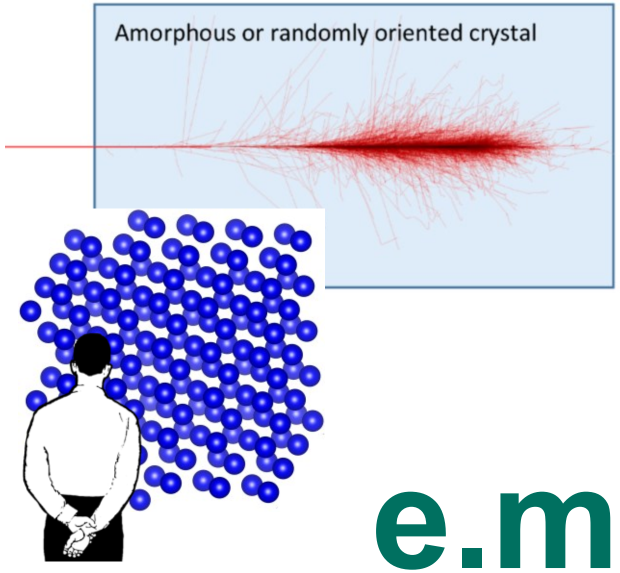
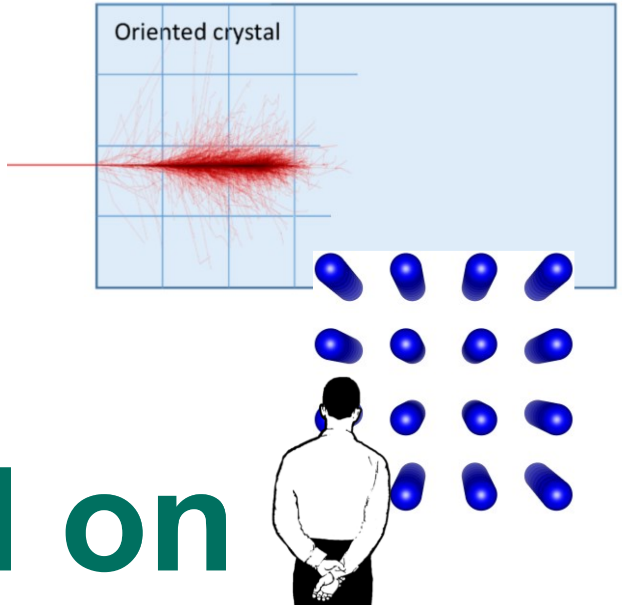




Compact forward e.m. calorimeter based on oriented crystals

EPS HEP2023 HAMBURG

23 August 2023

Marco Romagnoni

on behalf of OREO collaboration

INFN, Section of Ferrara

romagnoni@fe.infn.it

INFN Istituto Nazionale di Fisica Nucleare

The INFN OREO experiment
ORiEnted calOrimeter

✓ **INFN Ferrara and University of Ferrara**

L. Bandiera (*national coordinator*), N. Canale, V. Guidi, L. Malagutti, A. Mazzolari, R. Negrello, M. Romagnoni, M. Soldani, A. Sytov

✓ **INFN Legnaro Labs and University of Padua**

N. Argiolas, D. De Salvador, F. Sgarbossa

✓ **INFN Milan Bicocca and Insubria University**

S. Carsi, G. Lezzani, P. Monti-Guarnieri, L. Perna, M. Prest, A. Selmi, E. Vallazza

✓ **INFN Frascati**

M. Moulson, M. Soldani

Outlook

- Introduction to the strong crystalline field and electromagnetic shower modification in oriented crystals
- Experimental tests on PWO samples at CERN SPS extracted lines
- First prototype of an ORiEnted calOrimeter
- Application in ultra-compact e.m. calorimeters for high-energy physics and astrophysics
- Summary and Conclusions

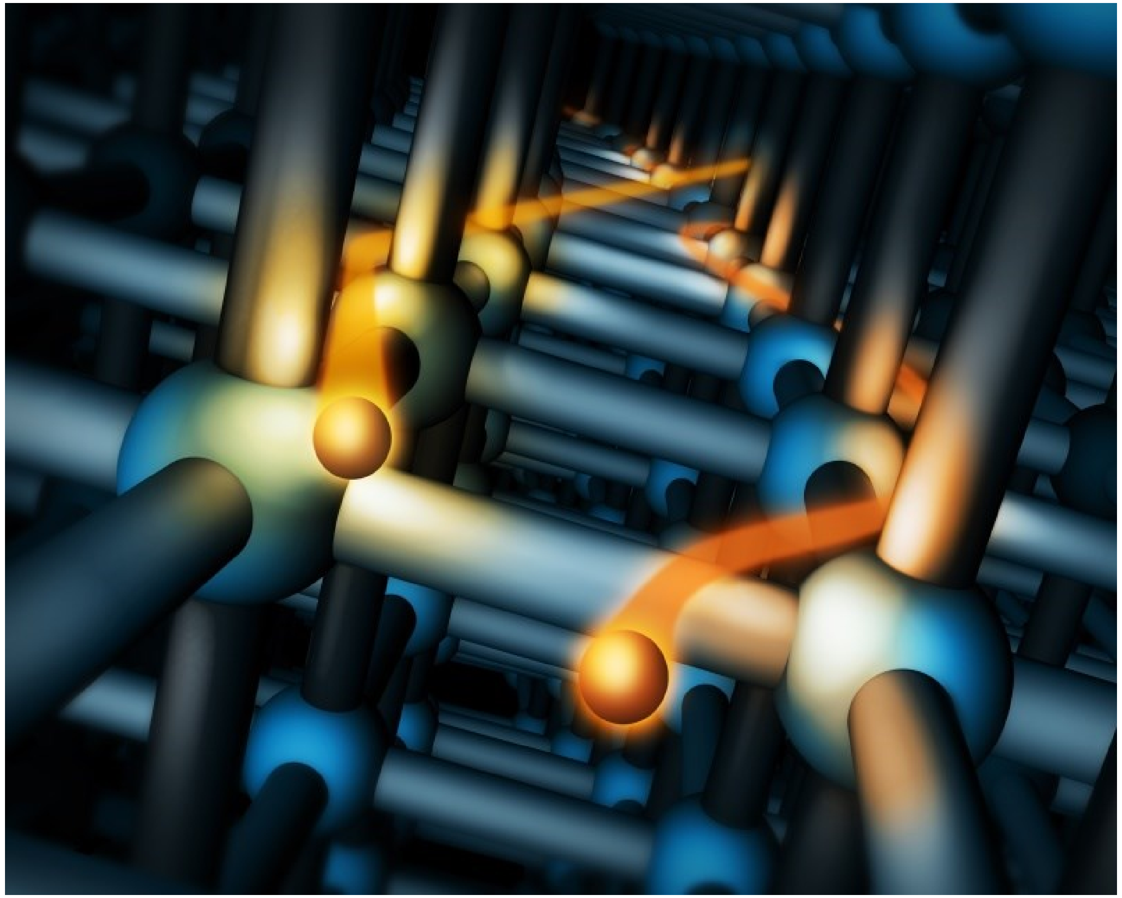
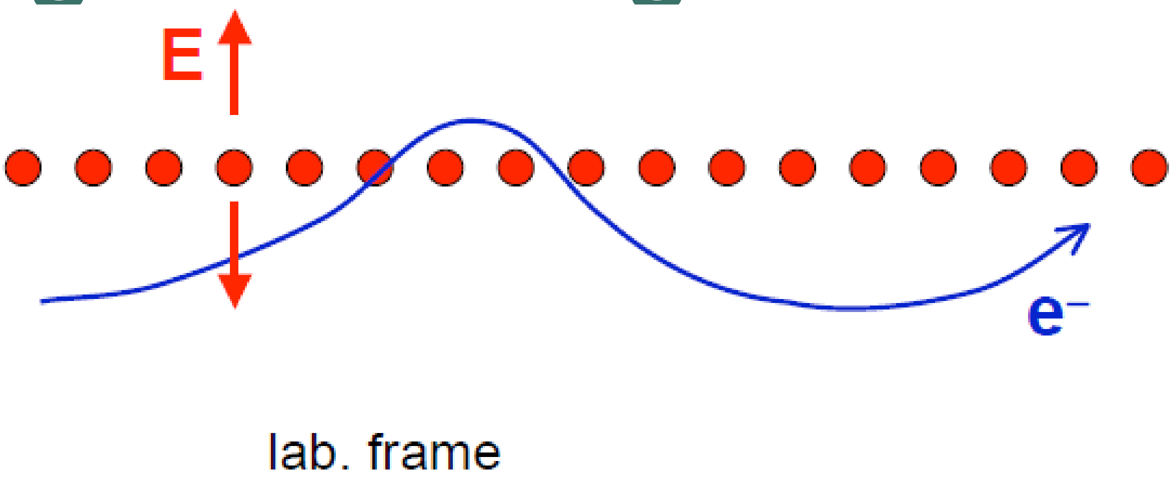
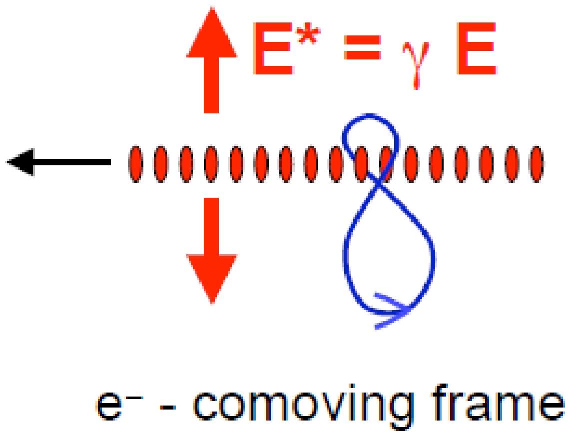


Image from https://www6.slac.stanford.edu/news/2015-02-25-slac-led-research-team-bends-highly-energetic-electron-beam-crystal.aspx

Strong electromagnetic field in oriented crystals



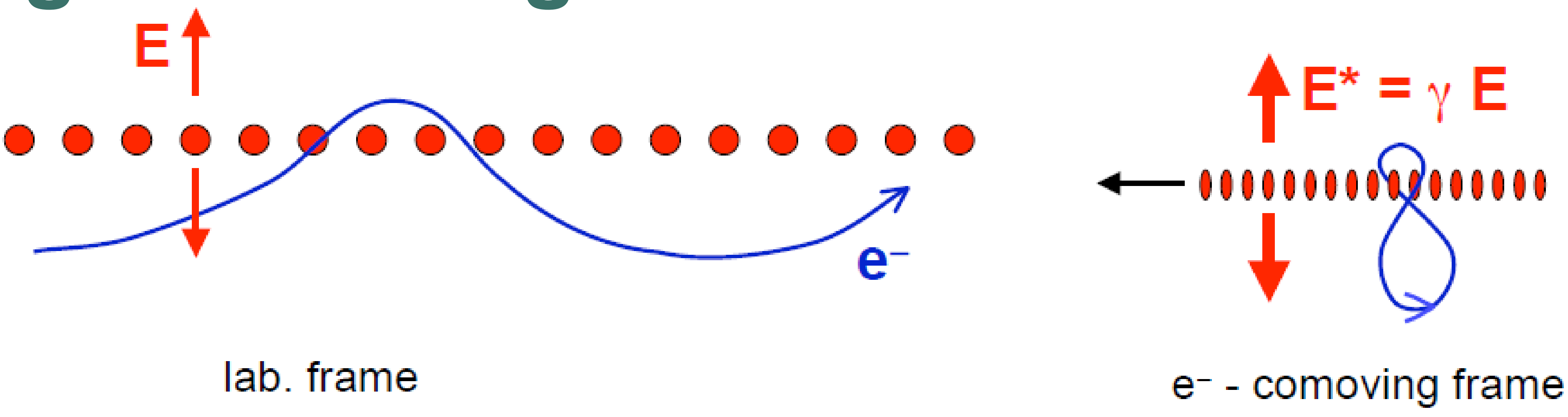


In the comoving frame, the **Lorentz contracted Electric field** can be computed as:

$$E^* = \gamma E$$

Being the Axial field of high-Z crystals $E \approx 10^{11}$ V/cm

Strong electromagnetic field in oriented crystals



In the comoving frame, the **Lorentz contracted Electric field** can be computed as:

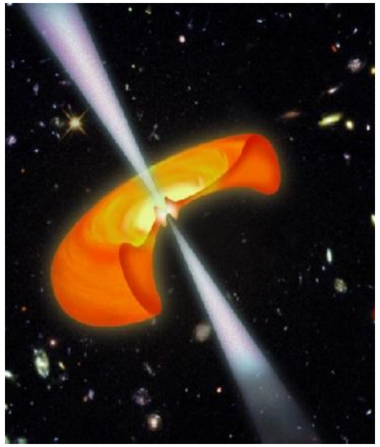
$$E^* = \gamma E$$

Being the Axial field of high-Z crystals $E \approx 10^{11}$ V/cm

At beam energies > 10 GeV, E* can reach the **Critical Schwinger QED field**:

$$E_0 = m^2c^3/e\hbar \simeq 1.3 \times 10^{16} V/cm$$

above which electrodynamics becomes non linear



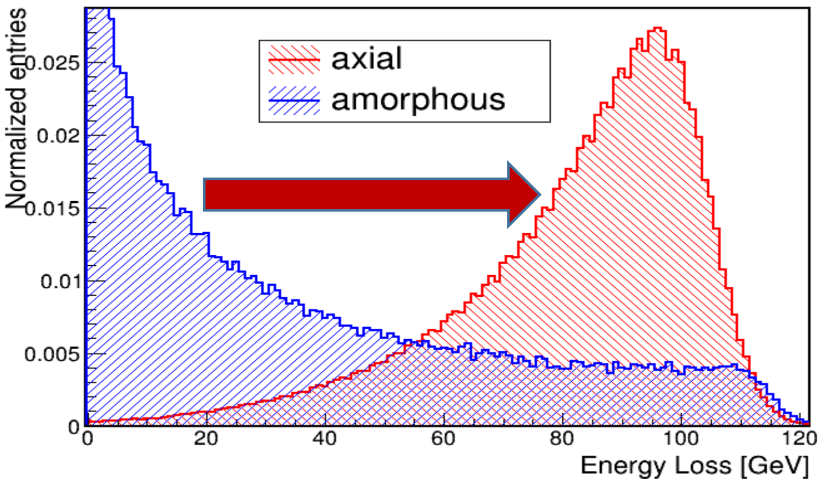
Magnetars

$B \approx 10^{10}$ T

Ulrik I. Uggerhøj, REVIEWS OF MODERN PHYSICS, VOLUME 77, OCTOBER 2005

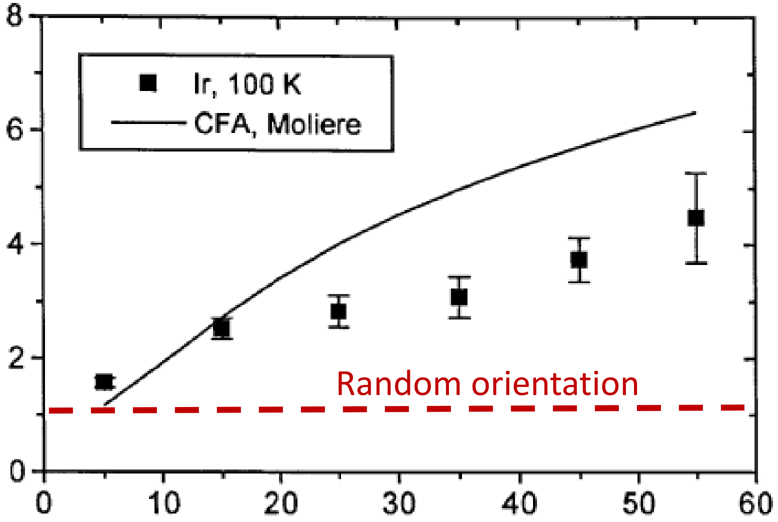
Radiation and pair production in axial alignment

Radiative energy loss spectrum of 120-GeV e$^-$ aligned with the <110> axis of a 2.8 mm long Ge crystal



Enhancement of pair production in a 3 mm Ir crystal axially oriented – compared to random orientation
Vs. photon energy

(NA48 exp. @CERN)



Strong field regime

$$E^* \geq E_0$$

- ***Radiation length reduction***
  - **X_0 decreases with initial energy increase.**
- ***Angular range:***
  - **V_0/m**
  - **few mrad up to 0.5°-1°** of misalignment between particle direction and crystal axes;
  - Depends weakly on particle energy.

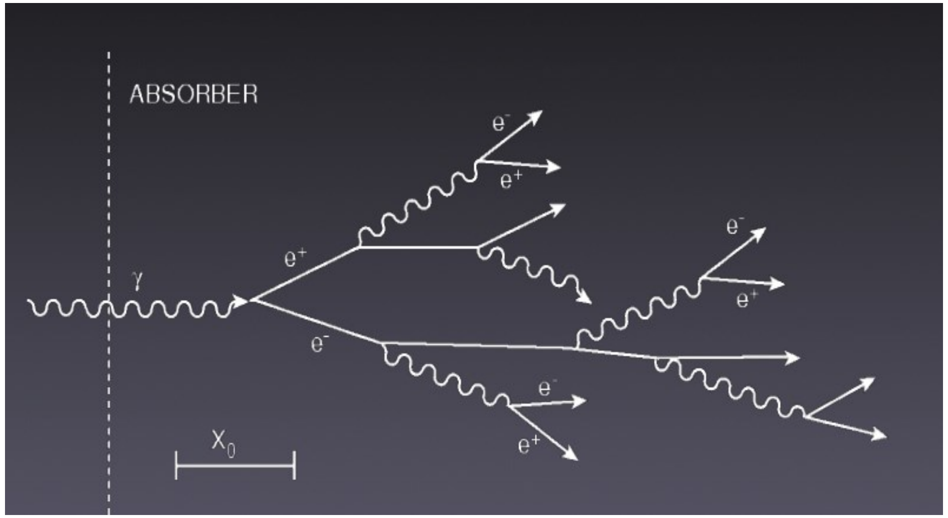
Strong increase in the energy radiated by the electrons and in the pair production probability by high-energy photons!

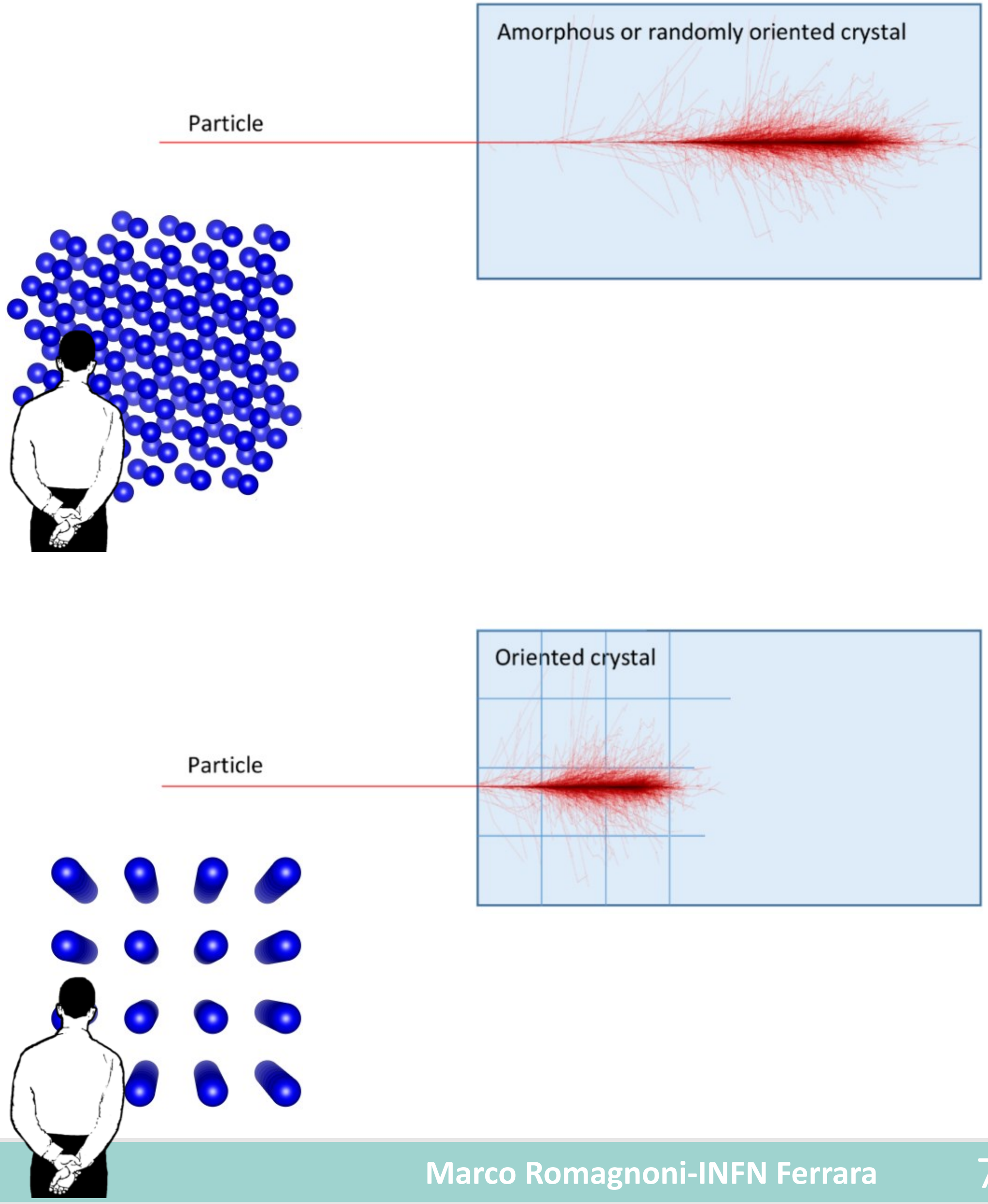
Electromagnetic shower acceleration

electromagnetic shower is way more compact

or equivalently

effective radiation length X_0 is much shorter





L. Bandiera et al., Phys. Rev. Lett. 121 (2018) 021603

Novel idea: orienting an e.m. calorimeter

scintillators emitters commonly employed in HEP electromagnetic calorimetry: lattice effects are neglected

the input photon or electron/positron showers can fully develop in a much lower thickness with respect to the current state-of-the-art detectors, with the same light yield

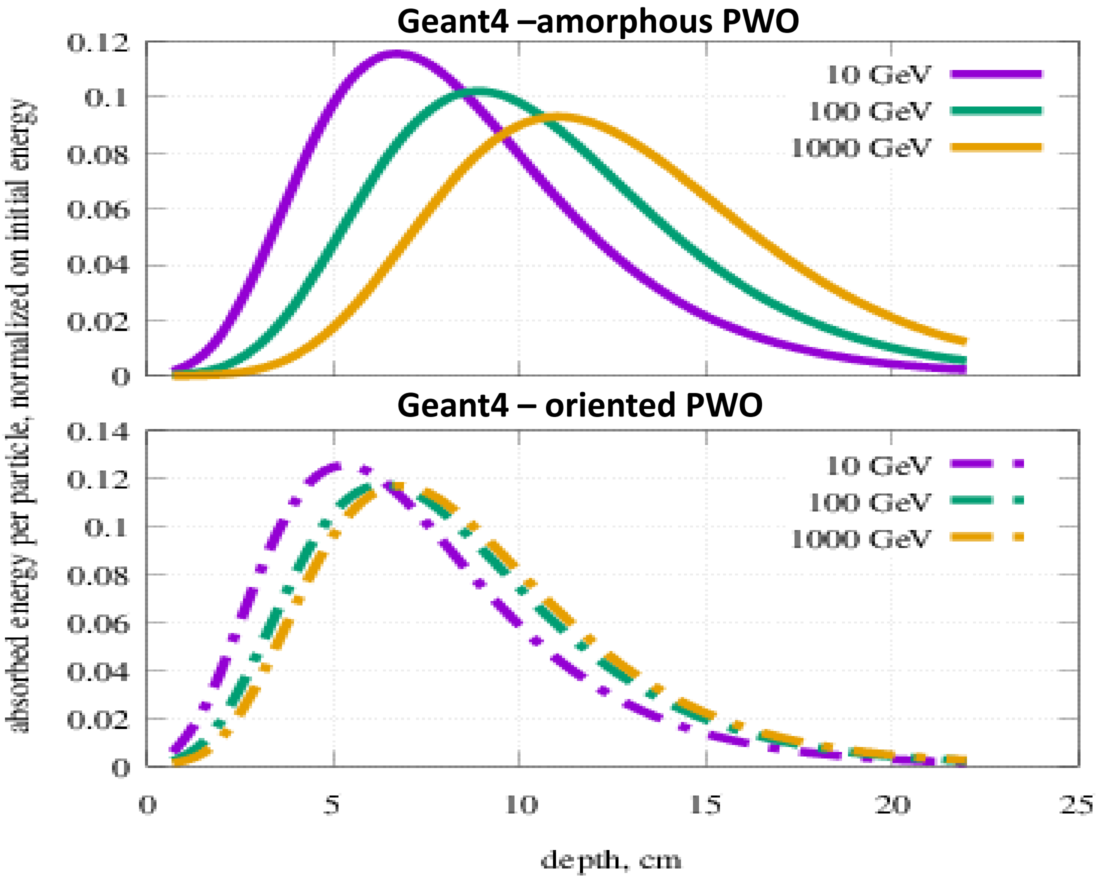
→ Enhanced compactness

→ Cost reduction

→ better n/γ discrimination

⇒ interesting for forward calorimetry in fixed-target HEP and space-borne experiments

Simulation of the e.m. shower of HE electrons in a PWO crystal



L. Bandiera, V.V.Haurylavets, V. Tikhomirov NIM A 936 (2019) p.124-126

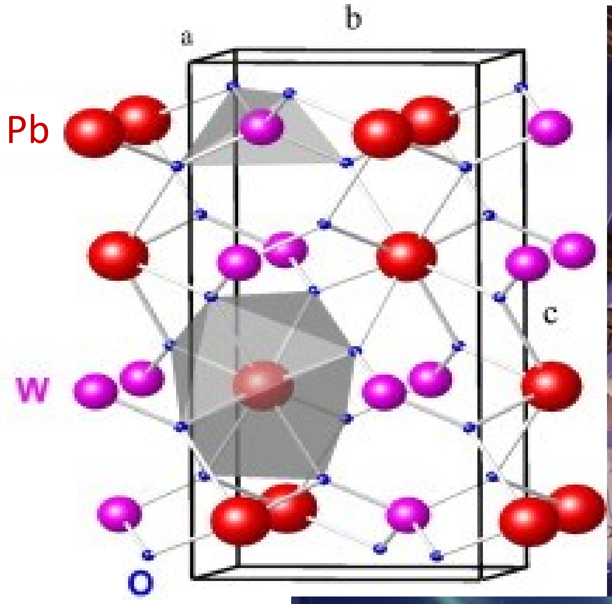
Crystal investigated: Lead tungstate ($PbWO_4$)

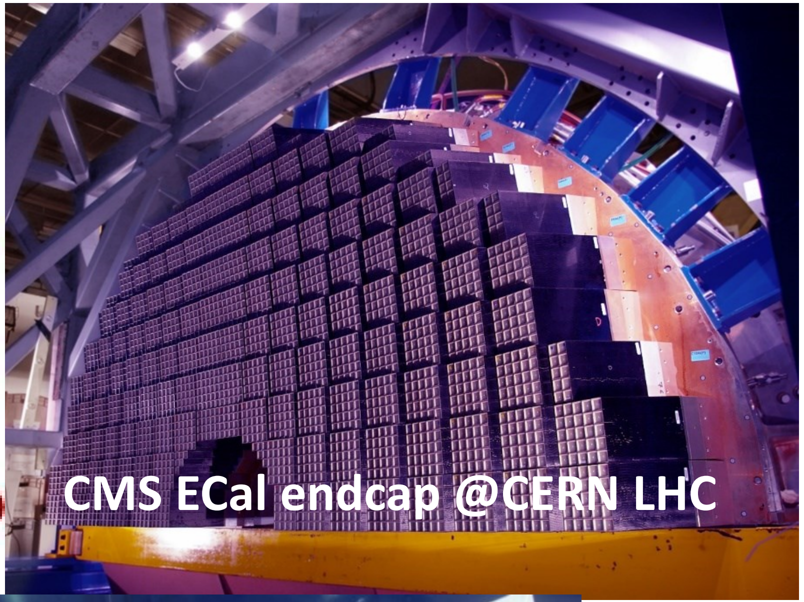
- scintillator, with well-peaked light emission in the blue
- optically transparent
- exploited by the CMS ECal → well known
- high density, high *Z* ***X_0 = 8.9 mm***
- radiation hard
- cheap fabrication into big samples
- **good crystalline quality (mosaic spread 0.1 mrad)**
- axes properties

	[100]	[001]
interatomic pitch	5.456 Å	6.01 Å
U_0	~700 eV	~500 eV
SF threshold	~25 GeV	

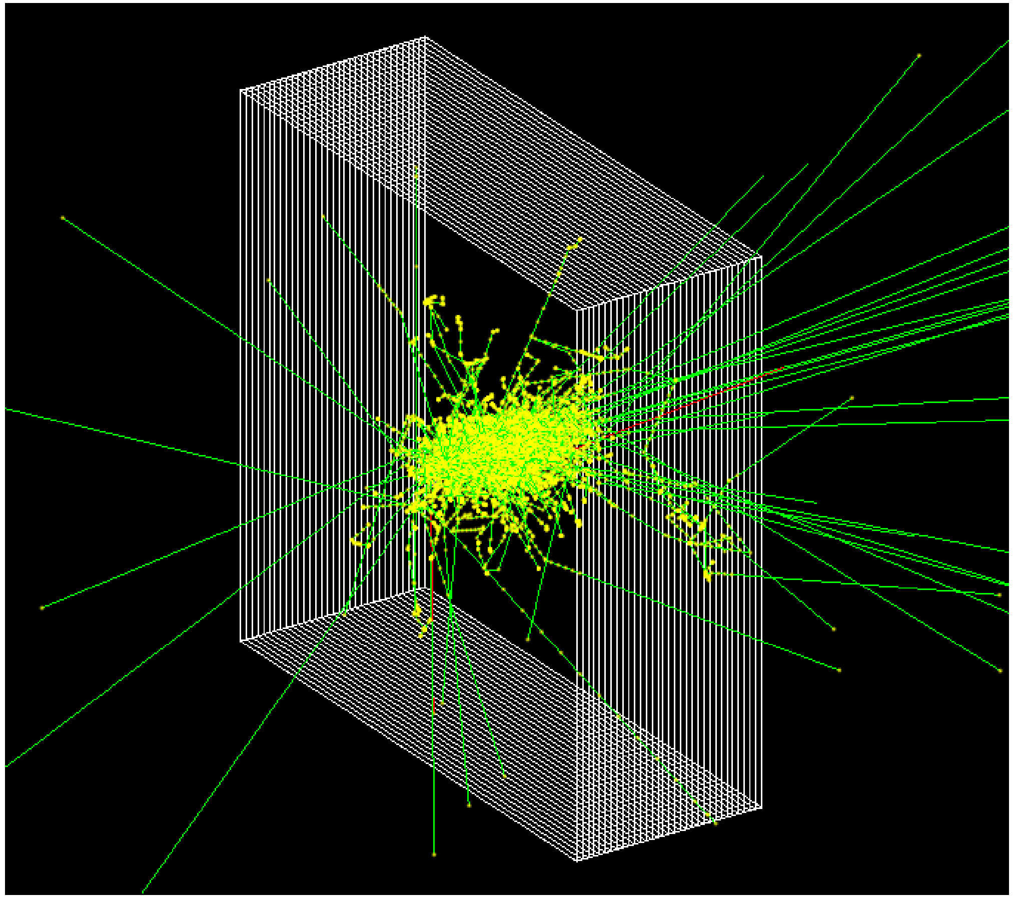
High-Z crystal for compact detectors

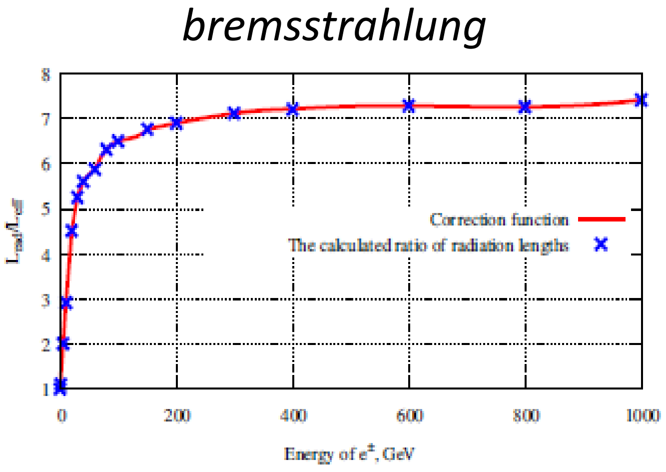
Maximum of Strong Field within V_0/m ≈1 mrad

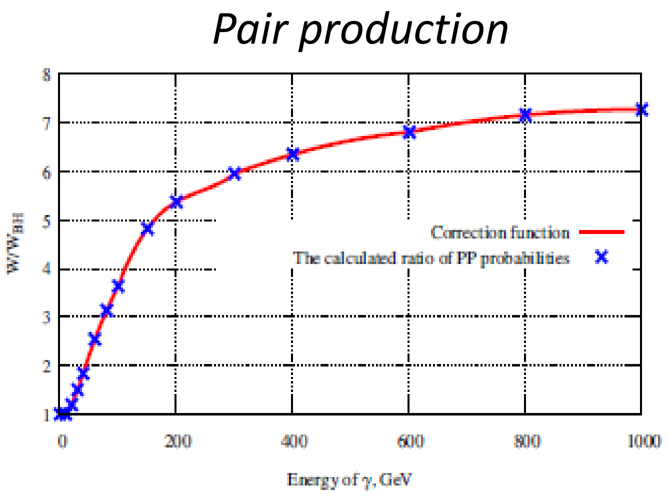




Oriented crystals in Geant4 simulations



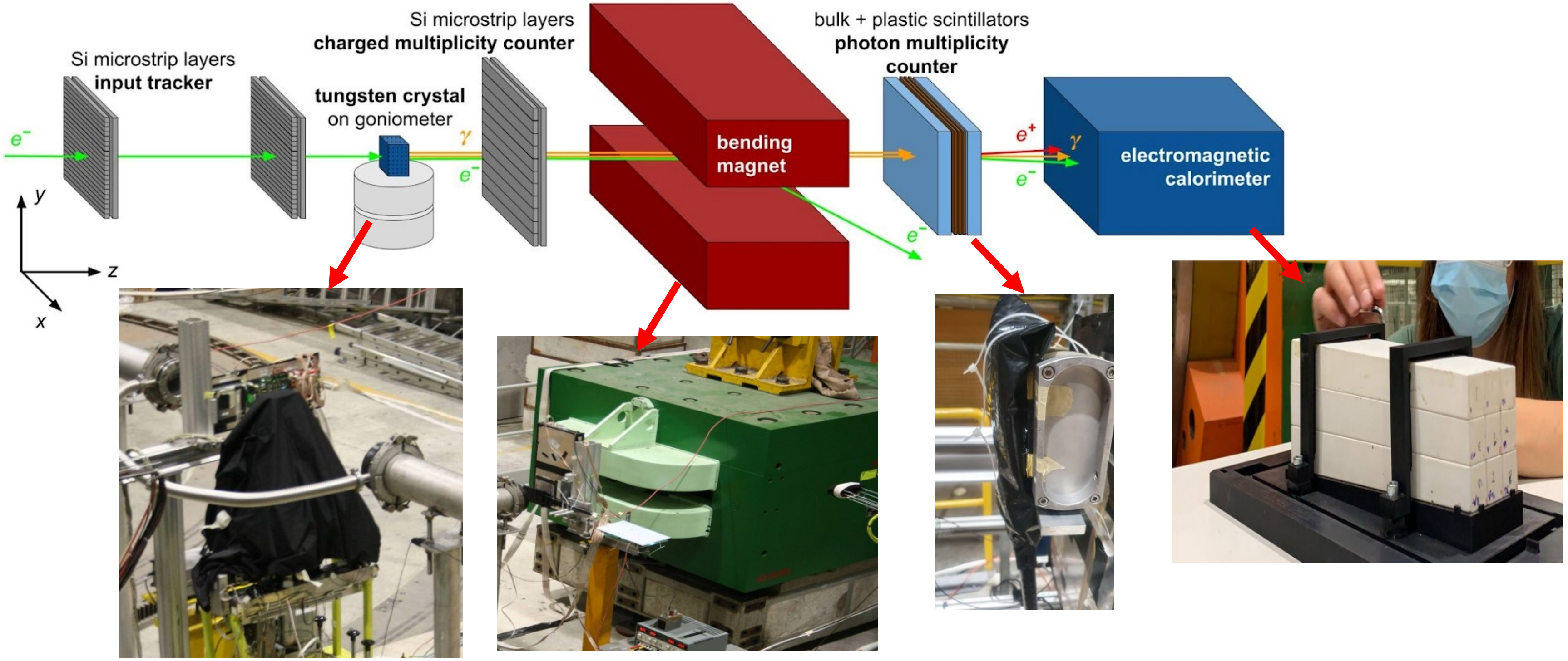


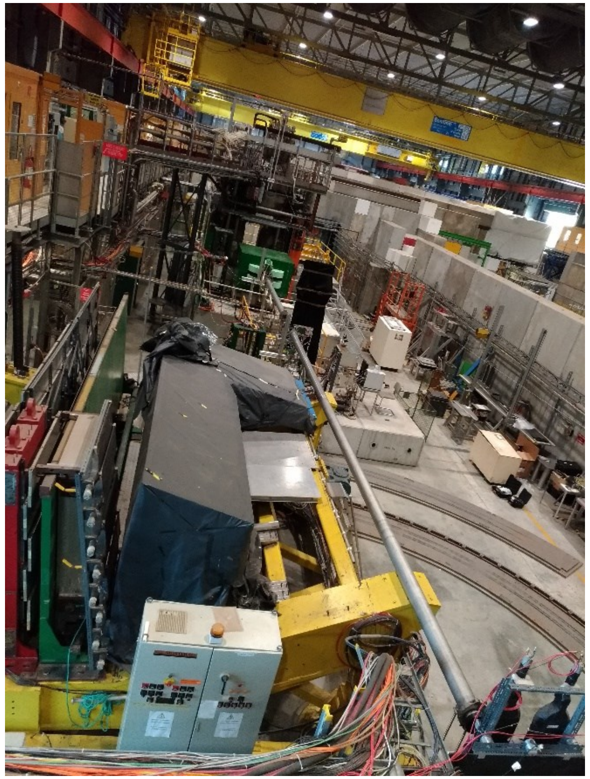


The electromagnetic shower is simulated using the **Geant4** toolkit in which the cross sections for **bremsstrahlung and pair production are rescaled** in agreement with full Monte Carlo including the strong field effects in crystals.

L. Bandiera, V.V.Haurylavets, V. Tikhomirov NIM A 936 (2019) p.124-126

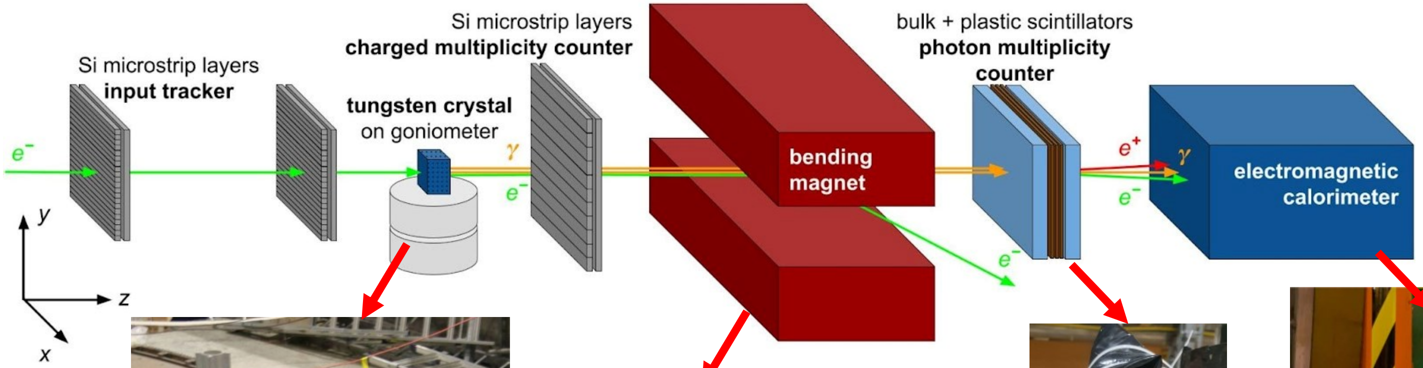
1. Test on single oriented crystals @CERN SPS

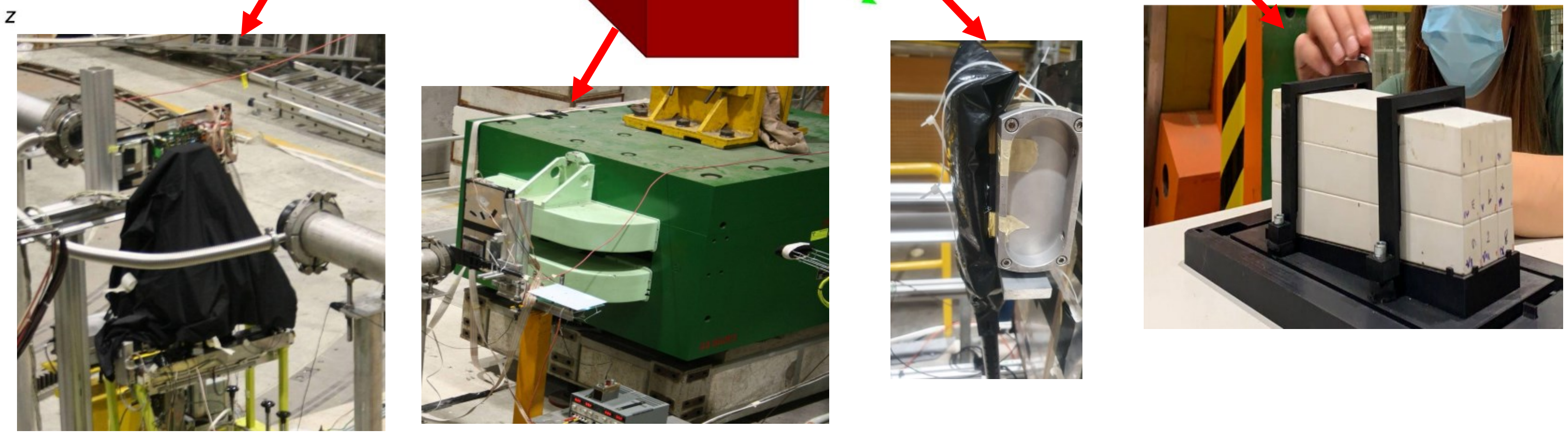




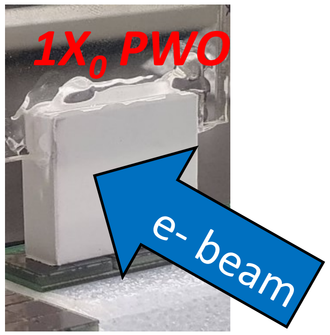
e^- & γ @ 10-120 GeV
CERN SPS NA H2
(Geneve, Switzerland)

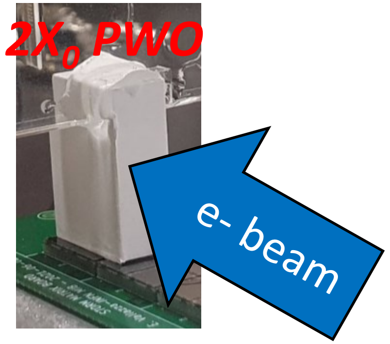
1. Test on single oriented crystals with e- @CERN SPS



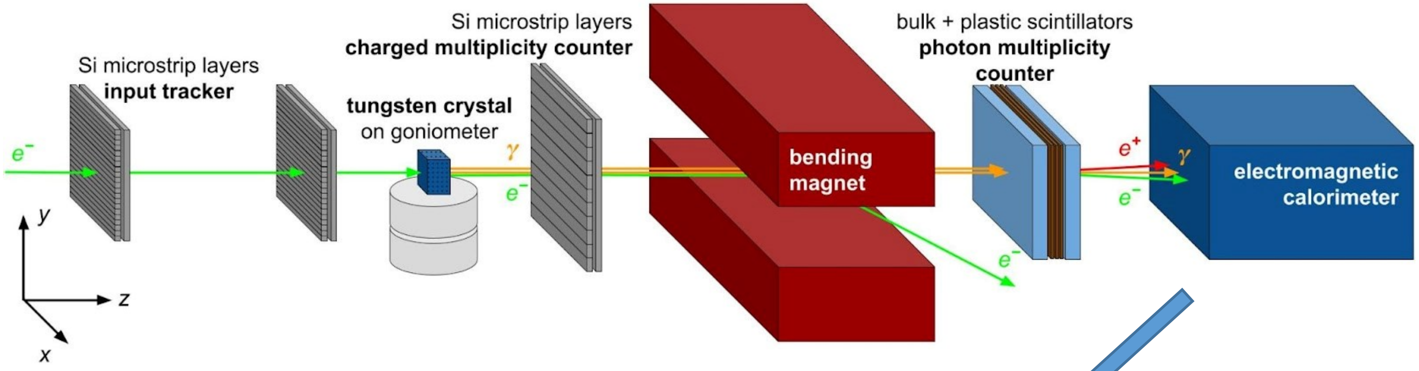


CERN SPS NA H2 beamline
Beam: e^- @120 GeV
Crystal: 1 & 2 X_0 PWO





1. Experiment & Monte Carlo – calorimeter data



CERN SPS NA H2 beamline
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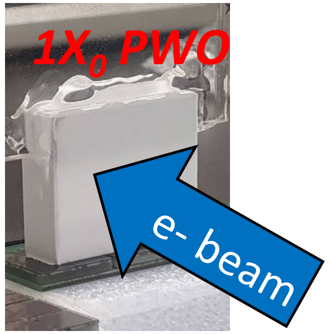
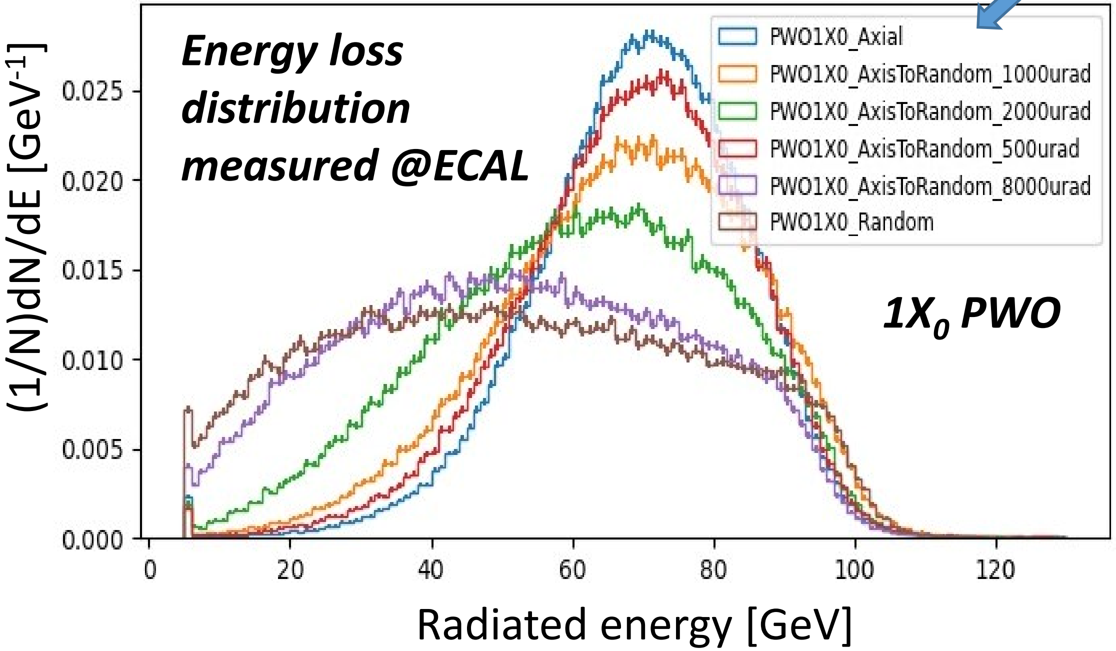
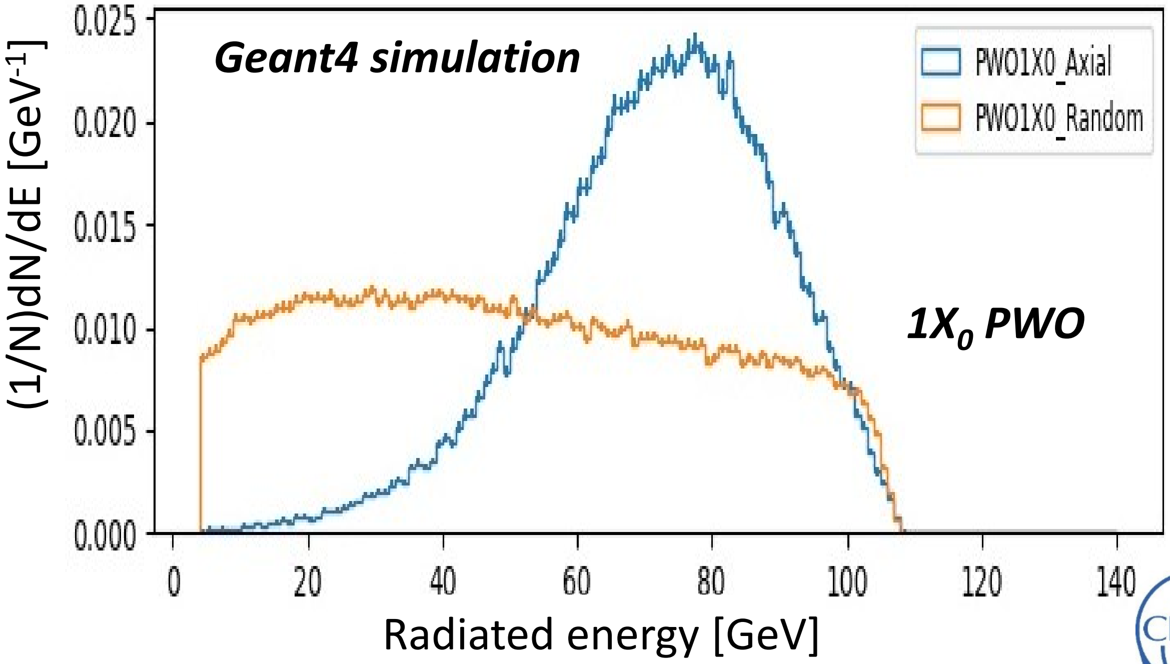


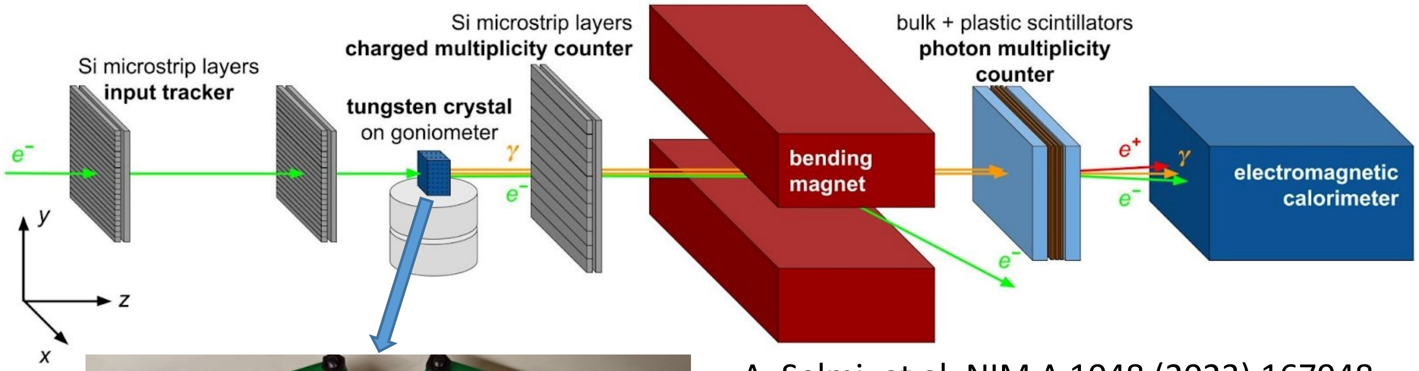


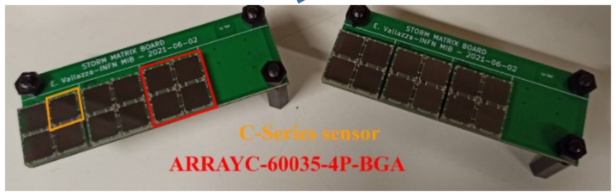


L. Bandiera et al., Phys. Rev. Lett. 121 (2018) 021603

North Area H2 line

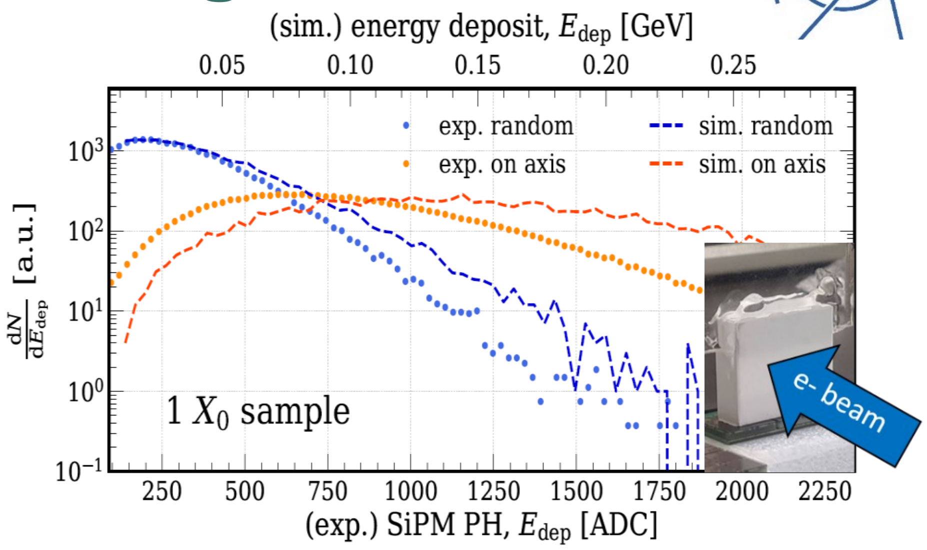
1. Experiment & Monte Carlo – scintillation light



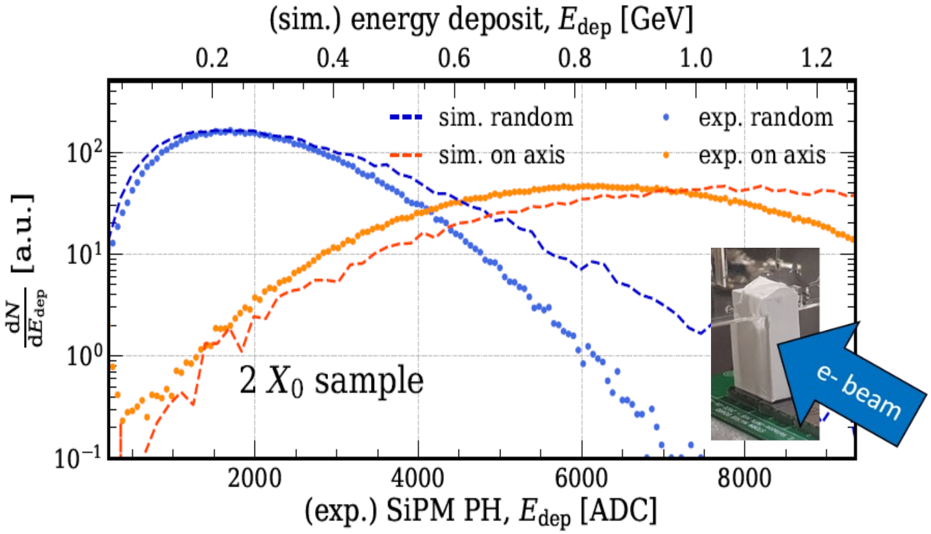


A. Selmi, et al. NIM A 1048 (2023) 167948

Developed @INSULAB & INFN Bicocca



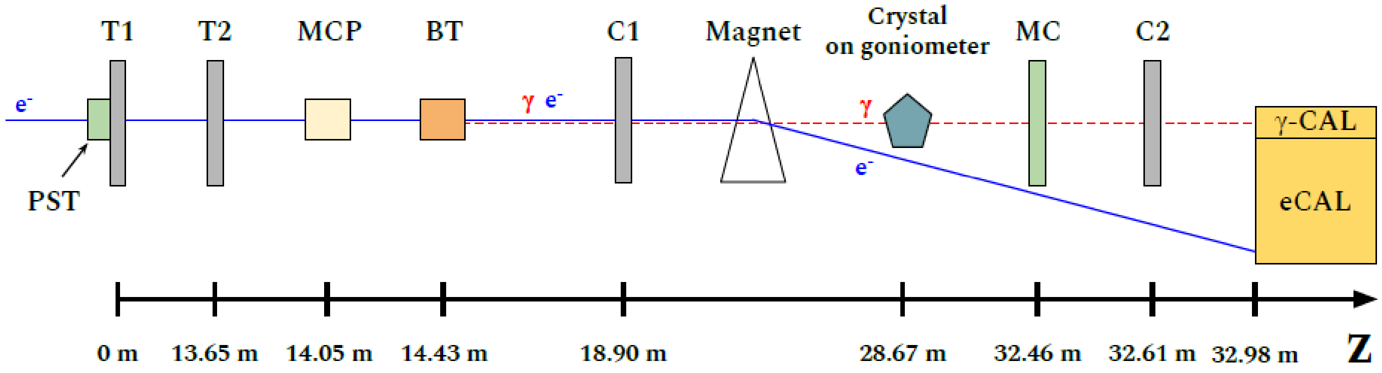
Thickness $[X_0^{std}]$	Eff. thickness $[X_0^{std}]$	Thickness enh. [%]	$\langle X_0^{app} \rangle$ [mm]	$\langle X_0^{app} \rangle$ $[X_0^{std}]$
0.45	$0.745^{+0.223}_{-0.301}$	$165.48^{+49.51}_{-66.97}$	$5.380^{+3.657}_{-1.239}$	$0.604^{+0.411}_{-0.139}$
~ 1	$1.520^{+0.256}_{-0.324}$	$151.98^{+25.65}_{-32.43}$	$5.858^{+1.589}_{-0.846}$	$0.658^{+0.178}_{-0.095}$
~ 2	$2.923^{+0.329}_{-0.397}$	$146.17^{+16.45}_{-19.84}$	$6.091^{+0.957}_{-0.616}$	$0.684^{+0.107}_{-0.069}$

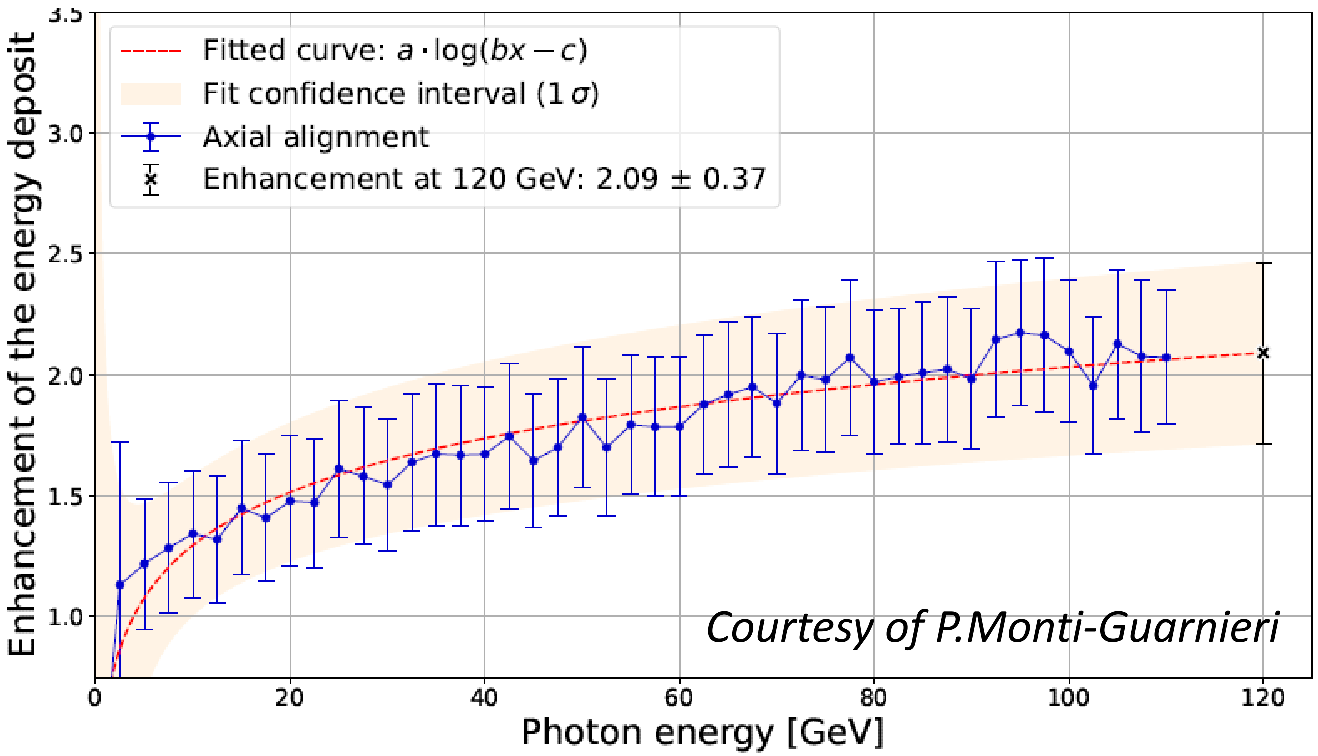


Effective thickness that a randomly oriented crystal should have to make the electrons lose the same amount of energy deposited on axis.

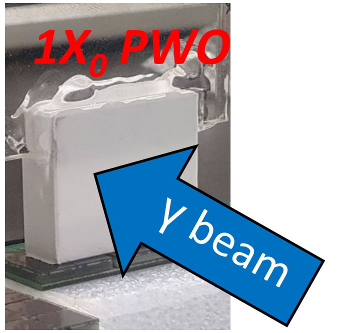
North Area H2 line

2. Experimental measurement with γ @CERN SPS





CERN SPS NA H2 beamline
Beam: γ @5-100 GeV
Crystal: 1 X_0 PWO



Enhancement of the energy deposited inside the crystal by the photon beam in axial orientation as measured by SiPM vs. the photon energy

Work done in collaboration with the HIKE/KLEVER & CRILIN team

North Area H2 line

Possible application of an ultra-compact calorimeter made of oriented crystals

Particle Physics

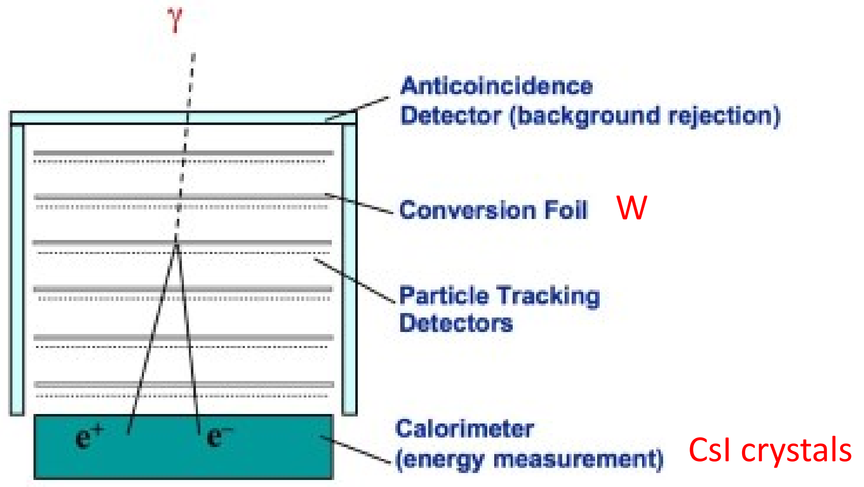
- in **fixed-target experiments**, which are intrinsically forward, to realize compact electromagnetic calorimeters or preshower with reduced volume w.r.t. to the state-of-the-art (collaboration with the NA62/KLEVER experiment on rare kaons decay at CERN)

- in **dark matter search**, to realize compact active beam dump with an increased sensitivity to light dark matter, such as dark photons etc…

Astroparticle

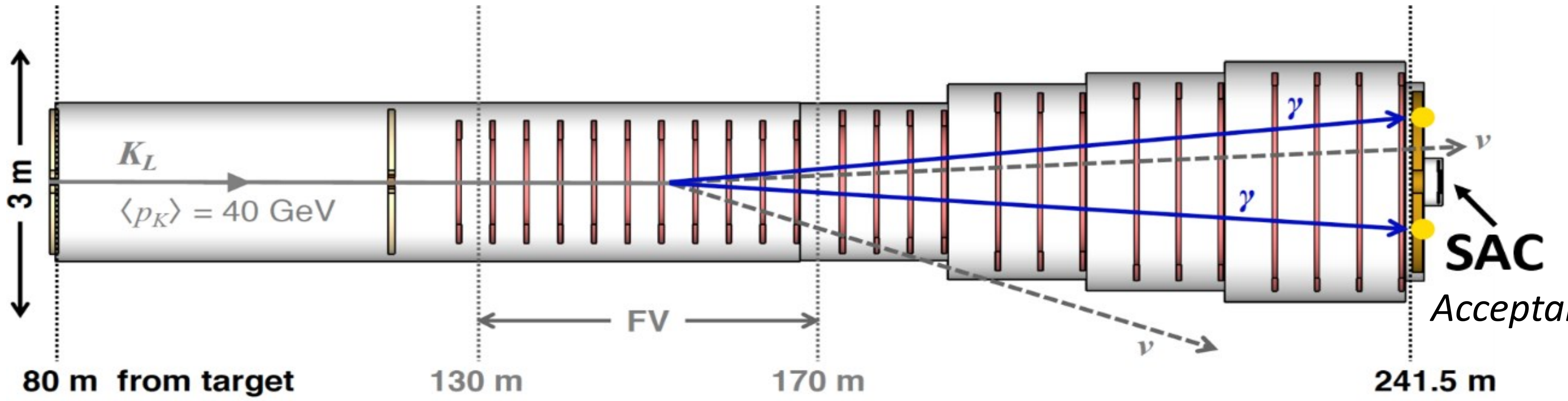
- **pointing a telescope towards a source**, thus measuring the spectrum of γ-rays with energy larger than 100 GeV can be completely contained in a quite compact volume, **reducing the necessary weight and cost.**

FERMI-LAT tower



The HIKE/KLEVER Small Angle Calorimeter

KLEVER is the last phase of HIKE, which is a proposed experiment in North Area @CERN as successor of NA62 in the same experimental area



Acceptance ~2 mrad

$K_L \rightarrow \pi^0 \nu\nu$

from K^+ (charged – NA62 experiment) to K_L (neutral) → new challenges

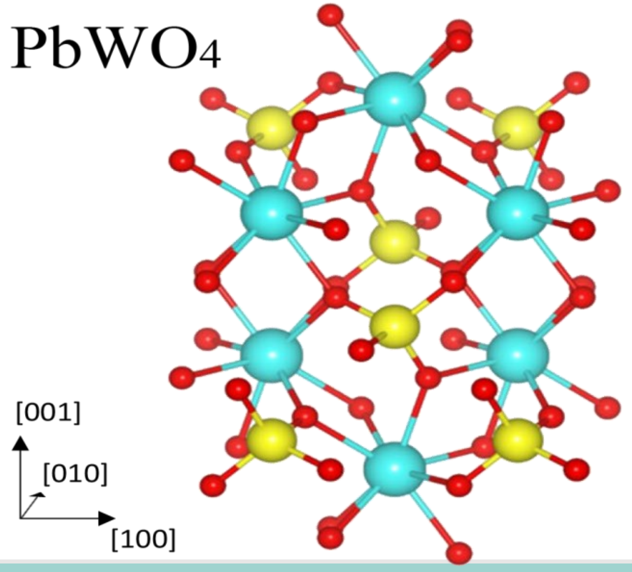
High-performance e.m. calorimeter is required for the **reconstruction of the π^0 coming from $K_L \rightarrow \pi^0 \nu\bar{\nu}$**, while any extra photons must be vetoed with very high efficiency!

This performance must be attained **while maintaining insensitivity to more than 500 MHz of neutral hadrons** in the beam

An ultra-compact SAC for HIKE/KLEVER with OREO technology

Requirements:

- Smallest X_0/λ_{int} possible in order to provide maximum transparency to beam hadrons while maintaining high photon-conversion efficiency- > **high-Z oriented crystals with reduced X_0**
- Excellent time resolution -> **Cerenkov readout & ultrafast scintillation**

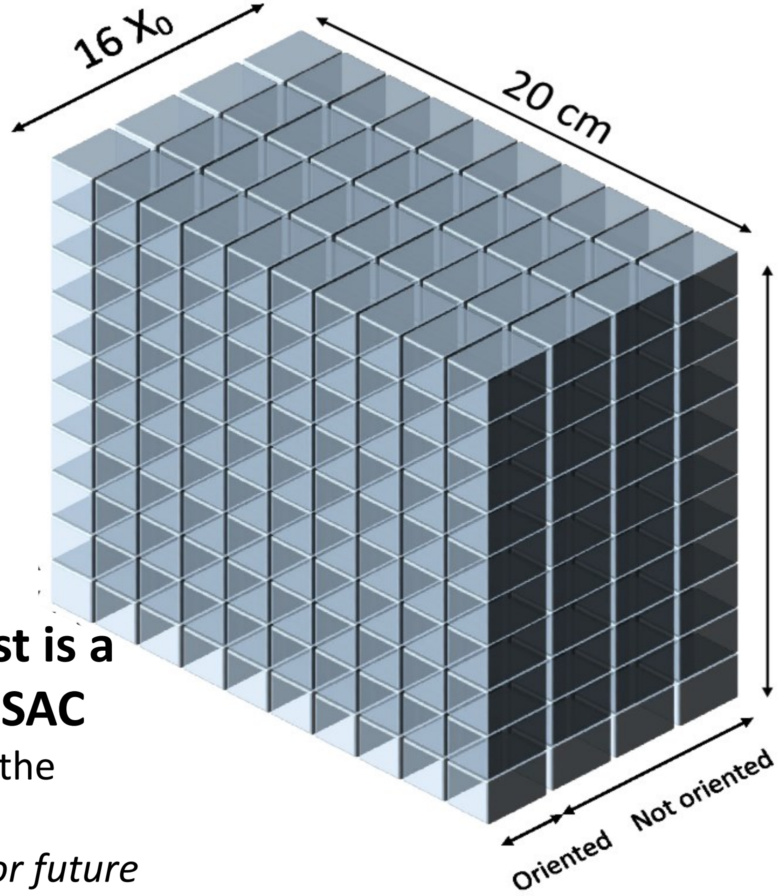


A newly developed PWO-Ultrafast is a candidate for the HIKE/KLEVER SAC

Scintillation decay decreased down to the subnanosecond (0.7 ns)

M. Korjik et al., *Ultrafast PWO scintillator for future high energy physics instrumentation*, NIM A, 1034 (2022) 166781

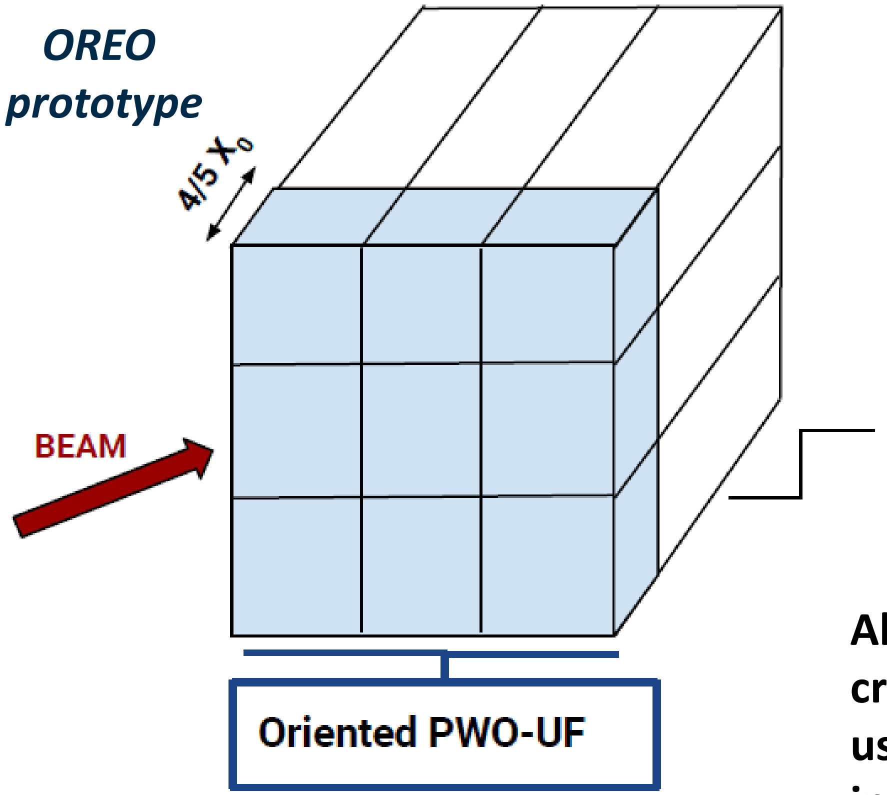
POSSIBLE KLEVER SAC DESIGN

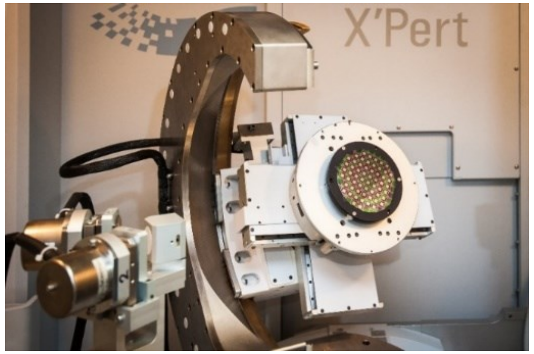


Transverse and longitudinal segmentation for a better n/γ discrimination

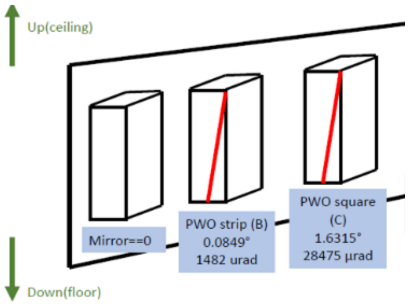
The ***ORiEnted calOrimeter*** prototype

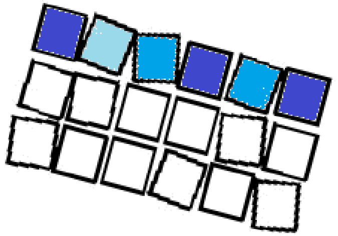
Challenge:
- Construction of an oriented layer of many crystals



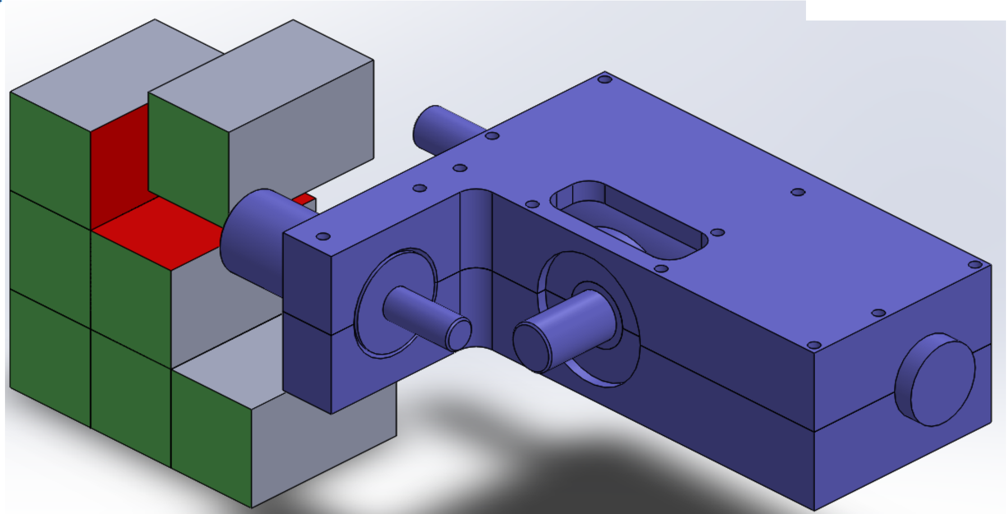


HR-XRD measurement of
- ***Miscut angle***
- ***Crystal mosaicity***

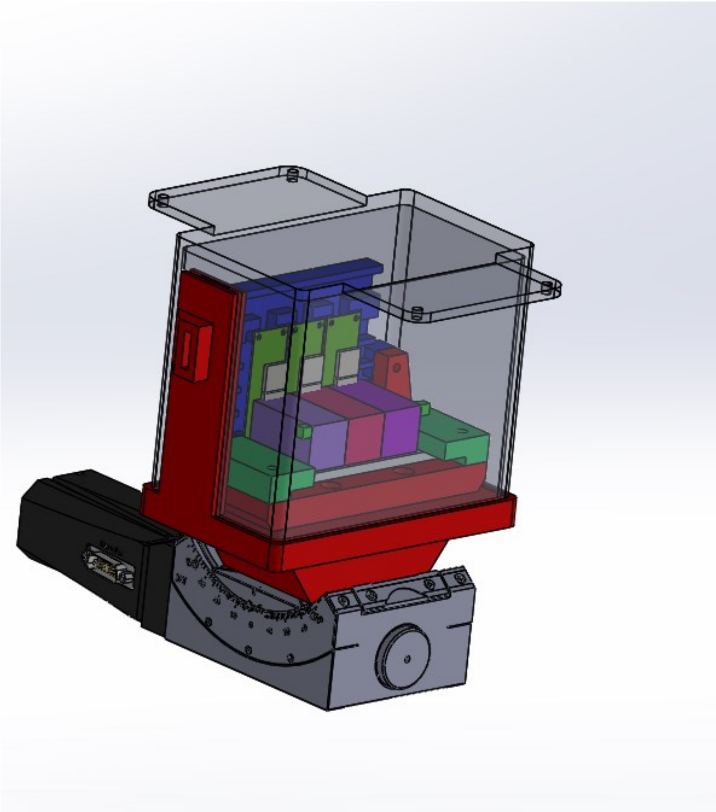


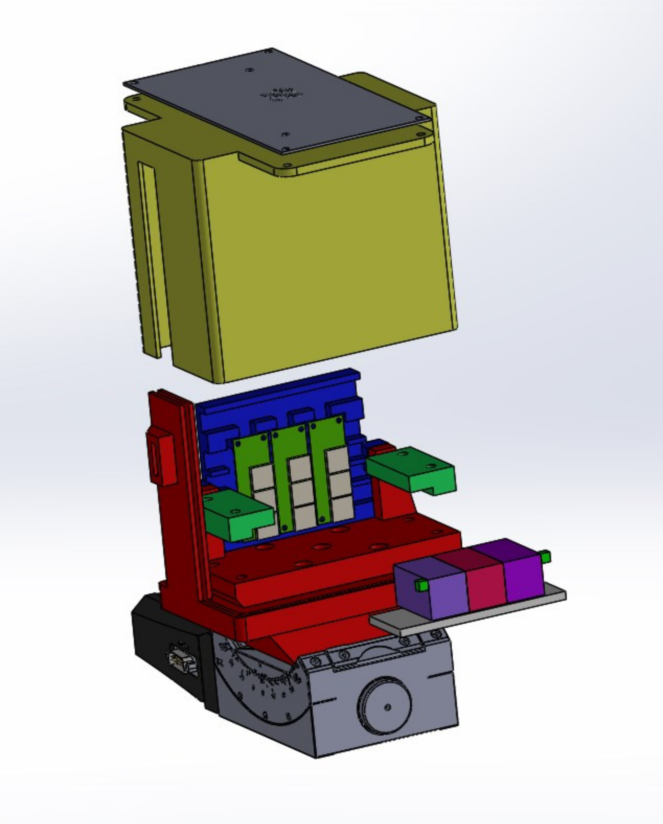


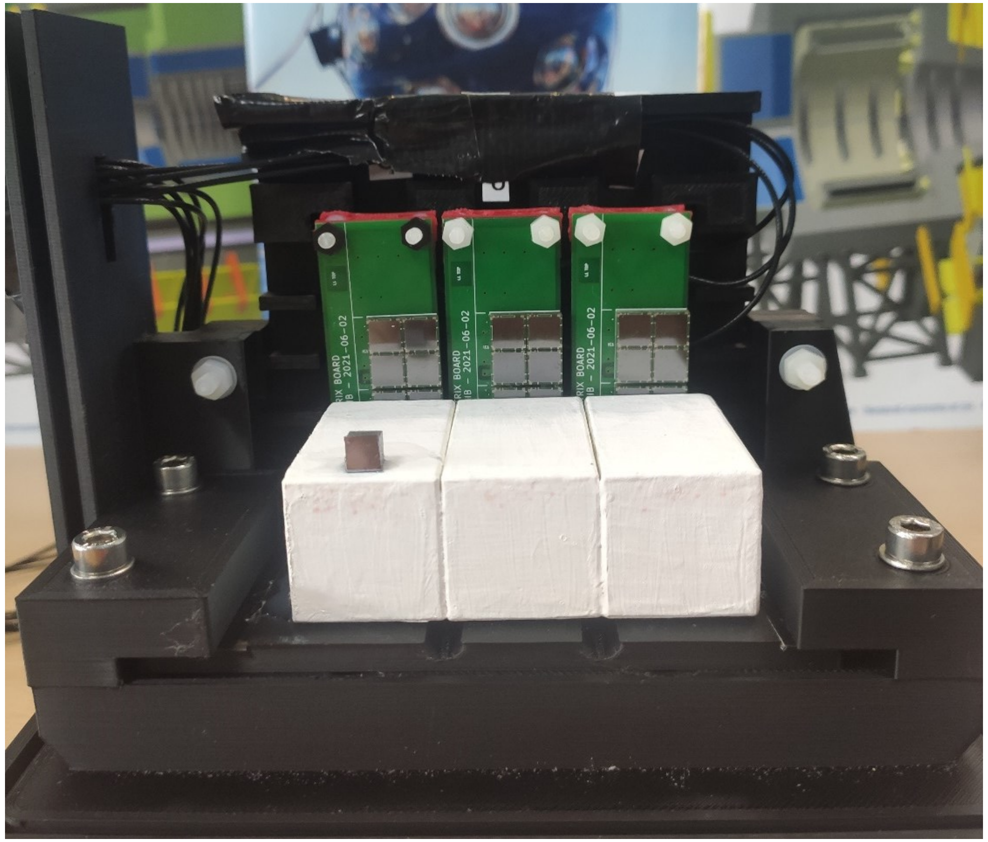
Alignment of one crystal to another using laser interferometry



The first **1x3 layer** of the ***OREO prototype***







Currently under test vs high-energy electrons at CERN PS&SPS extracted lines

Summary

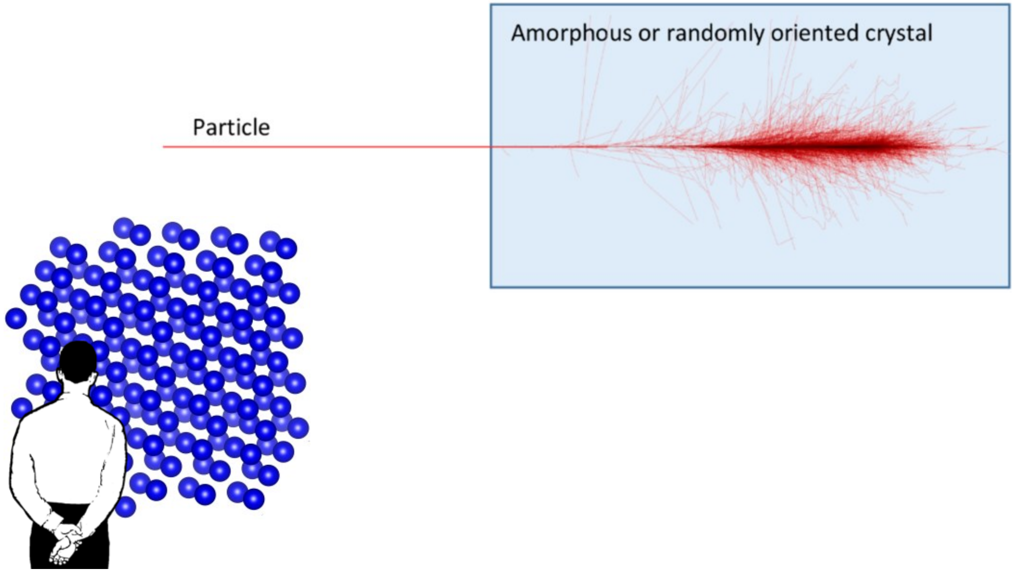
We introduced briefly…

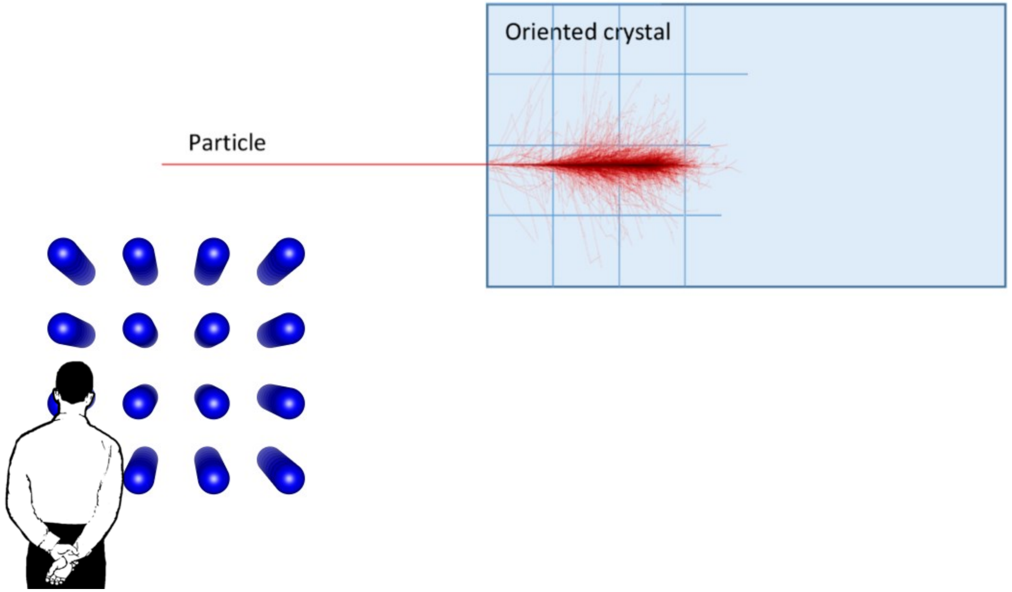
- **Strong crystalline field and e.m. shower acceleration in axially oriented crystal scintillators**

- **Experimental results with $PbWO_4$ samples:**
  - **Investigation of axial-to-random light emission vs crystal thickness**
  - **Comparison with Monte Carlo**

- **Application in particle and astroparticle physics:**
  - **Poyinting strategy high-energy gamma telescopes**
  - **Beam dump and fixed target experiments -> HIKE/KLEVER Small Angle Calorimeter**

- **First design of a fast and compact e.m. calorimeter based on oriented PWO-UF**





Thank you for the attention