Beam test characterization of oriented crystals in strong field conditions

Pietro Monti-Guarnieri

on behalf of the STORM, KLEVER and Muon Collider collaborations

University of Insubria & INFN Milano Bicocca

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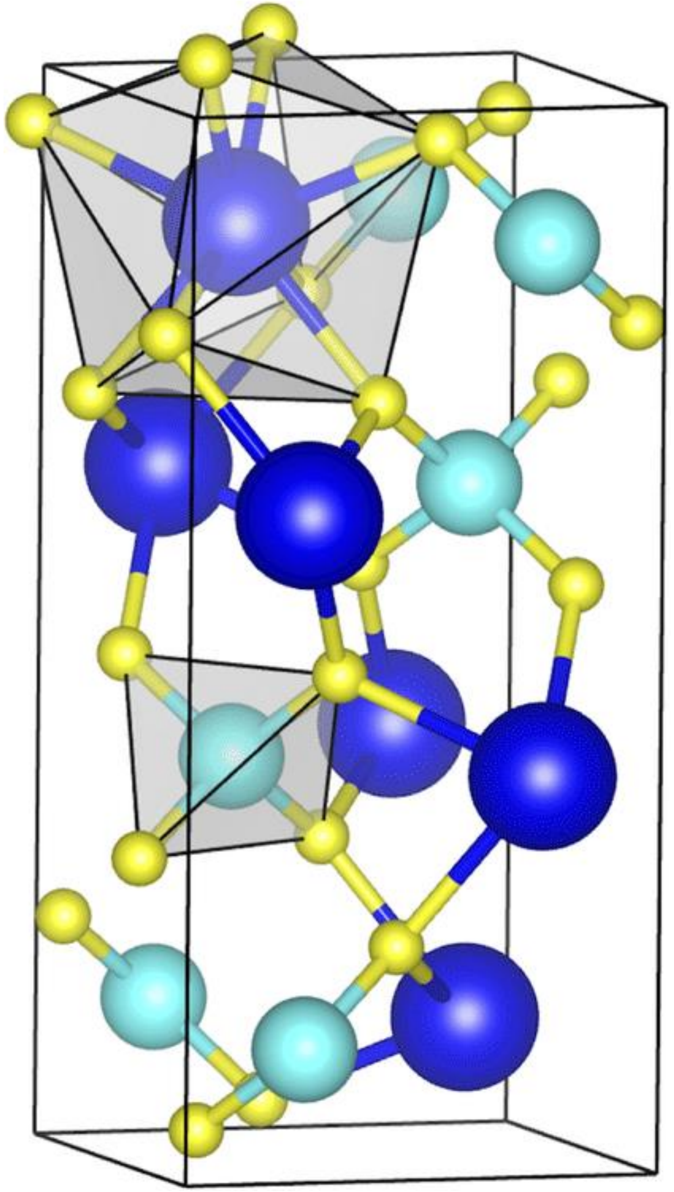
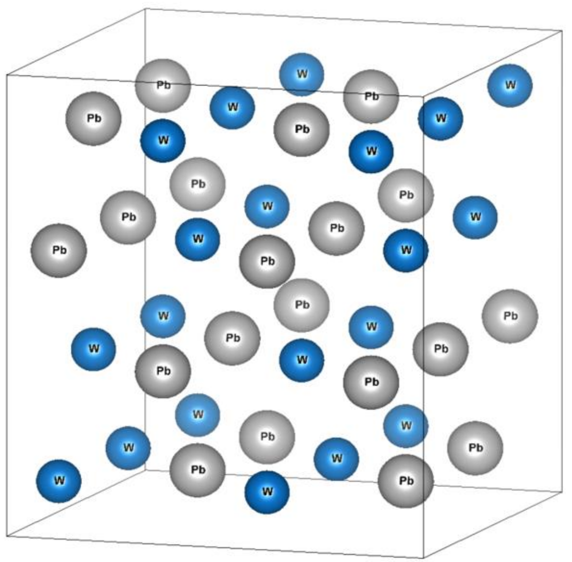
Overview

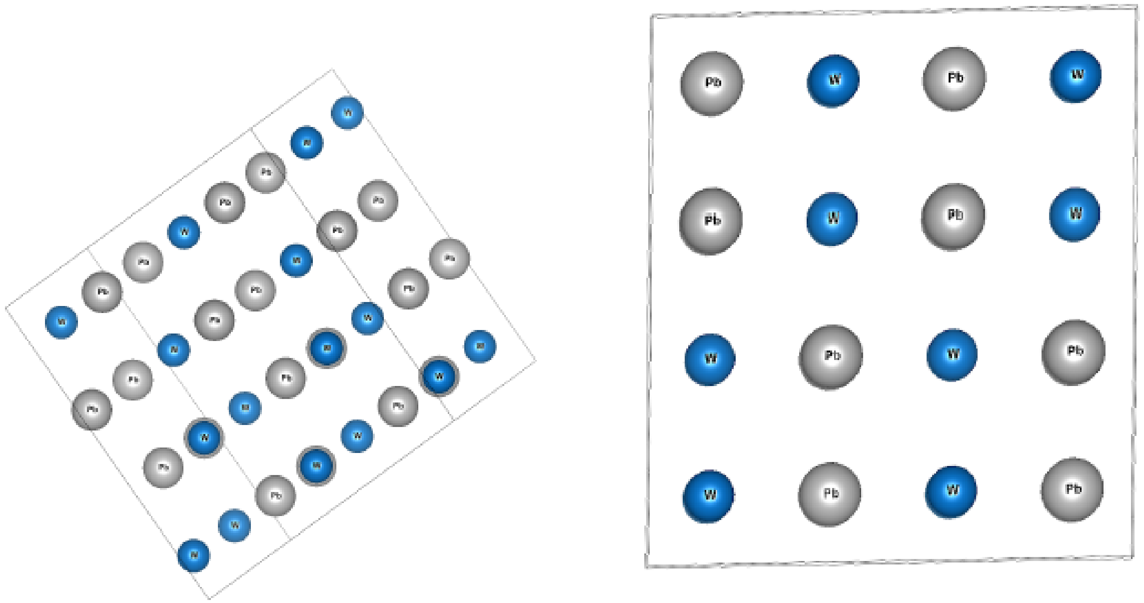
1. **What** is the **strong field condition** for an oriented crystal?
2. **When** is this condition satisfied?
3. **Why** should we care about it?
4. **How** did we observe it?



Oriented crystals (Lindhard)



Particles incident on randomly oriented matter ("amorphous")



Particles incident with small angle (θ) on an oriented lattice, arranged in planes or strings

Bethe-Heitler bremsstrahlung due to the interactions with single-nuclei electrical fields

If θ is small enough, the particles fall in a **bound state:** oscillatory dynamics (**channeling**) + **coherent** build-up of the **bremsstrahlung** radiation

The Strong Field Condition (SFC)

Ultra-relativistic particles experience a **constant and enhanced electrical field** and thus emit hard photons with high intensity, if it holds:

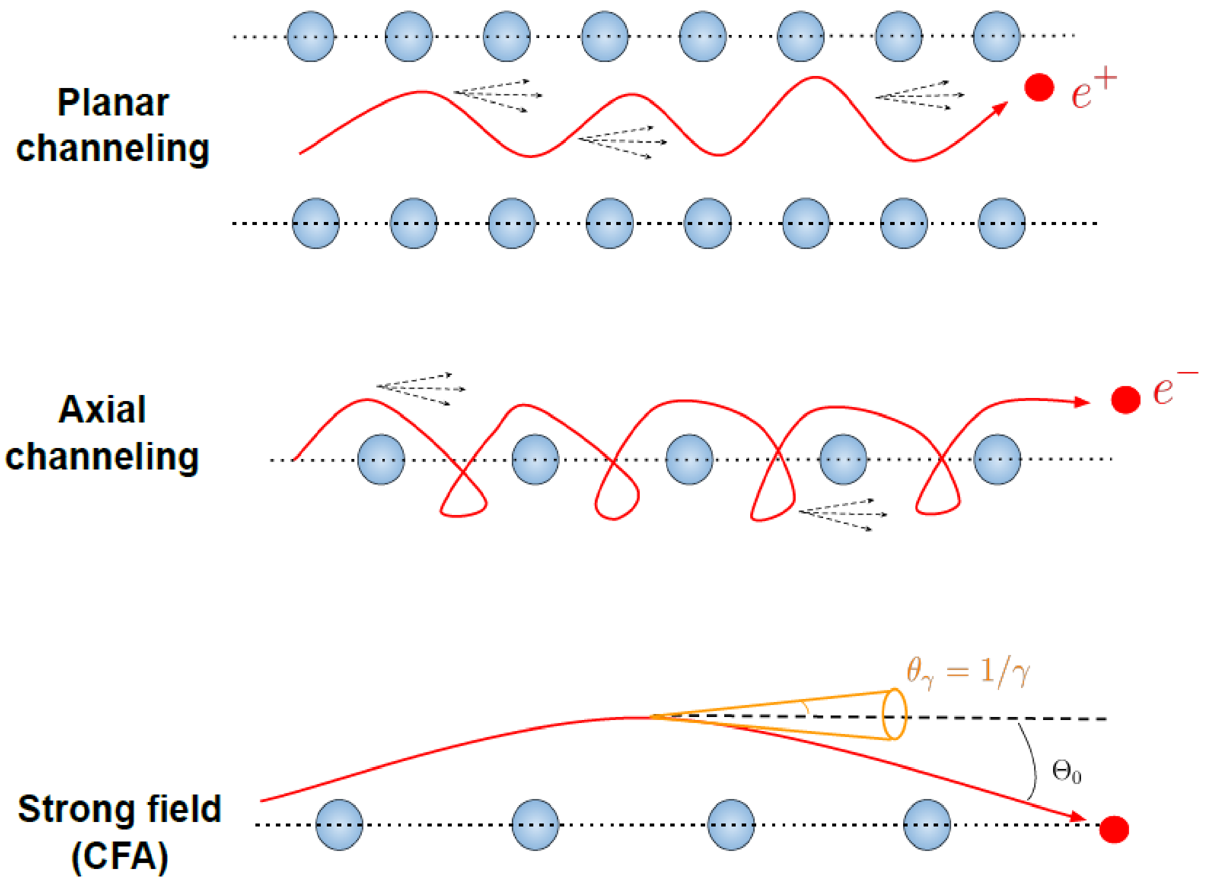
$$\chi = \frac{\gamma E}{E_0} > 1$$

$$\theta < \Theta_0 = \frac{U_0}{mc^2}$$

- The effect is visible already at $\theta \sim 1°, E \sim 10$ GeV

- The **angular acceptance** is **energy-independent** but crystal-dependent (since E, U_0 are the nuclei field and potential-well depth, while $E_0 \approx 1.3 \cdot 10^{18}\ \mathrm{V/m}$ is the Schwinger critical field).

For <111> axis in tungsten, $\chi = 1$ at 13.6 GeV and $\Theta_0 \sim$ 1.75 mrad

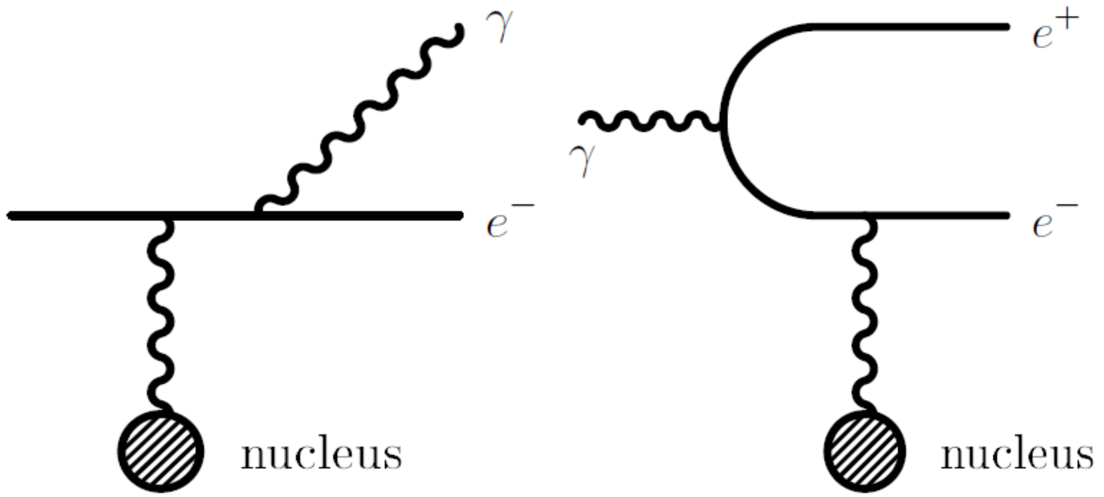


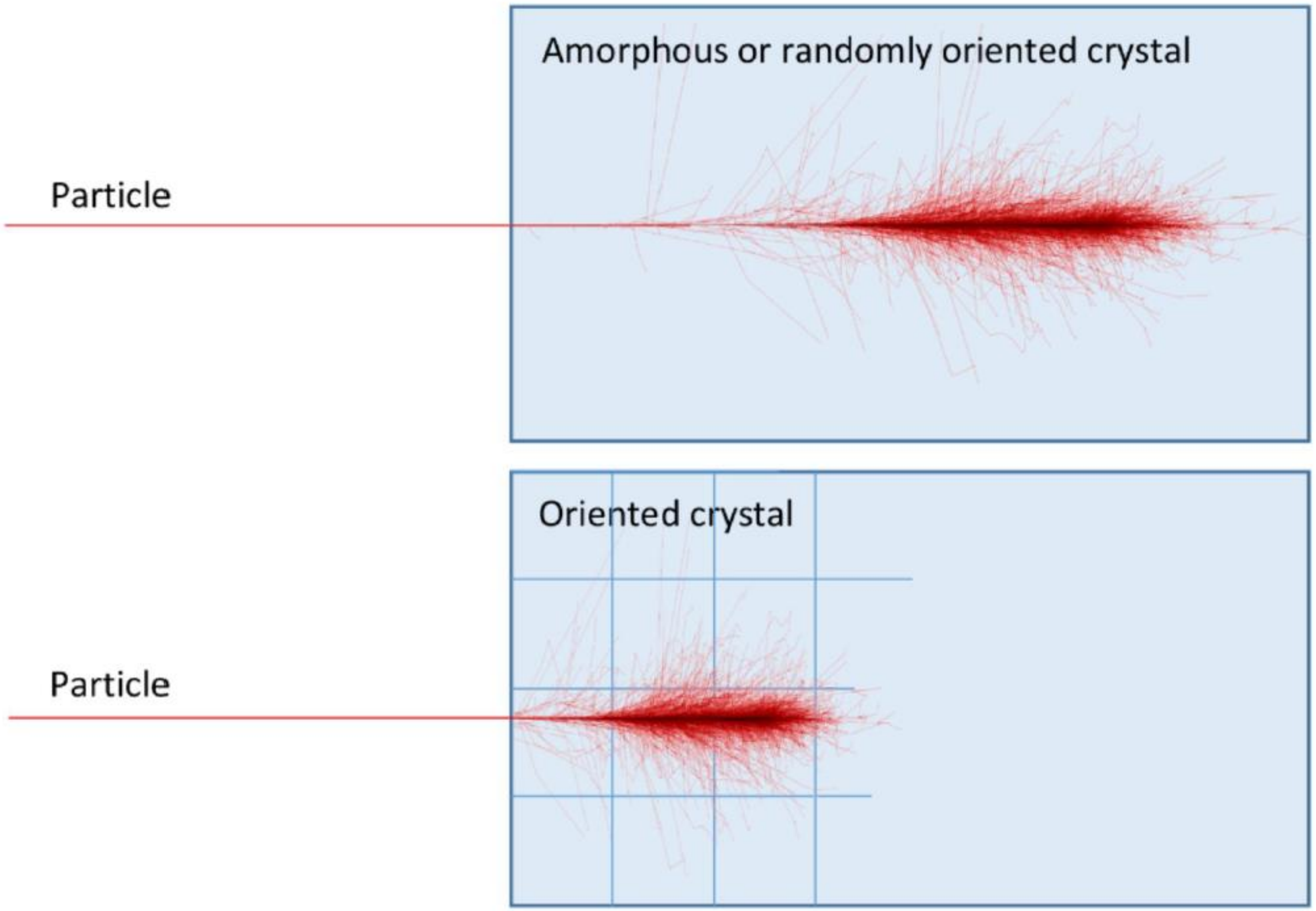
[values from *M. Soldani et al, arXiv:2203.07163 (2022).*]

The radiation length reduction

The strong crystalline field affects both **bremsstrahlung** and **pair production**. Thus, in an oriented lattice:

- Electromagnetic showers become much more compact
- The «effective» value of X_0 is expected to decrease



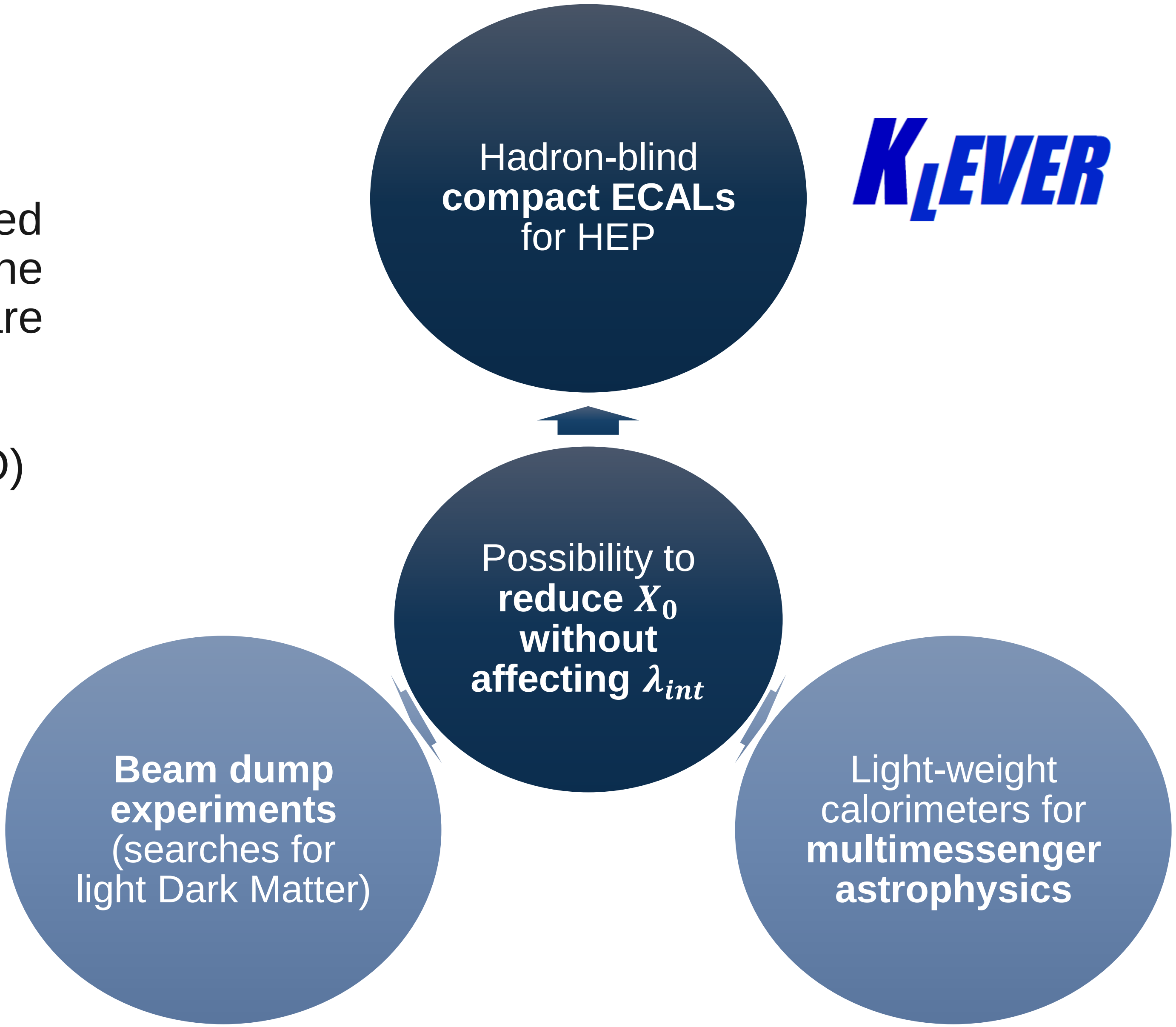


Why should we care?

There are several applications for oriented crystals in HEP and astrophysics, but the **experimental data** available today are **insufficient** for any practical purpose, due to:

- Scarcity of samples tested (e.g., Ir, W, BGO)
- Scarcity of lengths tested ($\sim 1\ X_0$)

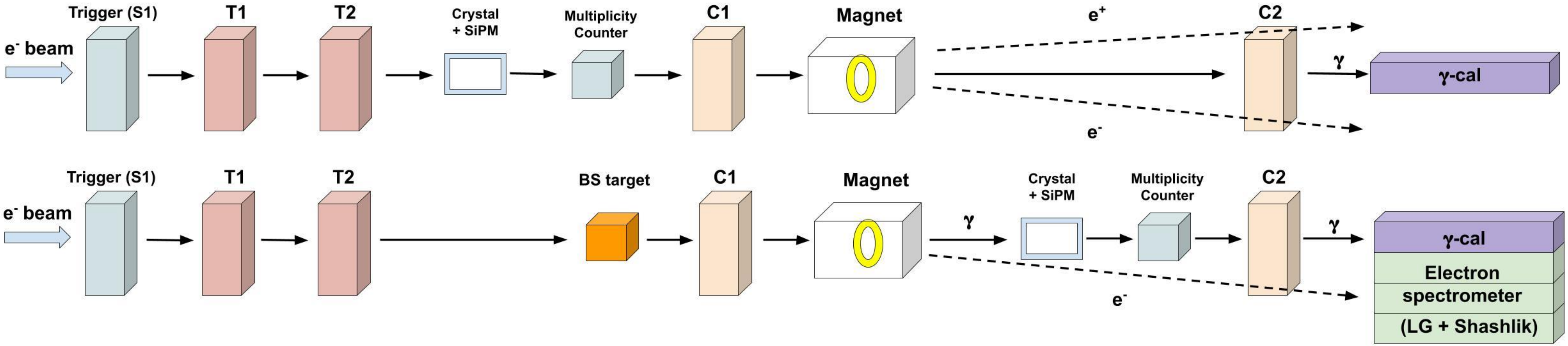
→ **More studies are needed!**



The experimental setup at the CERN SPS

August 2021: 2 weeks-long beam test at the H2 extracted beam line.

Goal: characterization of several crystal samples (1 and 2 X_0 $PbWO_4$, $2\,X_0$ PbF_2) with **120 GeV electrons** (top) or **tagged photons** (bottom).

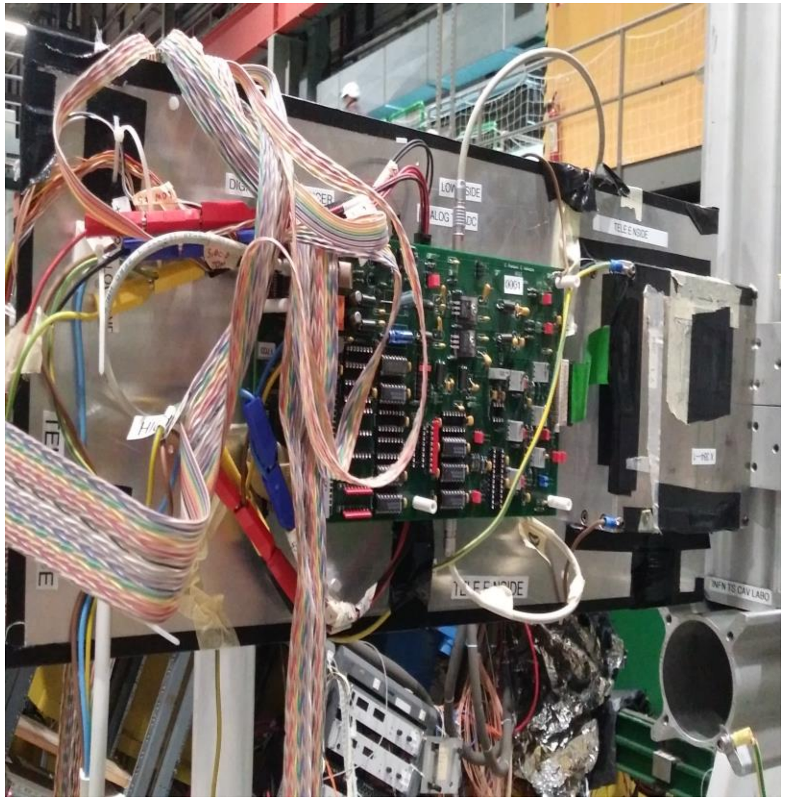


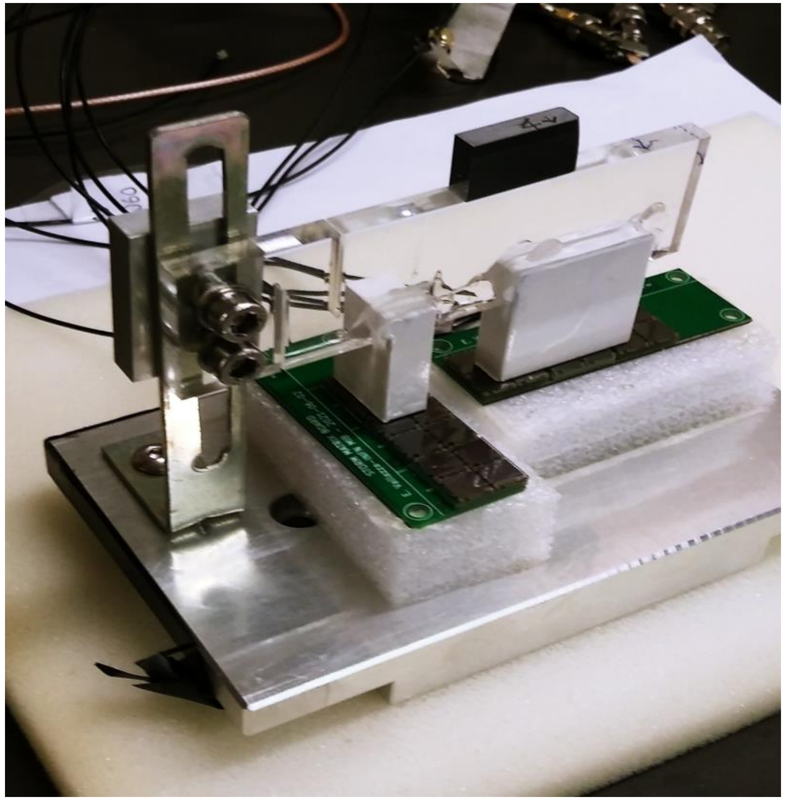
The reference detectors

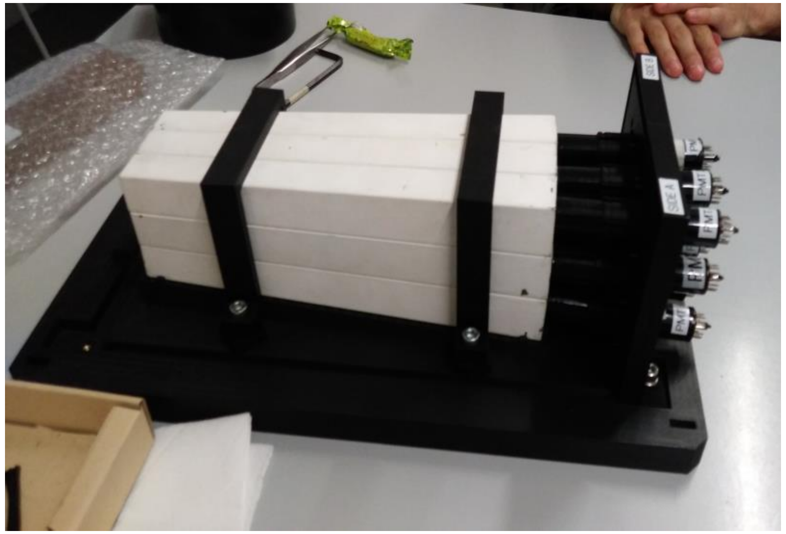
Silicon strip tracking detectors ($10 \div 30\ \mu m$ spatial resolution)

SiPMs coupled to the crystal under investigation

γ-calorimeter (3×3 matrix of BGO crystals, $\approx 20.5\ X_0$)



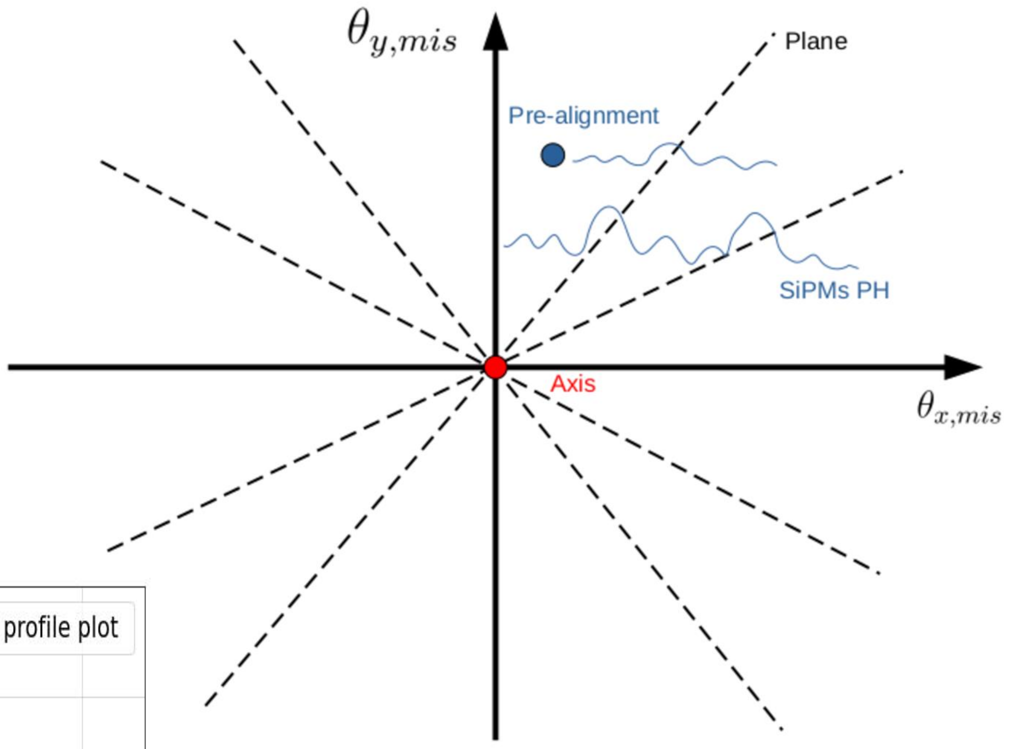


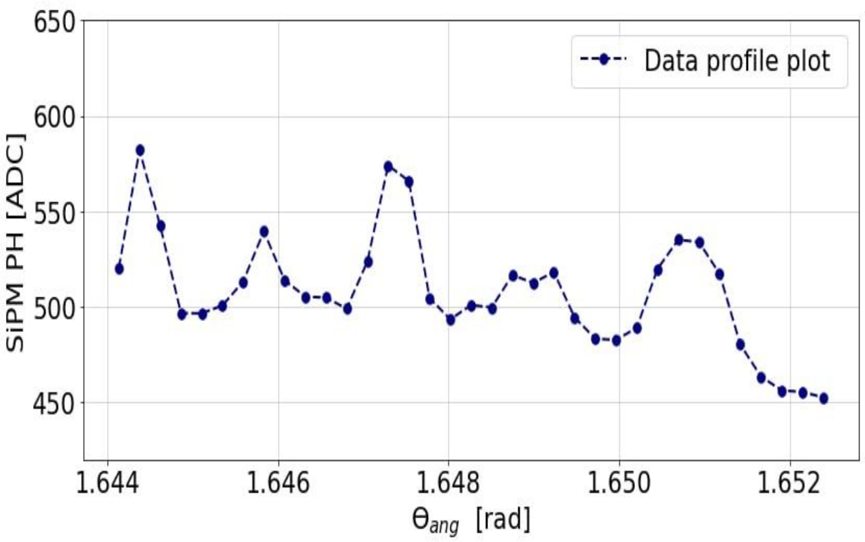


The crystal-beam alignment

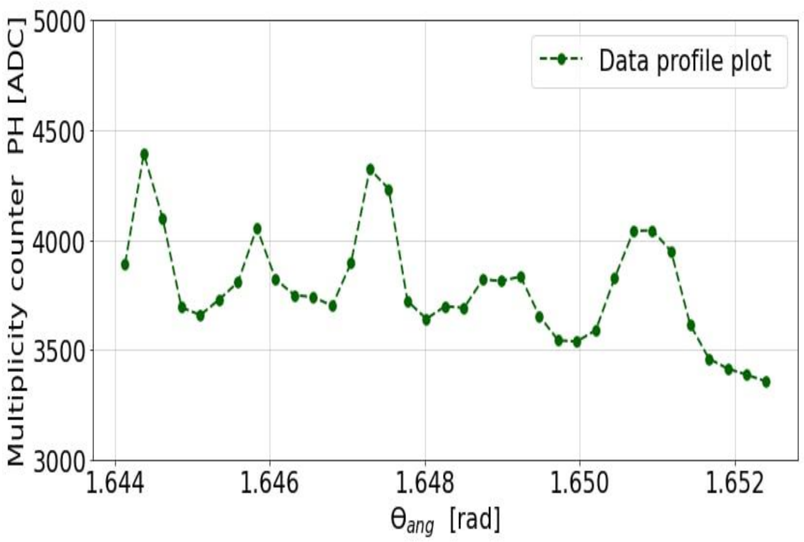
After a preliminary laser-guided pre-alignment, the **stereogram reconstruction** allows the determination of the correct **alignment** between the crystal axes and the particle beam.

This procedure is carried out by performing several **angular scans,** in search for the position of **maximum particle multiplicity and maximum energy deposit.**

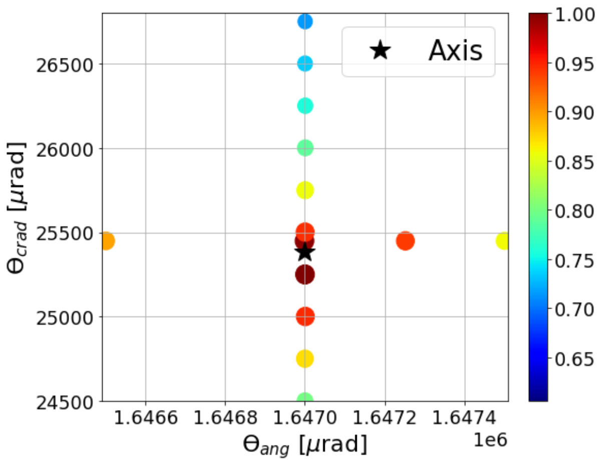




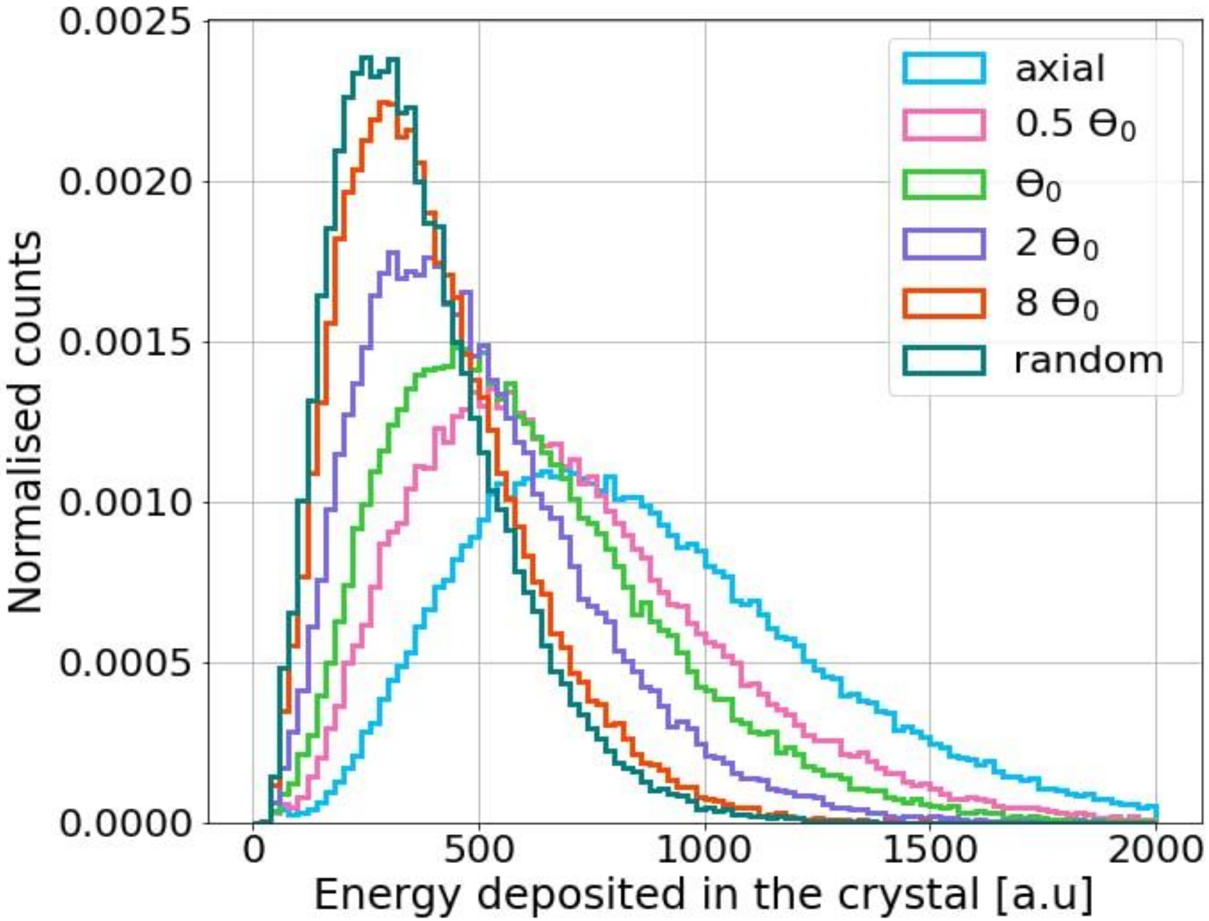
SiPM

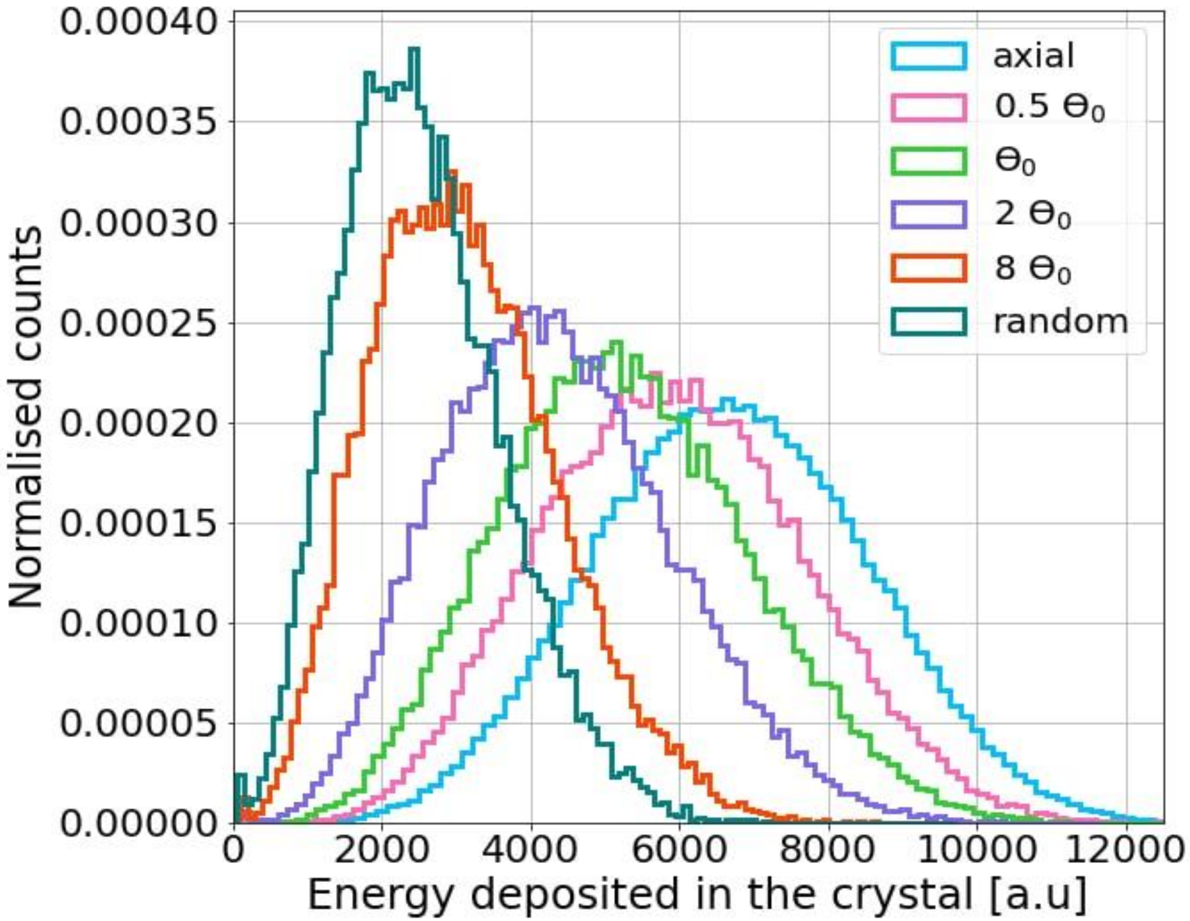


Multiplicity Counter



Preliminary results: $\mathbf{PbWO_4}$ (<100> axis)

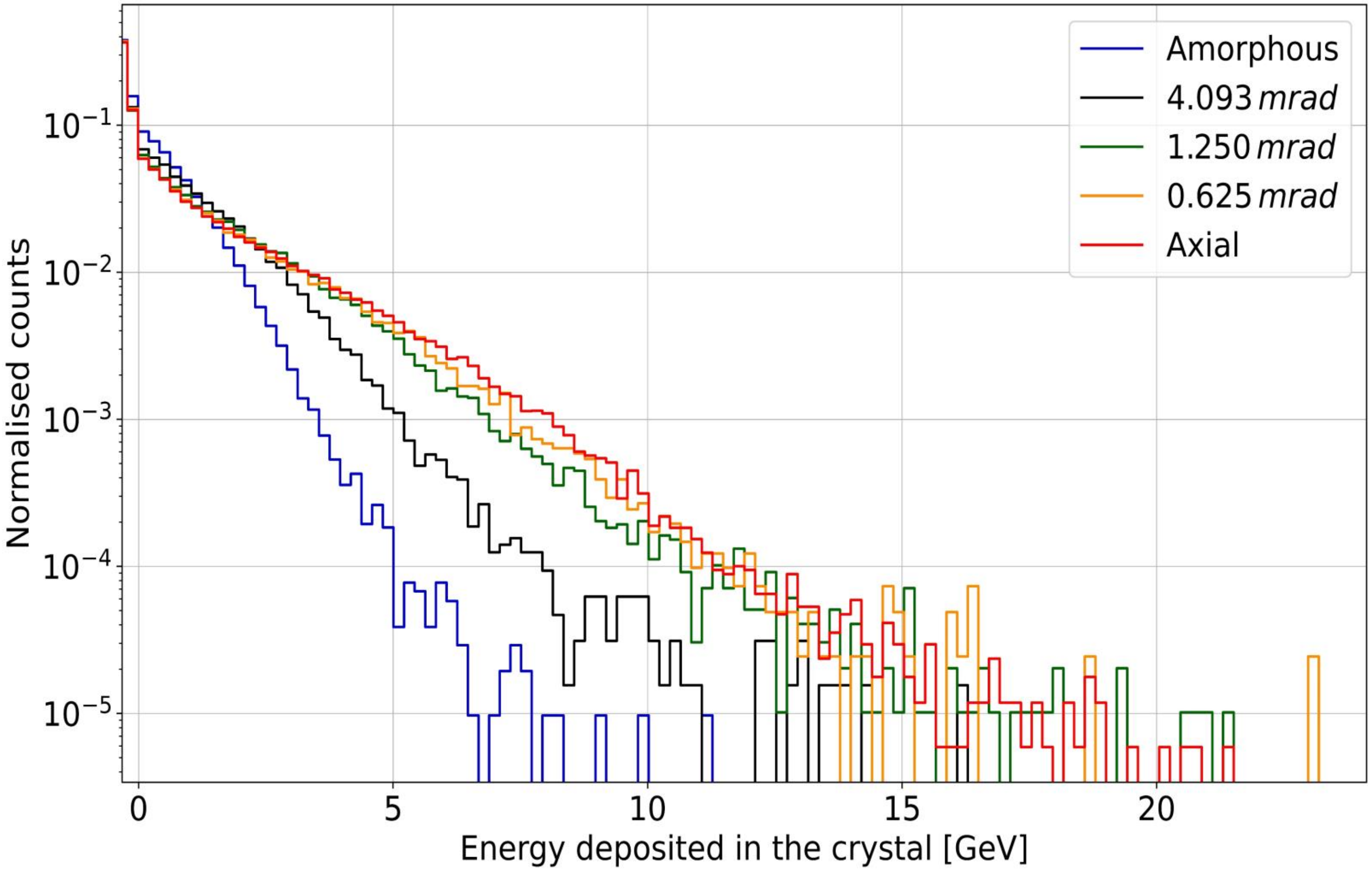




$\mathbf{1\ X_0}$: $E_{axial} \approx \mathbf{2.5}\ E_{random}$

$\mathbf{2\ X_0}$: $E_{axial} \approx \mathbf{3}\ E_{random}$

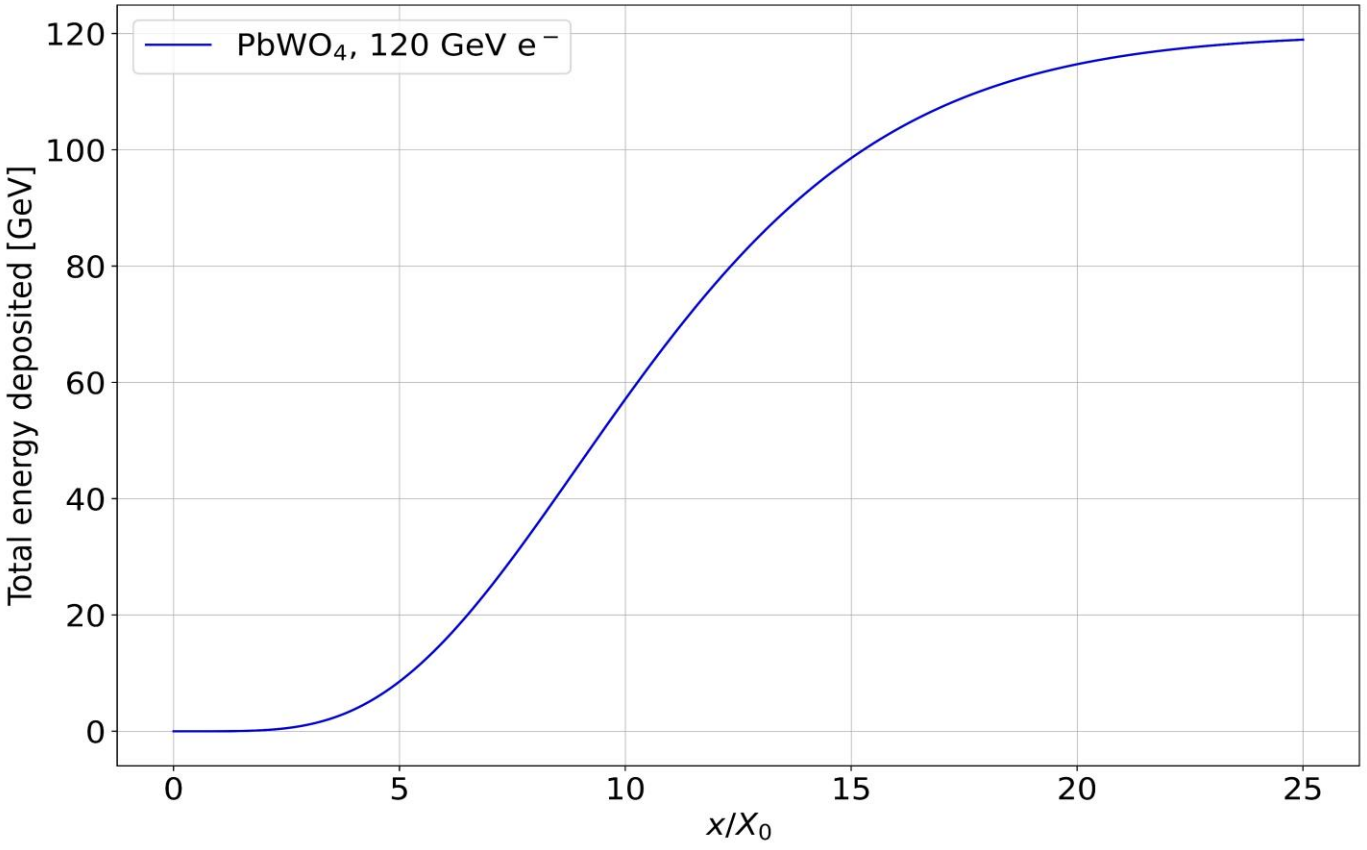
Preliminary results: $\mathbf{PbF_2}$ (<110> axis)



$$\mathbf{2\ X_0}:\ E_{axial} \approx \mathbf{(2 \div 2.5)}\ E_{random}$$

Estimation of the radiation length reduction

Idea: **simulate the shower development** inside the crystal and evaluate the ratio of the lengths needed to obtain the measured **energy deposit enhancement.**



Crystal sample	X_0 reduction
$PbWO_4$ (1 X_0)	29%
$PbWO_4$ (2 X_0)	30%
PbF_2 (2 X_0)	(25 ÷ 30) %

Conclusions & outlooks

- ✓ Strong field effects have been measured in several **scintillating crystals**, with both electrons and tagged photon beams, in terms of:
  - **Enhancement** of the energy deposited
  - Reduction of the **radiation length**
- ✓ For the first time ever, the SFC was observed also in a **Cherenkov radiator.**
- ✓ **SiPMs** coupled to the crystals showed comparable or better performances than plastic scintillators, for the **stereogram reconstruction** and X_0 reduction estimation.

What comes next:

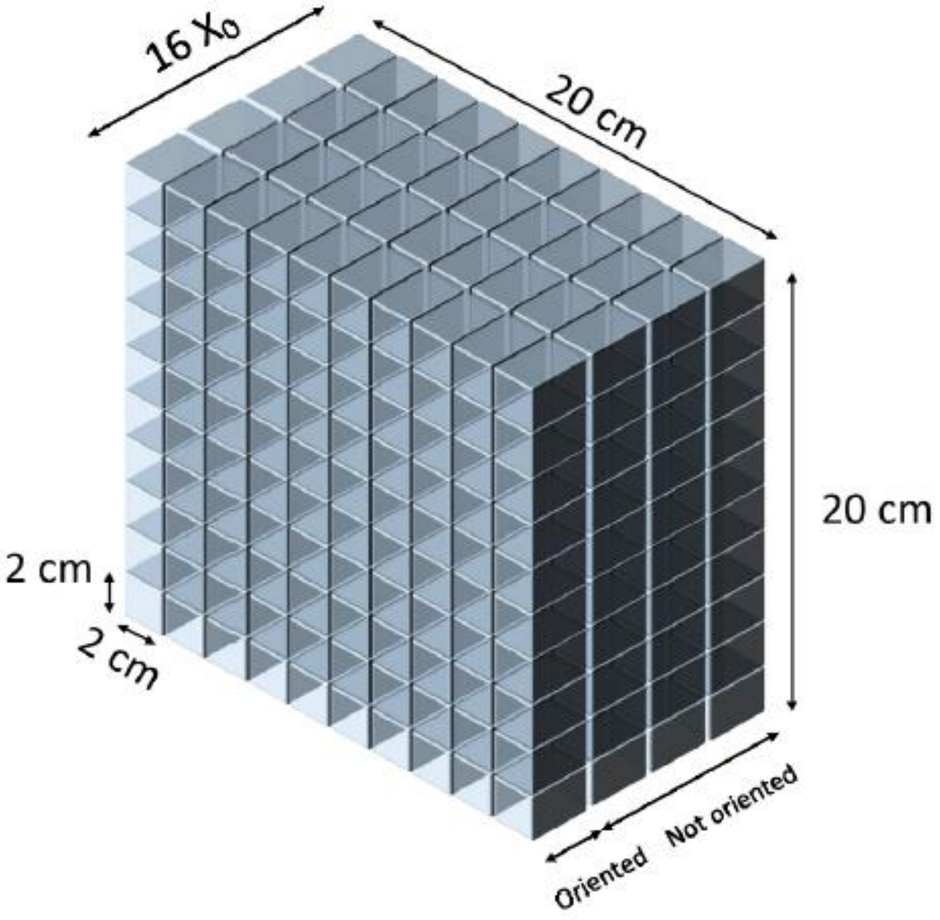
- ❑ **Simulation** of the experimental setup, to confirm our findings
- ❑ **Realization** of the **first particle detector based on oriented crystals.**

Thank you for your attention!

For questions or comments please contact: pmontiguarnieri@studenti.uninsubria.it

The KLEVER experiment

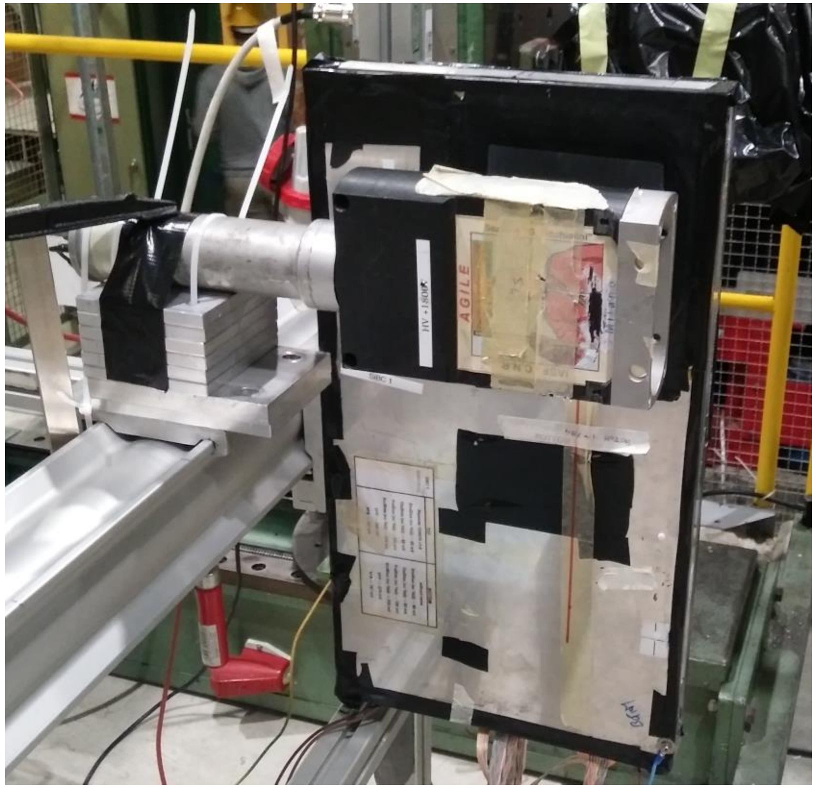
- Goal: measure for the first time $\mathbf{BR}\,(\mathbf{K_L} \to \boldsymbol{\pi^0 \nu \bar{\nu}})$ up to $\sim 20\%$ precision
- 5 years-long data taking during **LHC Run 4**, in NA62-like conditions (400 GeV/c protons)
- Very complex setup, due to the high background induced by kaon decay products (mainly soft photons and neutrons).
- Oriented crystals could be useful for the realization of the **Small Angle Calorimeter,** which will sit directly in the beam line:
  - Goal: measure $> 30\,\mathrm{GeV}$ photons with $< 10^{-4}$ inefficiency, while remaining blind to hadrons ($\sim 440\,\mathrm{MHz}$ of neutrons)
  - Baseline solution: ultra-fast Cherenkov sampling calorimeter ($\mathrm{PbF_2}$), partially-oriented, with $100\,\mathrm{ps}$ temporal resolution and 2-pulse separation at $\sim 1\,\mathrm{ns}$.



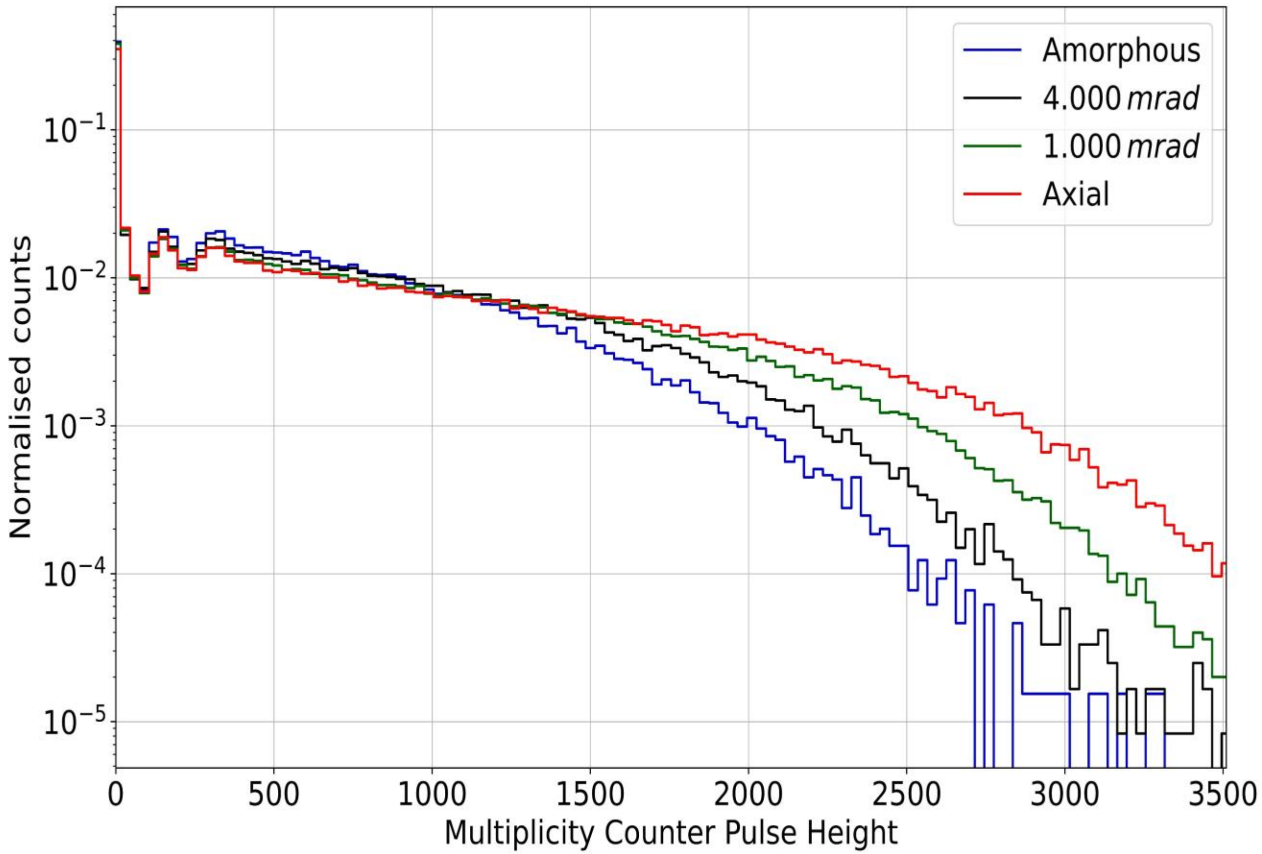
The experimental setup at the CERN SPS

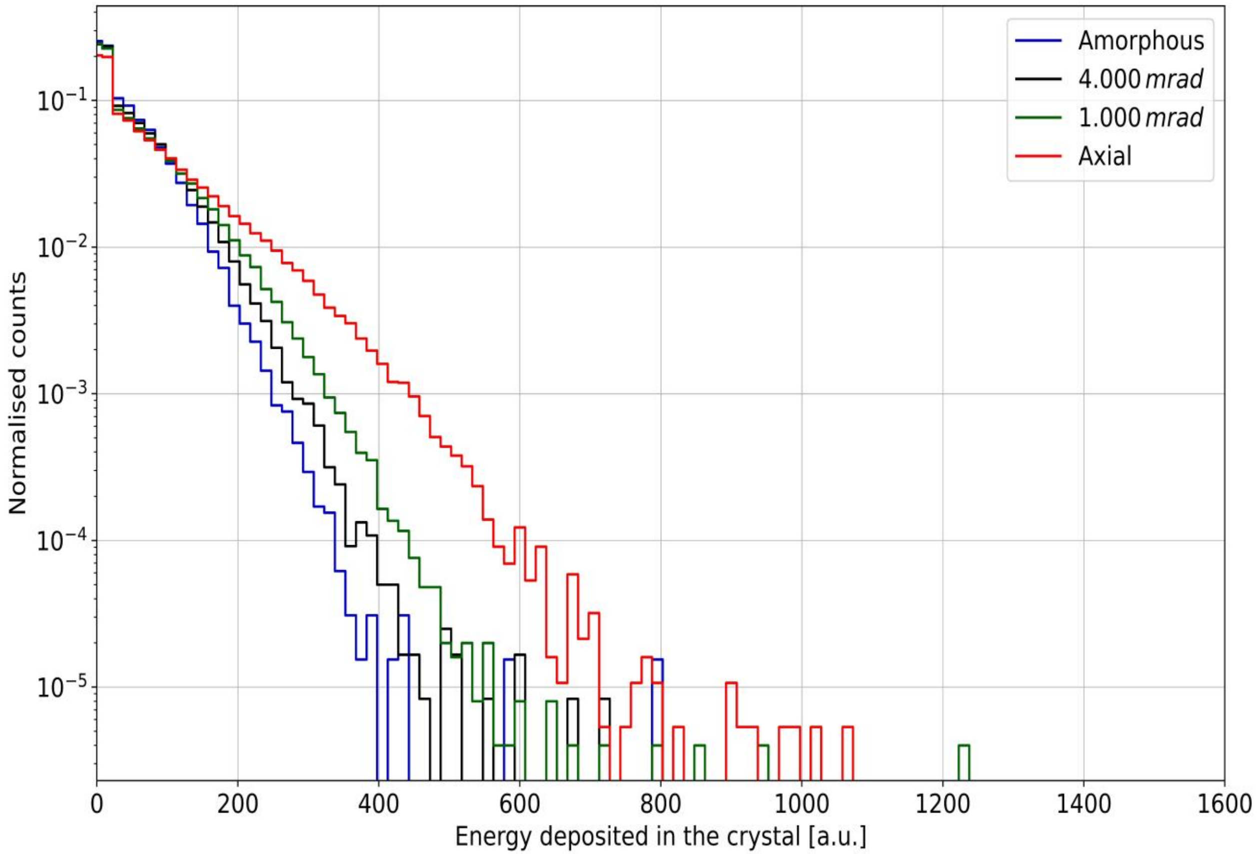
Electron spectrometer (7 Lead Glass homogenous ECALs + 1 lead-scintillator shashlik ECAL)

Plastic scintillator (≈ 5 cm thick) used as charged particle multiplicity counter



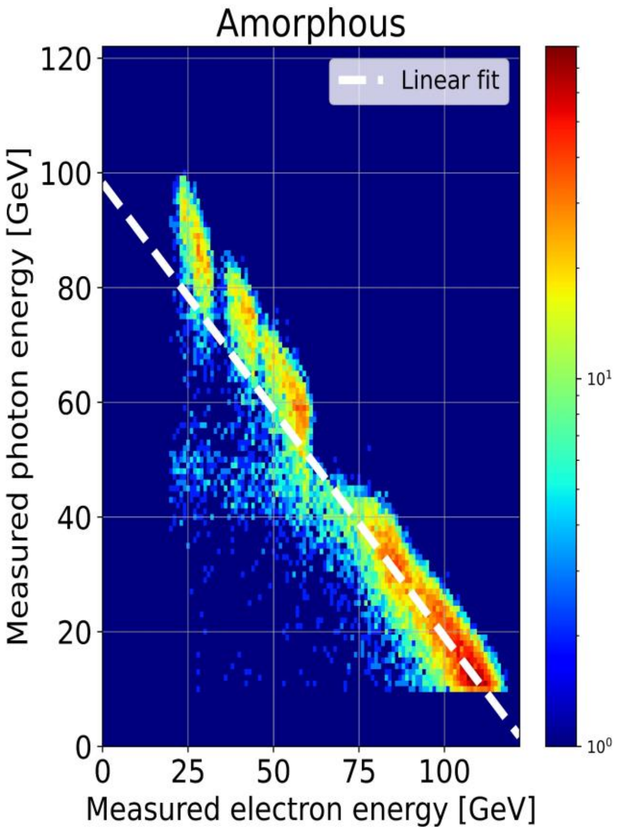
Preliminary results: $PbWO_4$ $(1\,X_0)$

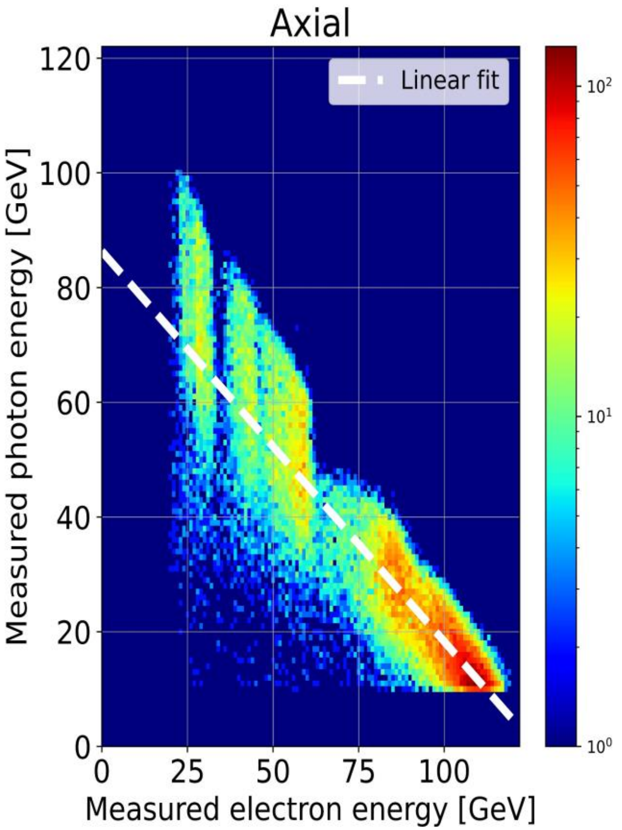


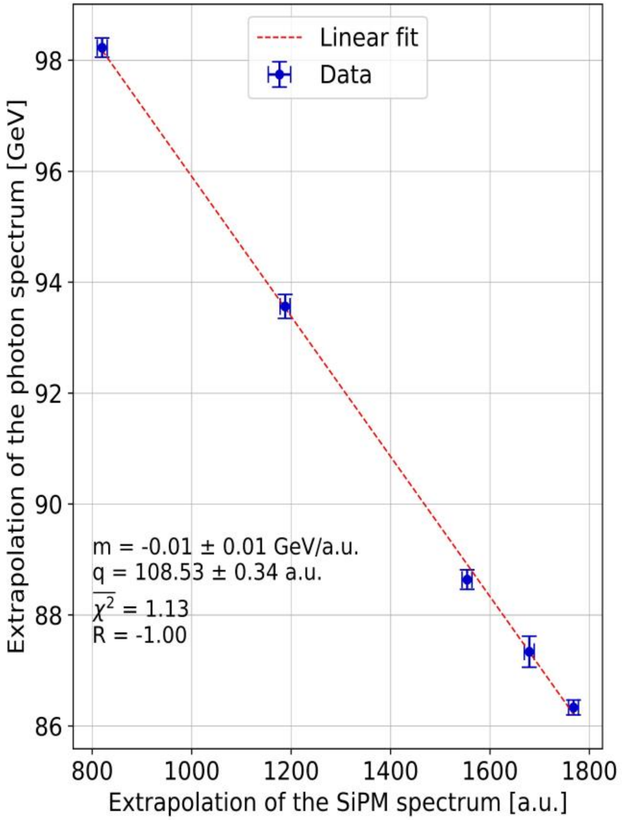


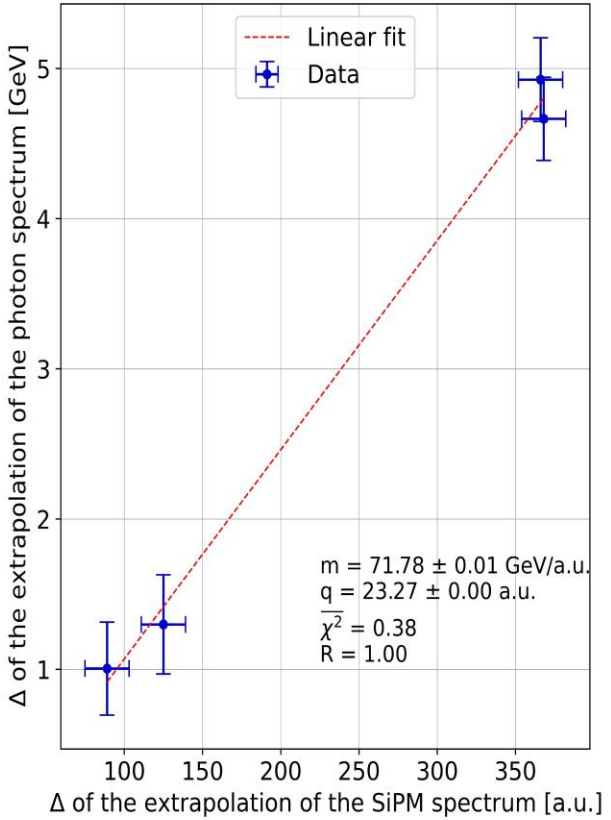
Multiplicity counter spectra (left) and SiPM spectra (right) for a tagged photon beam impinging on the crystal sample.

Energy calibration of the SiPM (PbF_2)









Estimation of the radiation length reduction

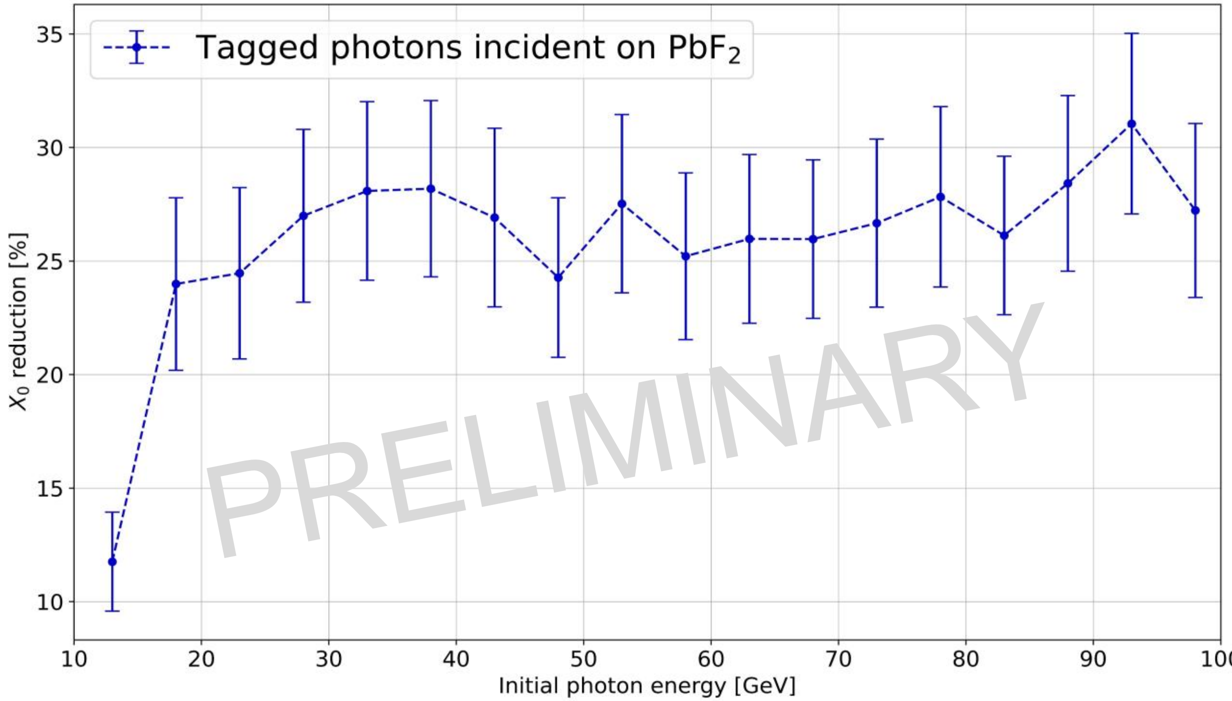
An alternative way to estimate the reduction of X_0 in an oriented crystal uses the following model for the longitudinal shower development:

$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1} e^{-bt}}{\Gamma(a)}$$

where a depends on the critical energy of the material and $b \approx 0.5$. The total energy deposited inside a crystal of length t_0 is:

$$E(t_0) = \int_0^{t_0} dt\, \frac{dE}{dt} = E_0 \frac{\Gamma(a,0) - \Gamma(a, bt_0)}{\Gamma(a)}$$

The ratio of axial vs amorphous energy deposits is measured experimentally (SiPMs). Thus, setting $t_0^{axial} > 1$ and $t_0^{amorphous} = 1$, one can solve numerically the equation and estimate t_0^{axial}.



Shower model from *E. Longo and I. Sestili, Nuclear Instruments and Methods 128.2 (1975)*