration strategies have been evaluated: the first was based on the measurement of the light pulses produced in the crystals by 80 GeV muons, which are Minimum Ionizing Particles and whose average energy loss in a medium is well known. The second approach was based on a full Geant4 simulation of the experimental setup, which compares the predicted energy deposit of the tagged photon beam in the randomly oriented crystal with the experimentally measured spectrum, thus providing an estimation of the SiPM calibration coefficient. These strategies have been found to be in excellent agreement and allowed an accurate estimation of E_γ^0 .

The SF enhancement of the pair production cross-section was evaluated by measuring the variation of the SiPMs and MC Pulse Heights as a function of E_γ^0 and of the angle between the incident photon beam and the reference axes of the crystals. After properly selecting the acquired data, an increase of the energy deposited in the aligned PbF₂ crystal of 2 – 2.75 was estimated, with respect to the random orientation, for incident photons with an energy of 20 – 75 GeV. Similar results have been obtained with the PbWO₄ crystal, where the enhancement values were found to be 1.5 – 2, for incident photons with an energy of 20 – 100 GeV. It has been estimated that these enhancements correspond to an effective reduction of the PbF₂ and PbWO₄ radiation lengths of 20% – 25% and 15% – 20%, respectively. Such effects were observed for all the incidence angles within the Strong Field regime angular acceptance ($\Theta_0 \sim 1$ mrad). A smaller but non negligible enhancement was observed also for incidence angles as large as ~ 8 mrad, due to the onset of the Coherent Bremsstrahlung and Coherent Pair Production phenomena.

The results obtained in this thesis are in excellent agreement with the ones reported in [56], which is the only known study where the Strong Field effects occurring in an oriented scintillator were characterized in a similar way. The combined results of these studies will be fundamental in the development of a simulation toolkit capable of modelling the interactions of the high energy particles inside oriented crystals.

The datasets acquired for the characterization of the Strong Field processes were used to evaluate the performance of the CRILIN and STORM photodetection systems. An additional dataset was used for the same purpose: it was acquired with two 4.3 X_0 non oriented PbF₂ crystals coupled to CRILIN. The “zero-crossing” extrapolation algorithm was used to measure the instants in time corresponding to the trigger of the detectors under test (t_0). The spread of the distribution of the time residual, namely the difference between t_0 and a reference time measured by the MCP detector, provided an estimation of the time resolution of the SiPMs as a function of the energy deposited in the crystals. Time resolutions better than ~ 90 ps at a 1 GeV energy deposit were measured for all the CRILIN SiPMs, while the STORM photodetectors featured resolutions of 230 – 470 ps. These results confirm the possibility of using the CRILIN photodetection system for the SAC readout,

while showing also the necessity of an improvement of the frontend electronics, to avoid a two-peak shape in the SiPM output signals. Such an intervention has already been carried out in 2022, obtaining a faster shaping time and eliminating the double-peak structure. However, further improvements will still be necessary.

Two steps are foreseen for the future development of the KLEVER SAC. On one hand, a prototype calorimeter based on oriented crystals must be developed and tested as soon as possible: this is the goal of the ORiEnted calOrimeter (OREO) project, which has been recently approved by the National Institute for Nuclear Physics (INFN, CSN V) for 2023-2024 [111]. On the other hand, the CRILIN photodetection system must be scaled from the current prototype to the full dimension required for the readout of the SAC. The performance of the scaled system will be evaluated in dedicated beamtests, possibly already in 2023-2024, to verify the compliance with the HIKE requirements.

EXPERIMENTAL METHODS

This appendix provides additional details on the experimental methods employed in the analysis of the KLEVER 2021 beamtest data.

A.1 RECONSTRUCTION OF THE PULSE HEIGHT OF THE MULTIPLICITY COUNTER

During the data analysis, it was observed that some of the Multiplicity Counter signals present a saturation effect, characterized by a flat signal peak (figure A.1). This effect is due to the fact that the MC pulses have a negative polarity and the DT5742 digitizer features a limited input range: due to the value of the digitization baseline used during the beamtest, some of the MC signals exceeded the digitizer input range and thus were partially flattened. Since the full waveform of each signal was saved by the DAQ, it has been possible to reconstruct the PHs of the saturated events using the Time Over Threshold (TOT) technique. This method is based on the calculation of the number of points in each waveform which exceeds a fixed threshold (figure A.1): in fact, it is well known that this number scales as the natural logarithm of the deposited charge and can be used to reliably estimate it [162].

The TOT method was applied considering the dataset acquired with the photon beam aligned with the axis of the PbF₂ crystal, namely where the largest MC PHs were measured. The average number of points in the waveforms corresponding to a signal value larger than 50 a.u. (i.e., the TOT) was computed as a function of the MC PH. The resulting curve (figure A.2) was fitted with a piecewise function, composed of a logarithmic core and different linear functions:

$$\text{TOT} = \begin{cases} a + b \cdot \log(\text{PH} + c) & \text{if } \text{PH} \leq 500 \text{ a.u.} \\ m_1 \cdot \text{PH} + q_1 & \text{if } 500 \text{ a.u.} < \text{PH} \leq 1500 \text{ a.u.} \\ m_2 \cdot \text{PH} + q_2 & \text{if } 1500 \text{ a.u.} < \text{PH} \leq 2500 \text{ a.u.} \\ m_3 \cdot \text{PH} + q_3 & \text{if } \text{PH} > 2500 \text{ a.u.} \end{cases} \quad (\text{A.1})$$

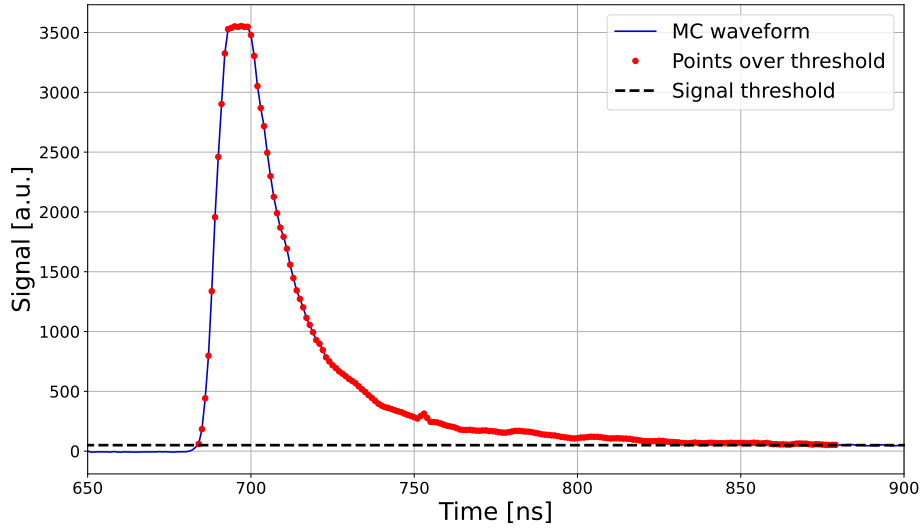


Figure A.1: Waveform of the Multiplicity Counter, showing a saturation effect due to the limited input range of the DT5742 digitizer. The points with a value larger than a fixed threshold (TOT) are shown in red.

The fitted parameters allowed the estimation of the PH of all the saturated events, namely the ones with a nominal PH (“raw”) larger than 3500 a.u.. A comparison of the MC PH spectra before and after the application of the TOT technique is presented in figure A.3.

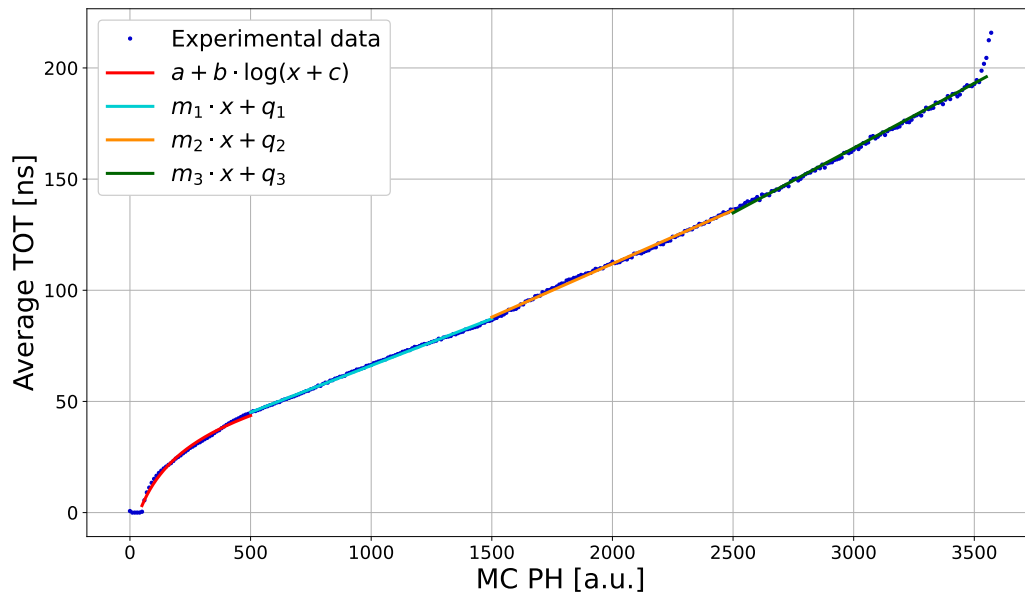


Figure A.2: Average number of points in the MC waveforms with a signal value larger than 50 a.u., computed as a function of the MC PH. The piecewise fitted function (eq. (A.1)) is shown in each of the sub-domains with a different color.

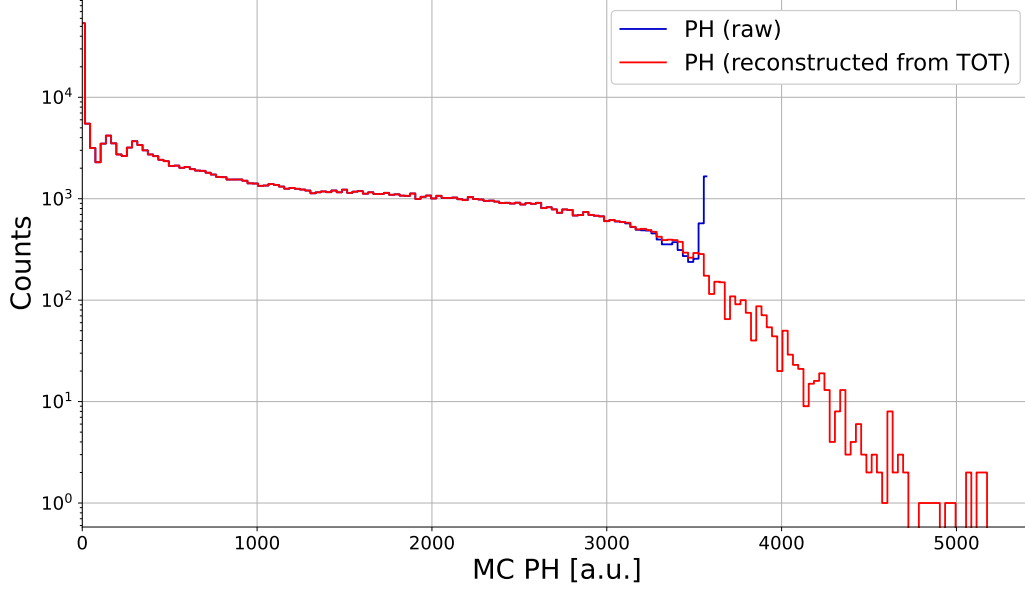


Figure A.3: Comparison of the MC PH spectrum computed using the nominal PH values (blue) and the TOT-reconstructed values (red).

A.2 GEANT4 SIMULATION OF THE EXPERIMENTAL SETUP

The simulation of the energy deposit in the randomly oriented PbF_2 and PbWO_4 crystals was performed using the Geant4 toolkit [161]. The features of the particle beam used in the simulation are reported in table A.1. A simplified geometry was used in the modelization of all the particle detectors, meaning that only the active volumes were reproduced, without the mechanical supports and the light-tight layers. The energy deposited in the crystals by the incident photon beam was simulated including only the energy loss processes: this means that the production, the transport and the detection of the Cherenkov (or scintillation) light in the active medium were not considered. The finite energy resolution of γCAL and eCAL was included in the simulation, using as a reference the resolution terms reported in table 3.9. All the simulation codes developed for this thesis, including the one used to simulate the energy loss curves in an arbitrarily long randomly oriented material, can be found in [163, 164].

To qualitatively evaluate the accuracy of the simulation, the energy spectra of γCAL (figure A.4) and eCAL (figure A.5) were computed and compared with the ones measured experimentally. The observed and simulated spectra show a similar trend: in particular, the eCAL spectrum and the correlation between the γCAL and eCAL energy deposits (figure A.6) confirm the limited angular coverage of the electron spectrometer, which is the reason why the calibration of the SiPM response was required. The similarity between the simulated and measured spectra could be further improved, by adding a more detailed model of each particle detector. Nevertheless, the main upgrade foreseen for this simulation is the inclusion of the physics of the oriented crystals, in order to predict the energy

Parameter	Value
Energy	120 GeV
$\Delta p/p$	0%
Transverse plane distribution	Uniform (rectangular)
FWHM_x	0.542 cm
FWHM_y	0.369 cm
Incidence angles distribution type	Gaussian (bidimensional)
σ_x	130.5 μrad
σ_y	83.0 μrad

Table A.1: Parameters of the monoenergetic electron beam used as particle source in the Geant4 simulation of the experimental setup. The FWHMs are the Full-Width at Half-Maximums of the beam profiles along the x and y axis. σ_x (σ_y) is the beam divergence along the x (y) axis.

deposited in the axially oriented crystals by the impinging photon beam. Since the Strong Field processes are not implemented in the standard Geant4 Physics List, this addition will require to follow the approach detailed in [55, 104].

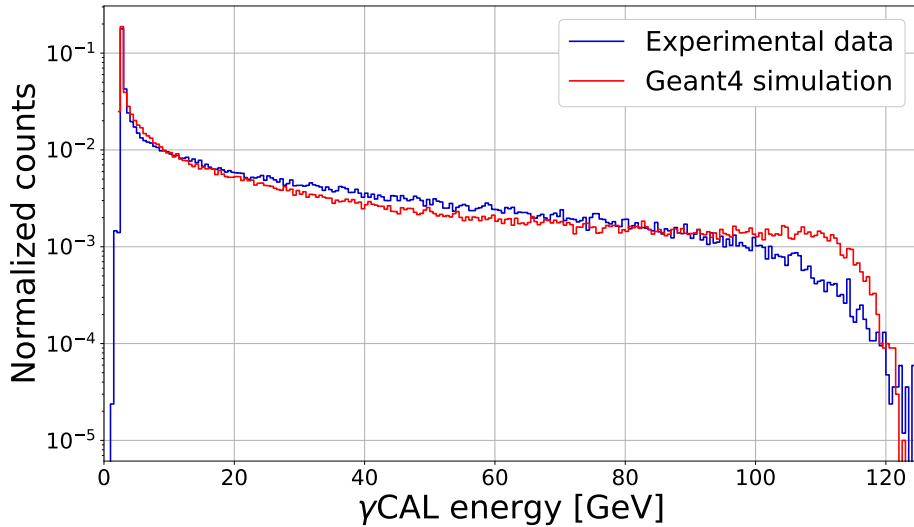


Figure A.4: Comparison of the simulated and measured γCAL energy spectrum, obtained with the PbF_2 crystal on the beamline. The histograms were normalized.

A.3 ANALYSIS OF THE CRILIN WAVEFORMS

Figure A.7 (on the left) presents the correlation between the PH and the signal time of one of the CRILIN SiPMs, measured in one of the runs with the non oriented PbF_2 crystals placed on the beamline. Both the PHs and signal times were computed by an online processing algorithm implemented in the DAQ system. The gap in the histogram around 1600 a.u. (PH) is due to the two-peaked shape of the SiPMs waveforms (figure A.8): since the ratio of the peak heights varies as a function of the energy deposited in the crystal, the

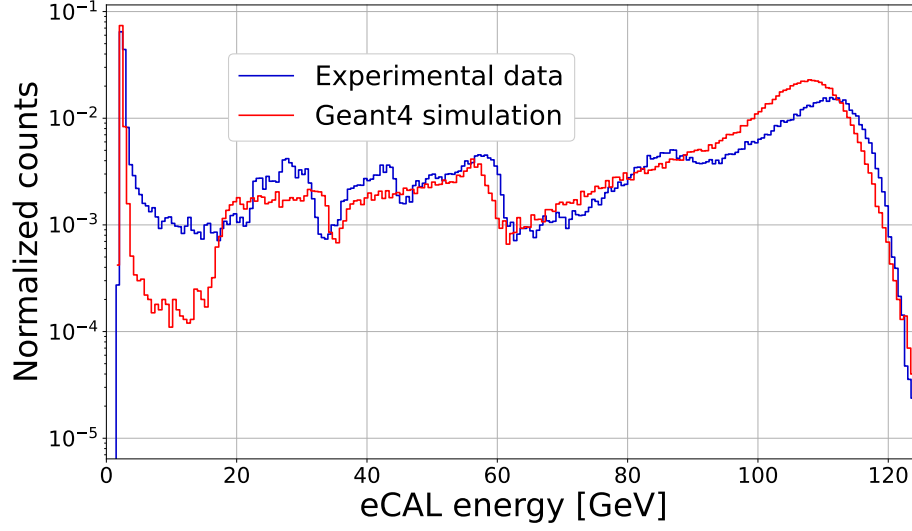


Figure A.5: Comparison of the simulated and measured eCAL energy spectrum, obtained with the PbF₂ crystal on the beamline. The histograms were normalized. The different shape of the spectra in the low energy tail (20 – 40 GeV) is due to additional gaps between the Lead Glasses, which were not included in the simulation.

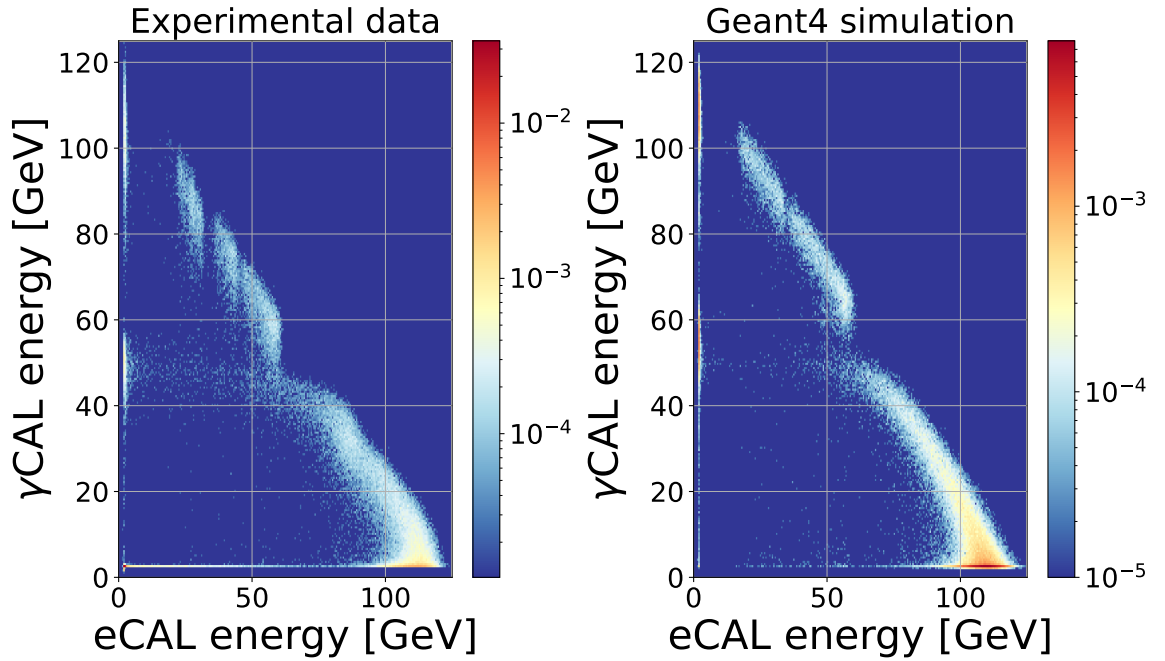


Figure A.6: Comparison of the simulated and measured correlation between the energy deposited in γ CAL and eCAL, obtained with the PbF₂ crystal on the beamline. The histograms were normalized.

measured signal time corresponds to the second peak if the energy deposit is small, and to the first peak if it is large. Since the time resolution analysis requires the precise knowledge of the height of the first peak (i.e., the faster signal component), it was necessary to manually reprocess the waveforms.

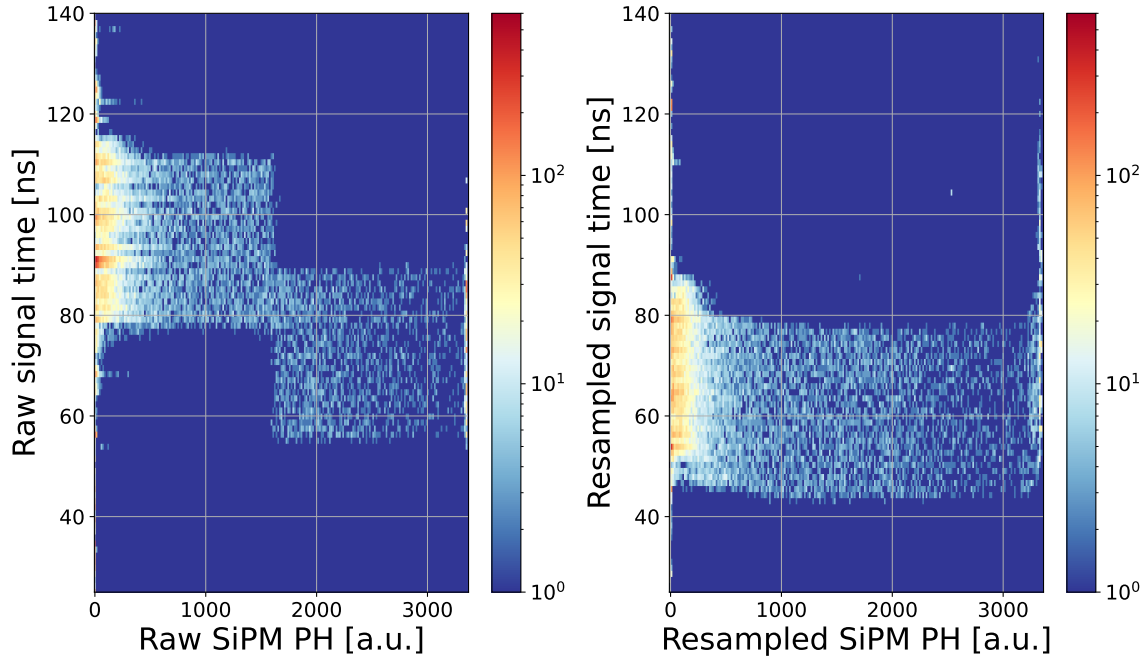


Figure A.7: Correlation of the PH and signal time of one of the CRILIN SiPMs, coupled to the non oriented PbF₂ crystal. Left: “raw” signal times, computed by the processing algorithm implemented in the DAQ system. Right: signal times reconstructed with the custom reprocessing algorithm.

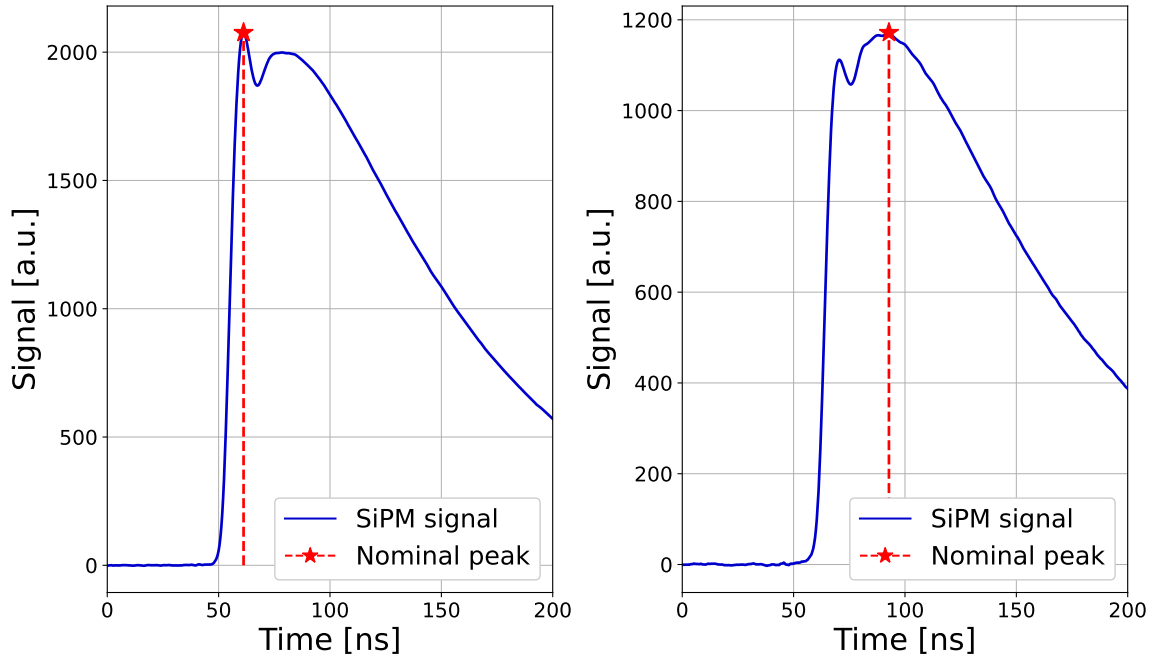


Figure A.8: Waveforms produced by one of the CRILIN SiPMs, coupled to the non oriented PbF₂ crystal, showing how the ratio of the height of the two peaks changes as a function of the energy deposited in the crystal.

The reprocessing algorithm has been structured as follows:

1. Every waveform is smoothed with a 5 tick-wide moving average filter.

2. The finite difference between the shifted signal ($s(t + \Delta t)$) and the original signal ($s(t)$) is computed. For $\Delta t = 1$, this operation is just the first derivative, while for $\Delta t > 1$ a “shifted derivative” is obtained; the optimal value for the shift was found to be $\Delta t = 5$.
3. The shifted derivative is smoothed with a 5 tick-wide moving average filter. The result is a signal which is null everywhere, except in the regions of the two rising edges, where there should be two peaks (with the second always smaller than the first).
4. The signal time of the filtered derivative is used as starting point for the search of the maximum value of the smoothed waveform. The search region has a predefined width of 30 ticks.

In figure A.9 all these steps are shown, while in figure A.7 (on the right) the correlation between the recomputed PHs and signal times is presented. As expected, reprocessing the waveforms led to the disappearance of the gap.

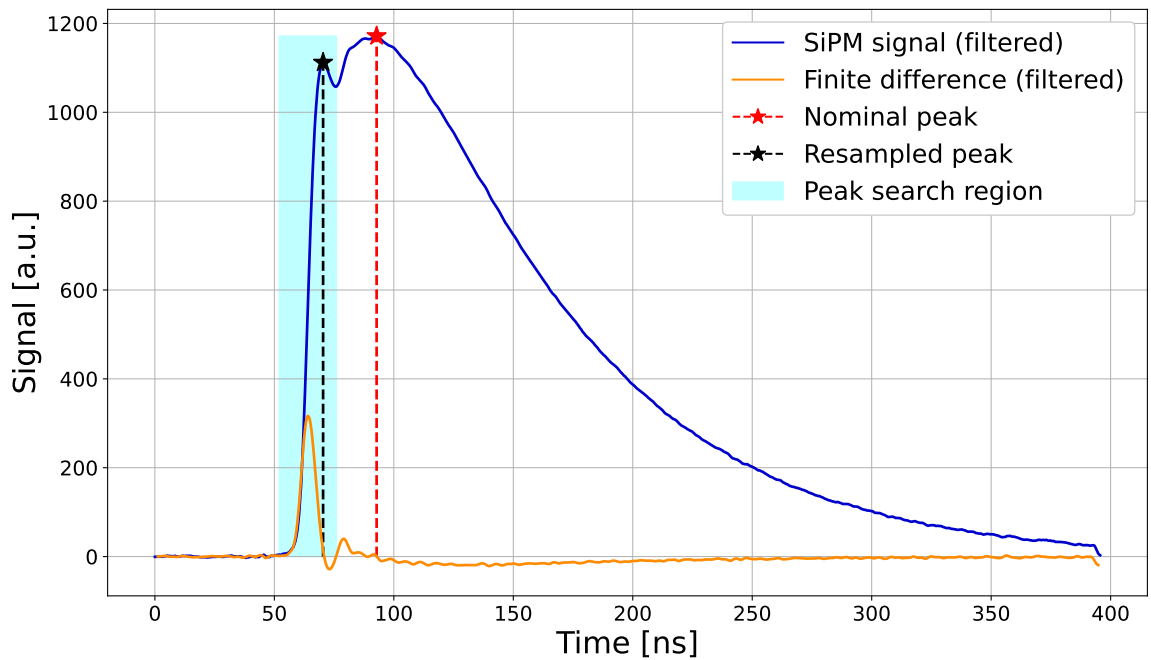


Figure A.9: Steps followed by the waveform reprocessing algorithm, which takes as input the SiPM analog signal (blue): after applying a smoothing filter, the finite difference is computed and smoothed (orange). The point of maximum of the finite difference curve defines a region in which the maximum of the SiPM waveform is searched (cyan). The height of the new point of maximum is the “resampled” Pulse Height of the event and the corresponding time is the “resampled” signal time.

ACRONYMS

a.u. arbitrary units

ADC Analog to Digital Converter

ALP Axion-Like Particle

ASIC Application Specific Integrated Circuit

ATLAS A Toroidal LHC ApparatuS

BCC Body Centered Cubic

BR Branching Ratio

BSM Beyond the Standard Model

BTF BeamTest Facility

CB Coherent Bremsstrahlung

CEPC Circular Electron-Positron Collider

CERN Conseil Européen pour la Recherche Nucléaire

CFA Constant Field Approximation

CHANTI Charged ANTI-coincidence detector

CKM Cabibbo-Kobayashi-Maskawa

CLIC Compact Linear Collider

CMOS Complementary Metal-Oxide Semiconductor

CMS Compact Muon Solenoid

CPP Coherent Pair Production

CR Channeling Radiation

CRILIN CRystal calorImeter with Longitudinal Information

DAQ Data AcQuisition

DESY Deutsches Elektronen-Synchrotron

DUNE Deep Underground Neutrino Experiment

e.f. enhancement factor

e.m. electromagnetic

e.m.s. electromagnetic shower

ESPP European Strategy for Particle Physics

FCC Future Circular Collider

FCNC Flavour-Changing Neutral Current

FEE Front-End Electronics

FIP Feebly Interacting Particle

FWHM Full-Width at Half Maximum

GM-APD Geiger-Muller Avalanche Photodiode

GTK Giga TracKer

GUT Grand Unified Theory

HASC HAdronic Sampling Calorimeter

HDF5 Hierarcal Data Format 5

HIKE High Intensity Kaon Experiments

ILC International Linear Collider

INFN Istituto Nazionale di Fisica Nucleare

INP Institute for Nuclear Problems

J-PARC Japan Proton Accelerator Research Complex

KTAG Kaon TAGger

LAV Large Area Veto

LG Lead Glass

LHC Large Hadron Collider

LNF Laboratori Nazionali di Frascati

LOI Letter Of Intent

LPM Landau-Pomeranchuk-Migdal

MC Multiplicity Counter

MCP-PMT Micro-Channel Plate PMT

MEC Main Electromagnetic Calorimeter

MUV MUon Veto detector

OREO ORiEnted calOrimeter

PBC Physics Beyond Colliders group

PCB Printed Circuit Board

PDE Photon Detection Efficiency

PH Pulse Height

PID Particle IDentification

PMT PhotoMultiplier Tube

PST Plastic Scintillator Trigger

PWO-UF PbWO₄-Ultra Fast

QCD Quantum ChromoDynamics

QED Quantum ElectroDynamics

RAS-ISSP Institute of Solid State Physics of the Russian Academy of Sciences

RICH Ring-Imaging Cherenkov detector

RMS Root Mean Square

SAC Small Angle Calorimeter

SB Standard Bremsstrahlung

SF Strong Field

SFPP Strong Field Pair Production

SiPM Silicon PhotoMultiplier

SM Standard Model

SPAD Single-Photon Avalanche Diode

SPP Standard Pair Production

SPS Super Proton Synchrotron

TAX Target Attenuator eXperimental areas

TOT Time Over Threshold

VME Versa Module Eurocard

VRB VME Readout Board

WLS Wavelength Shifter

LIST OF FIGURES

Figure 1.1	Standard Model fundamental forces and particles	6
Figure 1.2	Timeline of the future colliders across the world	9
Figure 1.3	Logo of the HIKE project	11
Figure 1.4	Timeline of the future upgrades of the LHC	12
Figure 1.5	Feynman diagrams of the $K_L \rightarrow \pi^0 \nu \bar{\nu}$ decay	13
Figure 1.6	Correlation between $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ and $\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})$	15
Figure 1.7	Layout and optics of the K12 high-intensity K^+ beamline	17
Figure 1.8	Scheme of the beamlines structure in the CERN North Area	18
Figure 1.9	Modifications of the T10 steering dipole magnets to increase the kaon production angle in the KLEVER phase	19
Figure 1.10	Baseline design of the K12 beamline, upgraded for HIKE Phase 2 and KLEVER	20
Figure 1.11	HIKE Phase 1 beamline and experimental layout	22
Figure 1.12	HIKE Phase 2 beamline and experimental layout	23
Figure 1.13	KLEVER beamline and experimental layout	23
Figure 1.14	Efficiency required for the SAC to veto the $K_L \rightarrow \pi^0 \pi^0$ decay	24
Figure 1.15	Design of the KLEVER SAC	25
Figure 2.1	Miller indices nomenclature for three crystallographic planes	31
Figure 2.2	Pictorial representation of a crystallographic stereogram, superim- posed on a perspective view of the corresponding crystal lattice	32
Figure 2.3	Motion of a particle channeled close to a lattice string	32
Figure 2.4	Transverse potential generated by one or more atomic strings in a W crystal in the transverse plane with respect to the $\langle 111 \rangle$ axis, in one and two dimensions	34
Figure 2.5	Channeling critical angles for the highest-potential axes of a pure W and a $PbWO_4$ crystal	36
Figure 2.6	Pictorial representation of planar channeling	37
Figure 2.7	Comparison of the potentials generated in the transverse plane by the $\langle 111 \rangle$ axis in a pure W crystal, for positive and negative charged particles	39
Figure 2.8	Comparison between the emission of Channeling Radiation and Co- herent Bremsstrahlung	40
Figure 2.9	Scheme of the radiative processes of a charged particle incident on the axis of an oriented crystal, as a function of the incidence angle and energy	41
Figure 2.10	Radiation emitted by an electron moving in an electromagnetic field	42

Figure 2.11	Channeling Radiation spectra	43
Figure 2.12	Synchrotron radiation emission spectrum	44
Figure 2.13	Intensity of the synchrotron radiation emitted by a particle moving in a constant electromagnetic field, as a function of the χ factor of the emitting particle	45
Figure 2.14	Coherent Bremsstrahlung spectrum	46
Figure 2.15	Relative enhancement of the photon emission probability for 15 GeV positrons incident on the $\langle 100 \rangle$ axis in a 80 μm diamond crystal . . .	49
Figure 2.16	Feynman diagrams of electron-positron pair production and bremsstrahlung	50
Figure 2.17	Pair production probability as a function of the energy of the incid- ent photon, for several crystals	51
Figure 2.18	Pictorial representation of the reduction of the distance required to fully contain an e.m. shower, due to the Strong Field-induced effects	53
Figure 2.19	Simulation of the development of the e.m. showers initiated by elec- trons and photons inside a tungsten absorber	54
Figure 3.1	Photos of the Proto-0 prototype case and the PbF_2 crystal sample . .	59
Figure 3.2	Photos of the 1 X_0 PbWO_4 sample and the mechanical support struc- tures	60
Figure 3.3	Lattice structures of the oriented crystals studied in the KLEVER 2021 beamtest	61
Figure 3.4	Pulse Height spectra of a SiPM matrix coupled to an oriented crystal exposed to a 120 GeV/c electron beam	61
Figure 3.5	Picture of a SiPM matrix and scheme of the equivalent circuit of a SiPM and a SPAD	63
Figure 3.6	CAD rendering of the Proto-0 prototype case readout board	65
Figure 3.7	The STORM photodetection system	66
Figure 3.8	Layout of the experimental area of the H2 extracted beamline	67
Figure 3.9	The experimental hall of the H2 beamline, viewed from above	67
Figure 3.10	Experimental setup installed on the H2 extracted beamline	69
Figure 3.11	The S1 and S2 plastic trigger scintillators, mounted on the T1 silicon telescope	69
Figure 3.12	A silicon telescope and a silicon chamber, coupled to the readout ASICs	70
Figure 3.13	Scheme of the MCP detector	71
Figure 3.14	Front and back view of the MCP detector and the copper target . . .	72
Figure 3.15	Photo of a beam chamber and the bending dipole magnet	73
Figure 3.16	Photo and scheme of the goniometer, which was used to control the relative alignment of the photon beam and the crystal sample	74
Figure 3.17	Photo of the Multiplicity Counter and the C2 beam chamber	74
Figure 3.18	A photo and a scheme of the BGO homogeneous calorimeter	75
Figure 3.19	Photo of the calorimeters employed on the H2 line	76

Figure 3.20	Photo of a Lead Glass calorimeter, without the cover layers	76
Figure 3.21	Front view and transverse profile of the shashlik sampling calorimeter	77
Figure 3.22	Scheme of the Data AcQuisition (DAQ) system	78
Figure 3.23	Frequency distributions of the electron incidence angles along the x and y axis, as determined by the silicon trackers, once aligned	80
Figure 3.24	Comparison of the transverse profile of the 120 GeV/c electron beam, obtained with two different trigger conditions	81
Figure 3.25	Distributions of the electron incidence angles on the x and y axis, obtained with two different trigger conditions	82
Figure 3.26	Beam divergence as a function of the energy	82
Figure 3.27	Correlation of the PH and signal time of the Lead Glass calorimeter and its PH spectrum	83
Figure 3.28	Calibration lines and resolution curves of the Lead Glass calorimeters	84
Figure 3.29	PH distributions of the γ CAL channels, using a muon	86
Figure 3.30	Dependence of the mean PH of the shashlik calorimeter channels on the beam hit position	87
Figure 3.31	Calibration lines and resolution curves of γ CAL and the shashlik calorimeter	88
Figure 4.1	Scheme of the crystal pre-alignment process	90
Figure 4.2	Correlation between the PH of one of the SiPMs coupled to the oriented PbF ₂ crystal and the θ_{rot} coordinate of the goniometer, during a pre-alignment angular scan	91
Figure 4.3	Reconstructed crystallographic stereogram of the oriented PbF ₂ sample	91
Figure 4.4	Correlation between the PH of the reference SiPM, coupled to the oriented PbF ₂ sample, and the angle between the goniometer axis and the photon incidence direction	92
Figure 4.5	Comparison of the average PH of the reference SiPM and the Multiplicity Counter, during a pre-alignment scan performed with the PbF ₂ crystal	93
Figure 4.6	Efficiency map of the PbF ₂ crystal	94
Figure 4.7	γ CAL and eCAL energy spectra, shown for different angles between the photon beam and the PbF ₂ crystal	95
Figure 4.8	Comparison of the PH spectra of the reference SiPM, for different angles between the photon beam and the PbF ₂ crystal	95
Figure 4.9	Comparison of the PH spectra of the Multiplicity Counter, for different angles between the photon beam and the PbF ₂ crystal	96
Figure 4.10	Dependence of the mean PH of the different detectors on the angle between the photon beam and the PbF ₂ crystal	96
Figure 4.11	Correlation between the energy deposits in eCAL and γ CAL, in random orientation and axial alignment	97

Figure 4.12	PH spectrum of the reference SiPM, coupled to the 4.3 X ₀ PbF ₂ crystal, exposed to a 80 GeV muon beam	99
Figure 4.13	PH distribution of the reference SiPM, measured with the oriented PbF ₂ crystal in the condition of random orientation, and the distribution of the energy deposited in the crystal, computed with a full Geant4 simulation of the experimental setup	100
Figure 4.14	Comparison of the energy deposited in the PbF ₂ crystal, for different incidence angles of the photon beam	101
Figure 4.15	Correlation between the energy deposited in the PbF ₂ crystal and the energy of the incident photons, when a high multiplicity of charged particles is observed	101
Figure 4.16	Correlation between the multiplicity of the charged particles exiting from the PbF ₂ crystal and the energy of the incident photons, when a high multiplicity of charged particles is observed	102
Figure 4.17	Enhancement of the energy deposited in the PbF ₂ crystal (e.f.), for different photon incidence angles	103
Figure 4.18	Enhancement of the energy deposited in the axially aligned PbF ₂ crystal, with respect to a non oriented lattice	104
Figure 4.19	Enhancement of the multiplicity of the charged particles produced in the PbF ₂ crystal (e.f.), for different photon incidence angles	104
Figure 4.20	Dependence of the energy deposited in a randomly oriented PbF ₂ crystal by a 120 GeV photon on the thickness of the material	105
Figure 4.21	Reduction of the equivalent radiation length of an axially oriented PbF ₂ crystal, with respect to the randomly oriented material	107
Figure 4.22	Comparison of the energy absorption curves in a PbF ₂ crystal, computed with the e.m.s. model and simulated with Geant4	107
Figure 4.23	Crystallographic stereogram of the oriented PbWO ₄ sample, reconstructed by measuring the average PH of the SiPMs in each point of the preliminary angular scans	108
Figure 4.24	Efficiency map of the PbWO ₄ crystal	109
Figure 4.25	γCAL and eCAL energy spectra, shown for different angles between the photon beam and the PbWO ₄ crystal	109
Figure 4.26	Comparison of the energy deposited in the PbWO ₄ crystal, for different incidence angles of the photon beam	110
Figure 4.27	PH distribution of the reference SiPM, measured with the oriented PbWO ₄ crystal in random orientation, and the distribution of the energy deposited in the crystal, computed with a full Geant4 simulation of the experimental setup	110
Figure 4.28	Comparison of the PH spectra of the Multiplicity Counter, for different incidence angles of the photon beam on the PbWO ₄ crystal . .	111
Figure 4.29	Dependence of the mean PH of the different detectors on the angle between the photon beam and the PbWO ₄ crystal	111

Figure 4.30	Correlation between the energy deposited in the PbWO_4 crystal and the energy of the incident photons, when a high multiplicity of charged particles is observed	112
Figure 4.31	Correlation between the multiplicity of the charged particles exiting from the PbWO_4 crystal and the energy of the incident photons, when a high multiplicity of charged particles is observed	113
Figure 4.32	Dependence of the enhancement of the energy deposited in the PbWO_4 crystal on the energy of the incident photons, for several incidence angles	113
Figure 4.33	Enhancement of the energy deposited in the axially aligned PbWO_4 crystal, with respect to a randomly oriented lattice	114
Figure 4.34	Enhancement of the multiplicity of the charged particles produced in the PbWO_4 crystal (e.f.), for different photon incidence angles . .	115
Figure 4.35	Reduction of the equivalent radiation length of an axially oriented PbWO_4 crystal, with respect to the randomly oriented material . . .	115
Figure 5.1	Application of the zero-crossing extrapolation algorithm to an analog signal produced by the MCP detector	118
Figure 5.2	Comparison of the waveforms produced by a SiPM (CRILIN), before and after applying a 5-tick wide moving average filter	118
Figure 5.3	Distribution of the residuals between the zero-crossing times of the two MCP channels, obtained acquiring the data at a sampling frequency of 2.5 GS/s	120
Figure 5.4	Comparison of the distributions of the residuals between the zero-crossing times of the two MCP channels, obtained acquiring the data at a sampling frequency of 2.5 GS/s and 1 GS/s	120
Figure 5.5	Experimental layout of the CRILIN photodetection system coupled to the non oriented PbF_2 crystals	121
Figure 5.6	Correlation between the PH and the signal time, computed on the waveforms of a SiPM (CRILIN)	122
Figure 5.7	Correlation between the PH of the CRILIN SiPMs and the hit coordinates of the incident particles along the x and y axis	123
Figure 5.8	Waveform produced by a CRILIN SiPM, coupled to one of the non oriented PbF_2 crystals	124
Figure 5.9	Correlation between the PH of the CRILIN SiPMs and the time residual, before and after the slew correction	124
Figure 5.10	Slew correction of the CRILIN SiPMs time residuals	125
Figure 5.11	Time resolution of the CRILIN SiPMs as a function of the energy deposit in the non oriented PbF_2 crystals	126
Figure 5.12	Time resolution of the CRILIN SiPMs as a function of the energy deposit in the oriented PbF_2 crystal	127
Figure 5.13	Correlation between the PH of the STORM SiPMs and the hit coordinates of the incident particles along the x and y axis	128

Figure 5.14	Comparison of the waveforms produced by a SiPM (STORM), before and after applying a 5-tick wide moving average filter	129
Figure 5.15	Correlation between the PH of the STORM SiPMs and the time residuals	129
Figure 5.16	Time resolution of the STORM SiPMs as a function of the energy deposit in the PbWO ₄ crystal	130
Figure A.1	Waveform of the Multiplicity Counter, showing a saturation effect due to the limited input range of the DT5742 digitizer and the application of the TOT technique	136
Figure A.2	Average number of points in the MC waveforms with a signal value larger than 50 a.u., computed as a function of the MC PH	136
Figure A.3	Comparison of the MC PH spectrum computed using the nominal PH values and the TOT-reconstructed values	137
Figure A.4	Comparison of the simulated and measured γ CAL energy spectrum	138
Figure A.5	Comparison of the simulated and measured eCAL energy spectrum	139
Figure A.6	Comparison of the simulated and measured correlation between the energy deposited in γ CAL and eCAL	139
Figure A.7	Correlation of the PH and signal time of one of the CRILIN SiPMs, coupled to the non oriented PbF ₂ crystal	140
Figure A.8	Waveforms produced by one of the CRILIN SiPMs, coupled to the non oriented PbF ₂ crystal	140
Figure A.9	Waveform reprocessing algorithm	141

LIST OF TABLES

Table 1.1	Particle fluxes inside the KLEVER beamline, determined by a full FLUKA simulation	21
Table 2.1	Comparison of the minimum photon energies required to observe a Strong Field enhancement of the pair production probability	51
Table 3.1	Crystal samples studied in the KLEVER 2021 beamtest	60
Table 3.2	Physical and crystallographic parameters of the crystal samples tested in the KLEVER 2021 beamtest	62
Table 3.3	Features of the SiPMs used in the CRILIN and STORM photodetection systems	66
Table 3.4	Features of the digitizers used in the KLEVER 2021 beamtest	78
Table 3.5	Trigger condition and sampling frequency used in the runs performed in the beamtest	79
Table 3.6	Silicon trackers alignment coefficients	80
Table 3.7	Dependence of the electron beam width and divergence on the used trigger condition	80
Table 3.8	Calorimeters calibration coefficients	84
Table 3.9	Calorimeters resolution terms	85
Table 3.10	Equalization coefficients of the photon calorimeter readout channels	85
Table 4.1	Angular scan performed with the oriented PbF_2 sample	94
Table 4.2	Calibration coefficients of the reference SiPM, coupled to the PbF_2 crystal	100
Table 4.3	Angular scan performed with the oriented PbWO_4 sample	108
Table 5.1	Time resolution of the MCP channels	120
Table 5.2	Time resolution terms of the CRILIN SiPMs, obtained by analyzing the signals sampled at a frequency of 2.5 GS/s	125
Table 5.3	Time resolution terms of the CRILIN SiPMs, obtained by analyzing the signals sampled at a frequency of 1 GS/s	127
Table 5.4	Time resolution terms of the STORM SiPMs, obtained by analyzing the signals sampled at a frequency of 1 GS/s	130
Table A.1	Parameters of the monoenergetic electron beam used as particle source in the Geant4 simulation of the experimental setup	138

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