DIRECT MEASUREMENT OF E.M. SHOWER ACCELERATION IN AN ORIENTED CRYSTAL SCINTILLATOR

L. Bandiera*, M. Soldani
INFN Ferrara
On behalf of the STORM experiment

**bandiera@fe.infn.it*

Istituto Nazionale di Fisica Nucleare

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The INFN STORM experiment
STrOng cRystalline electroMagnetic field

✓ **INFN and University of Ferrara**
L. Bandiera, V. Guidi, A. Mazzolari, M. Soldani, A. Sytov, M. Tamisari

✓ **INFN Legnaro Lab and University of Padua**
N. Argiolas, D. De Salvador, F. Sgarbossa

✓ **INFN of Milan Bicocca and Insubria University**
L. Bomben, S. Cardi, V. Mascagna, P. Monti-Guarnieri, A. M. Prest, F. Ronchetti, A. Selmi, E. Vallazza

✓ **INFN Frascati**
M. Moulson

Collaborators
INFN and Sapienza University of Rome, IJCLab Orsay, INP Minsk, CERN, MAMI, DESY

STORM is financed by INFN through the CSN V

Outlook

- Introduction to the strong crystalline field and electromagnetic shower modification in oriented crystals

- Experimental tests on PWO samples with hundred-GeV electrons at CERN SPS

- Application in ultra-compact e.m. calorimeters for high-energy physics and astrophysics

- Summary and Conclusions

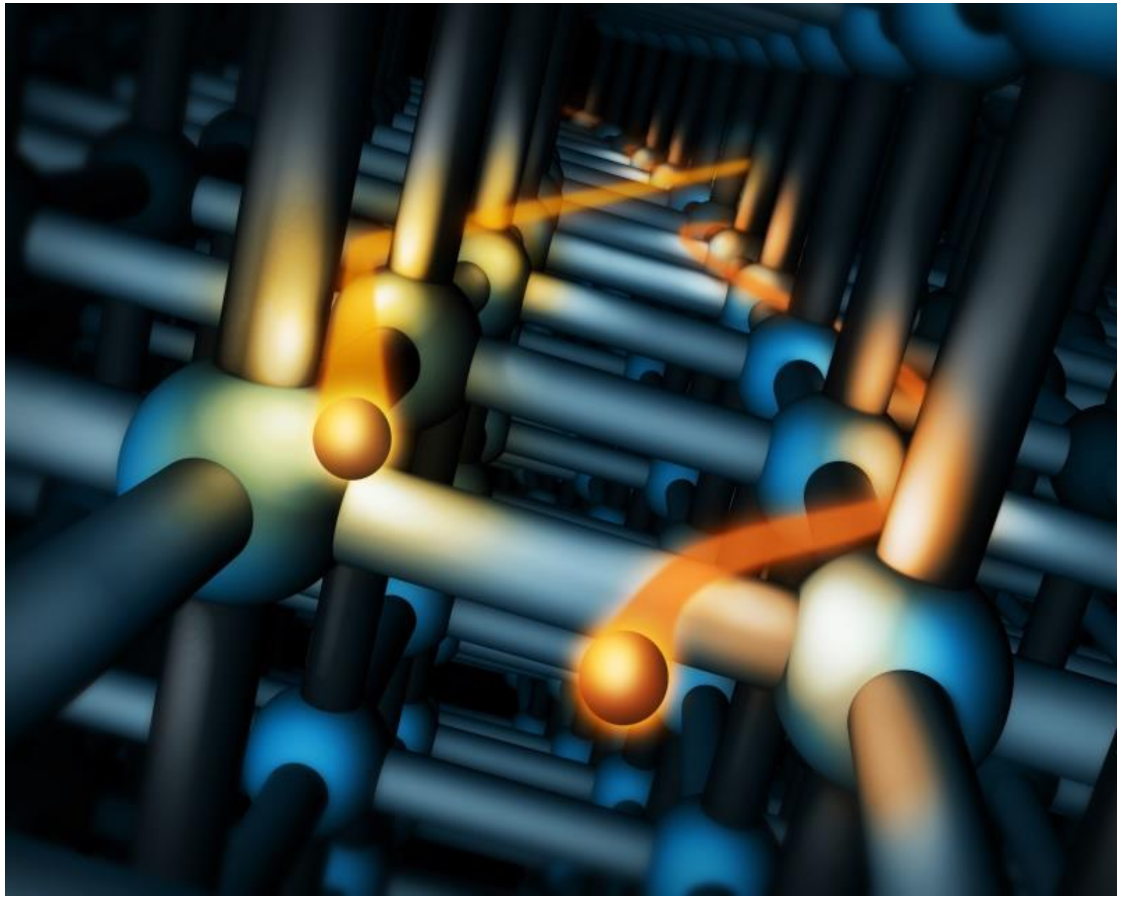
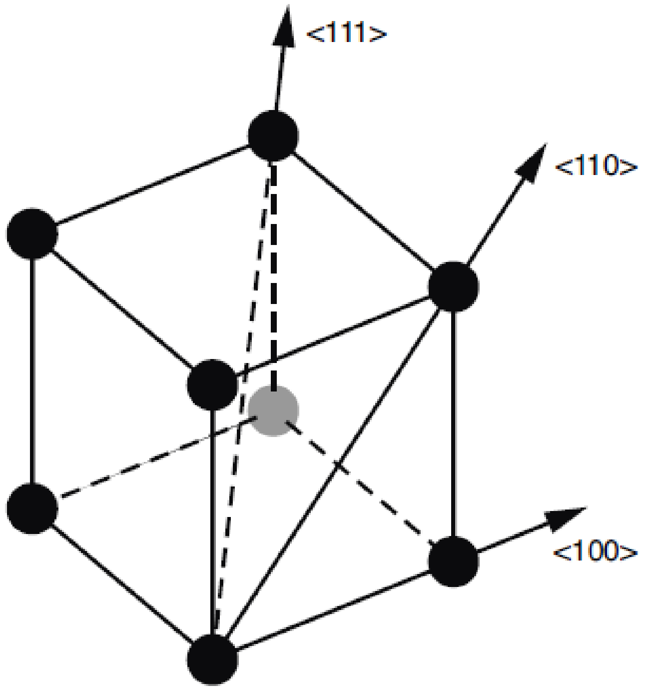
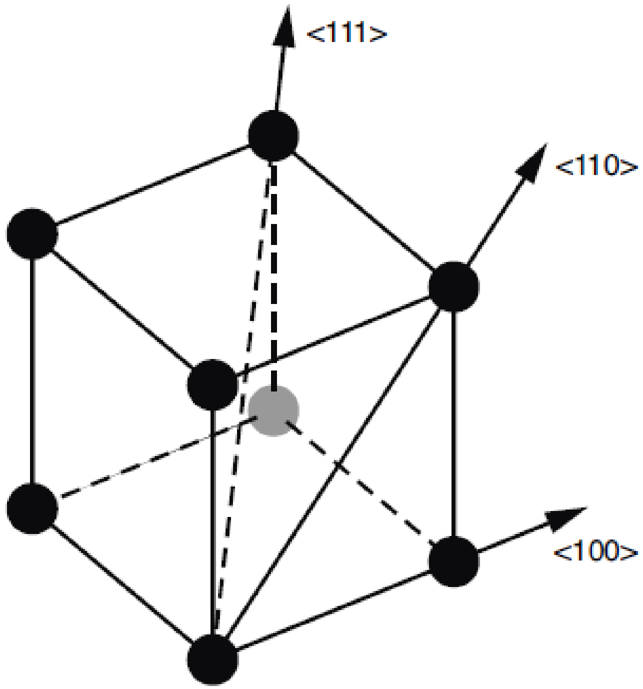


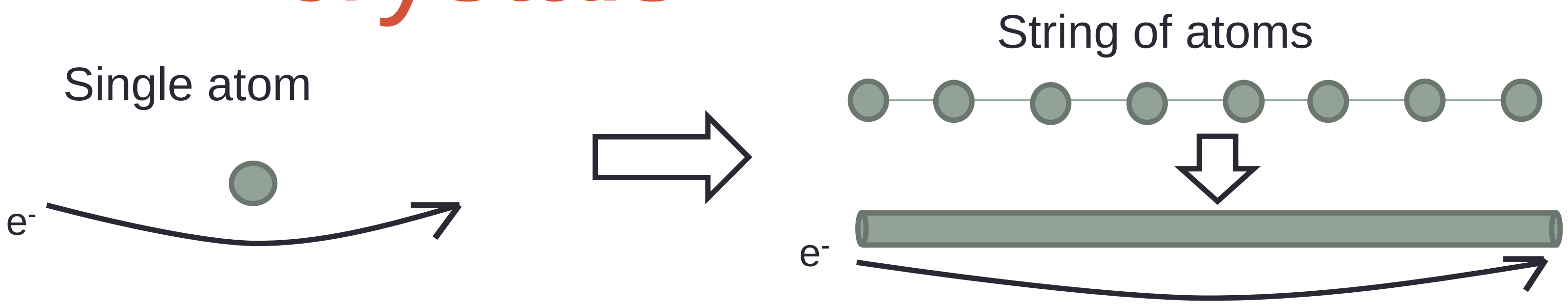
Image from https://www6.slac.stanford.edu/news/2015-02-25-slac-led-research-team-bends-highly-energetic-electron-beam-crystal.aspx

Enhancement of bremsstrahlung in aligned crystals



Enhancement of bremsstrahlung in aligned crystals





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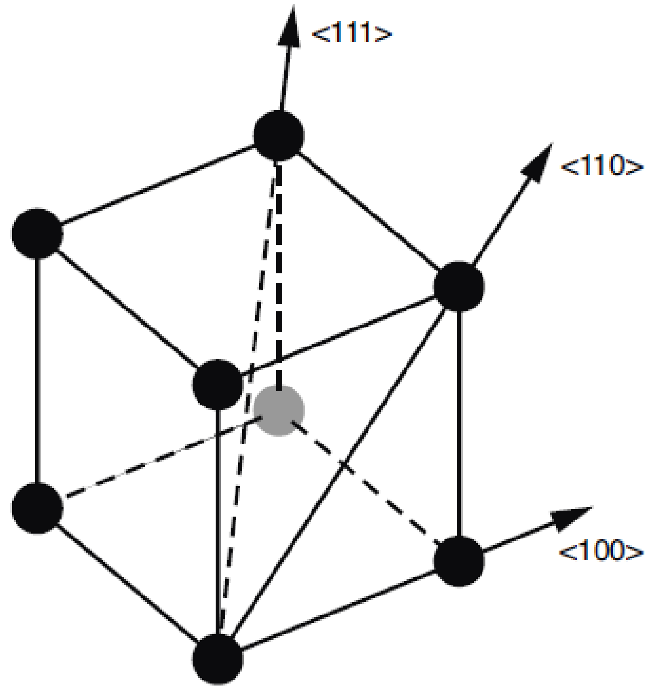
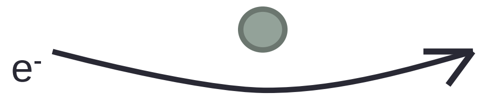
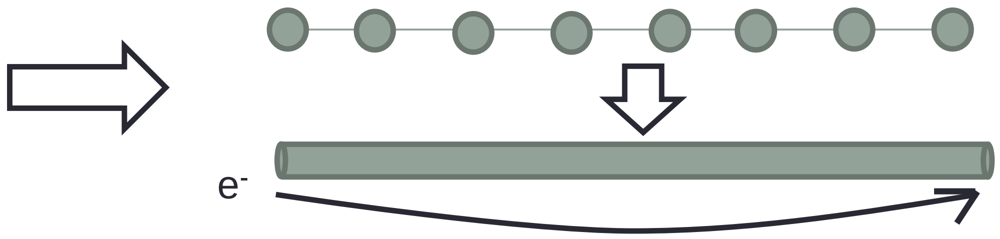


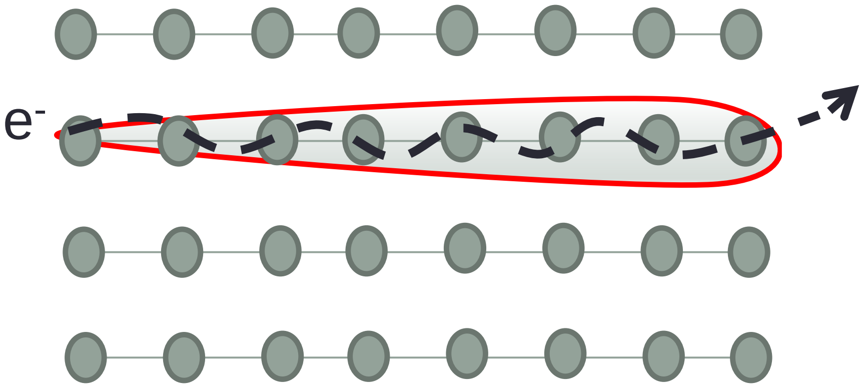
Single atom

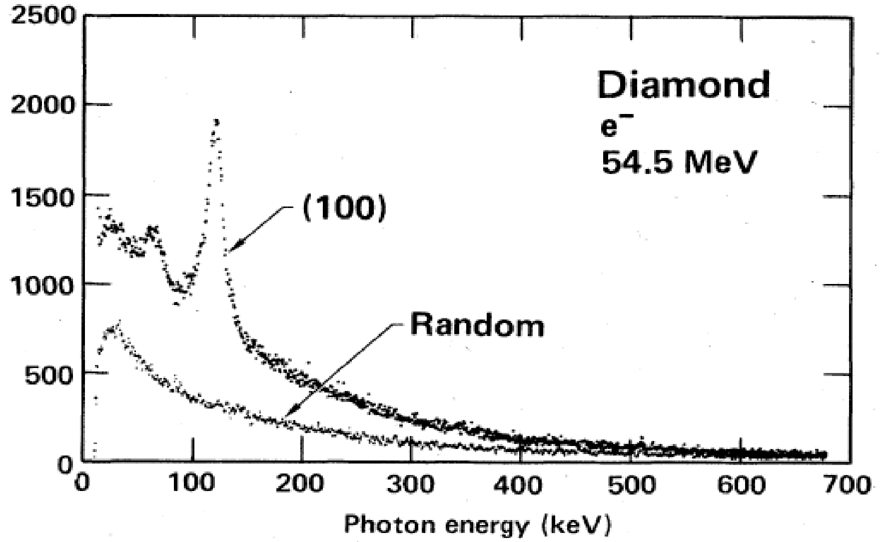


String of atoms

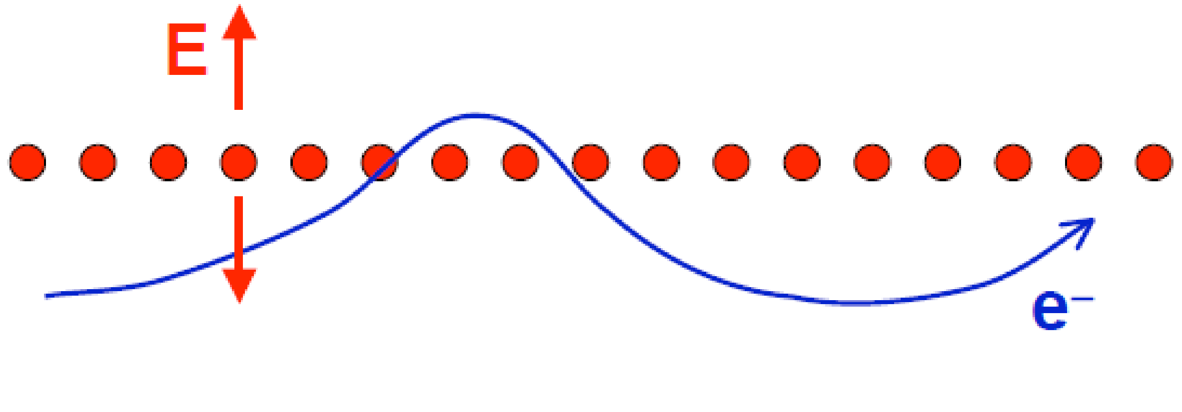


Channeling Radiation (1976, Kumakhov)

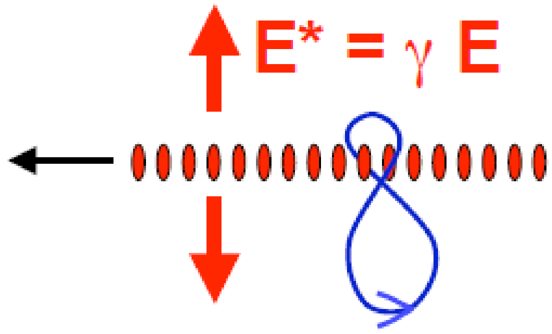




Strong field regime of Radiation in Crystals



lab. frame



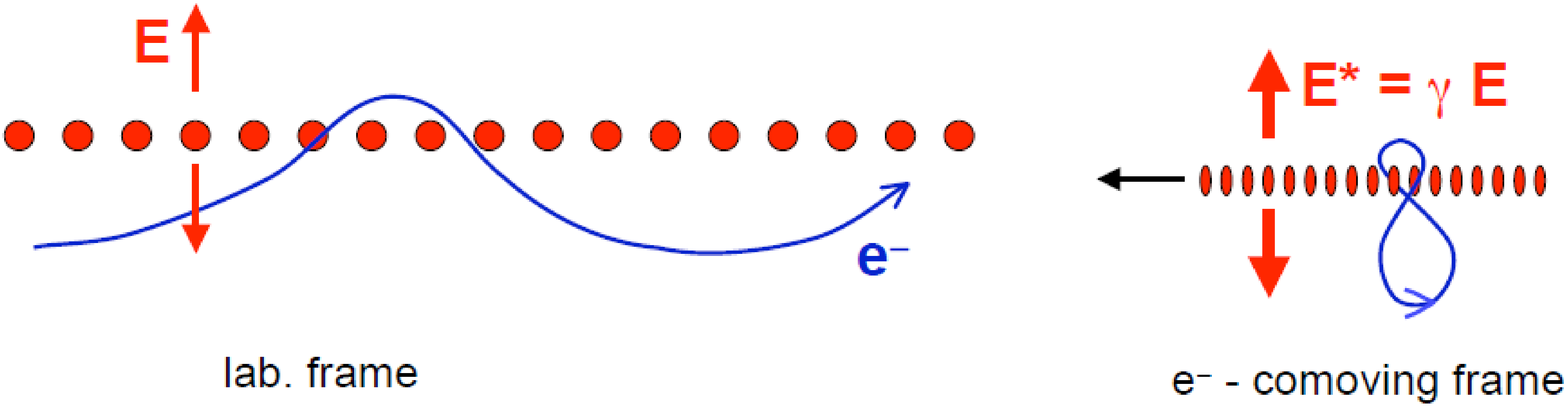
e⁻ - comoving frame

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 field regime of Radiation in 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

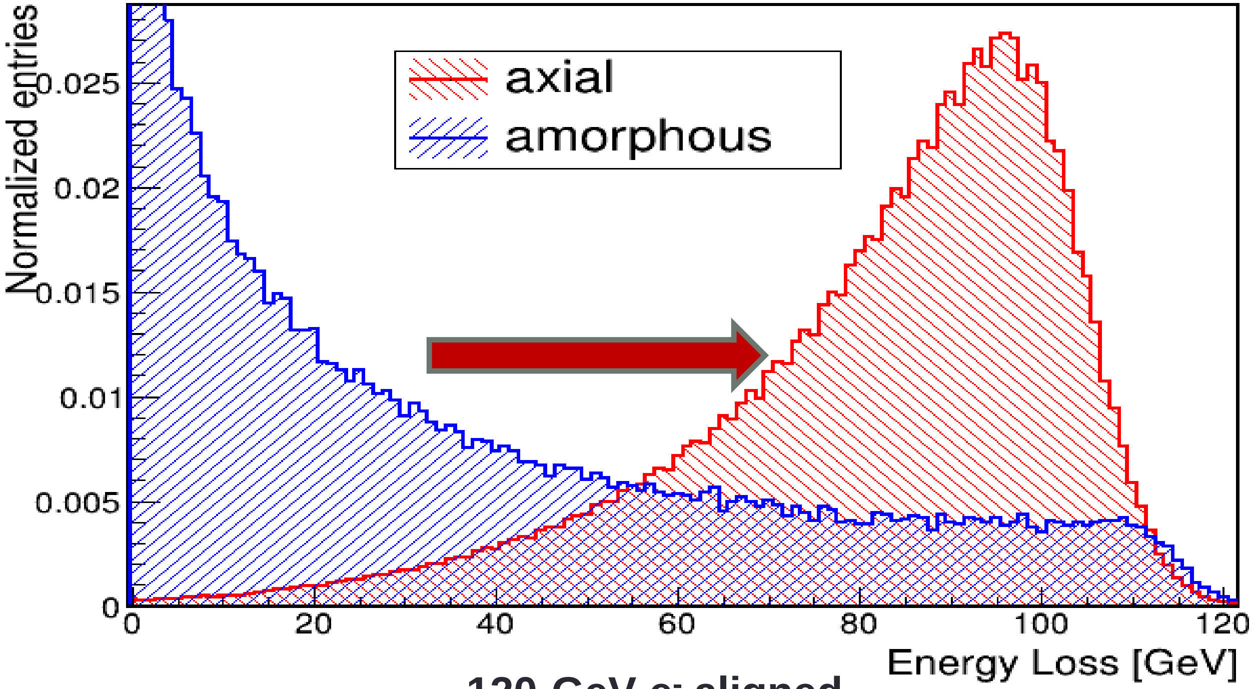
At beam energies > 10 GeV, E* can reach the **Critical Schwinger QED field**:

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

above which electrodynamics becomes non linear

Radiation emission in axial alignment

Effect of axial orientation in the radiation spectrum



120-GeV e⁻ aligned
with the <110> axis of a 2.8 mm long Ge crystal

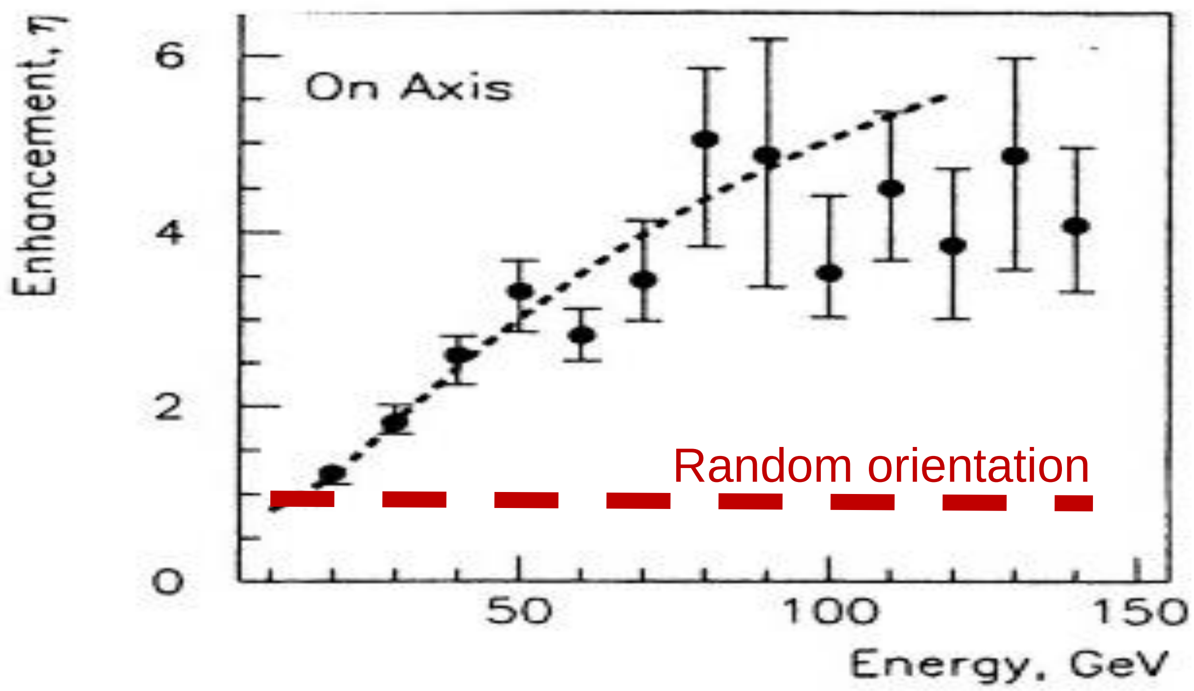
Strong field regime of radiation

$$E^* \geq E_0$$

- ***Radiation length reduction***
  - **X_0 decreases with initial energy increase.**
- ***Angular range:***
  - few mrad up to 1° of misalignment between particle direction and crystal axes;
  - Does **NOT** depend on particle energy.

Strong increase in the energy radiated by the electrons!

….and also pair production by high-energy photons

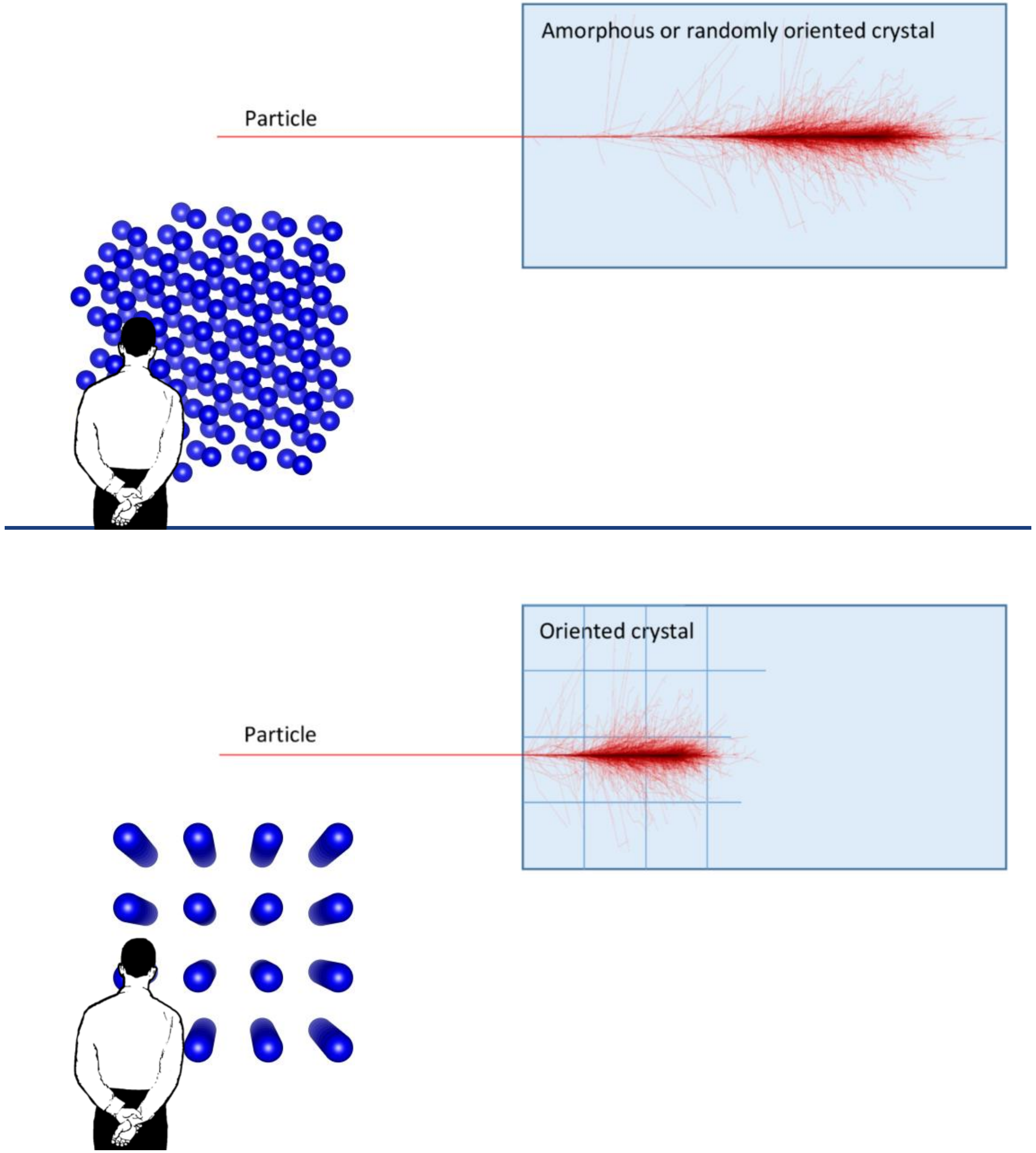


Enhancement of pair production in a W crystal axially oriented – compared to random orientation Vs. photon energy

- ***Radiation length reduction***
  - *X_0 decrease with initial energy increase.*
- ***Angular range:***
  - few mrad up to 1° of misalignment between particle direction and crystal axes;
  - Does NOT depend on particle energy.
- ***Also for pair production by a HE photon.***

Strong increase of the pair production probability by high-energy photons in an oriented crystal

..e.m. shower acceleration



electromagnetic shower is way more compact

or equivalently

effective radiation length X_0 is much shorter

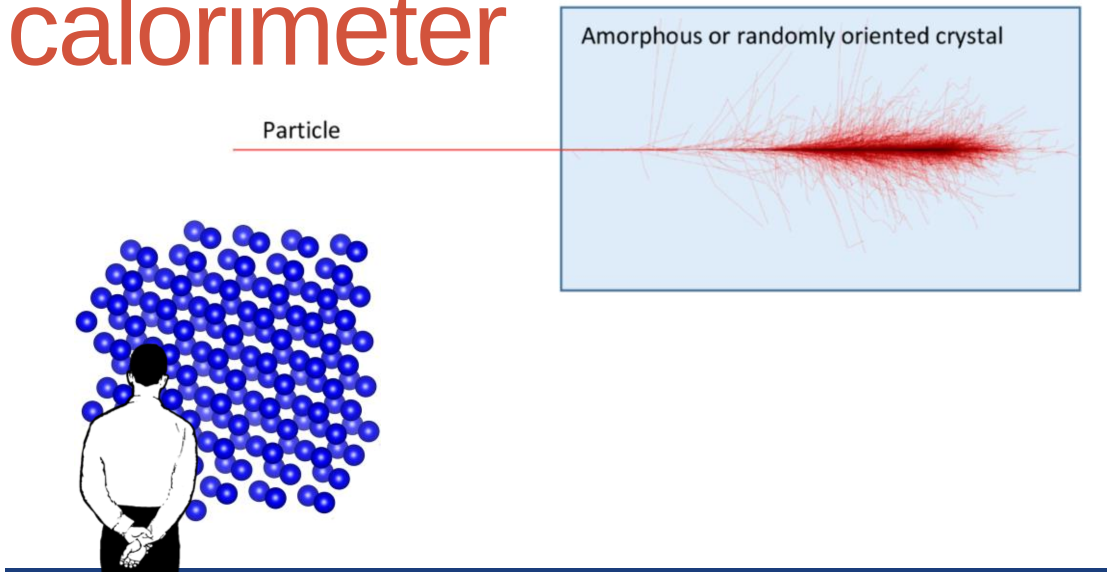
- ✓ the modern electromagnetic calorimeters are designed for experiments at energies of hundreds of GeV/TeV and these enhancement effects are expected to be quite important in this energy range
- ✓ the input photon or electron/positron showers can <u>fully develop in a much lower thickness with respect to the current state-of-the-art detectors</u>

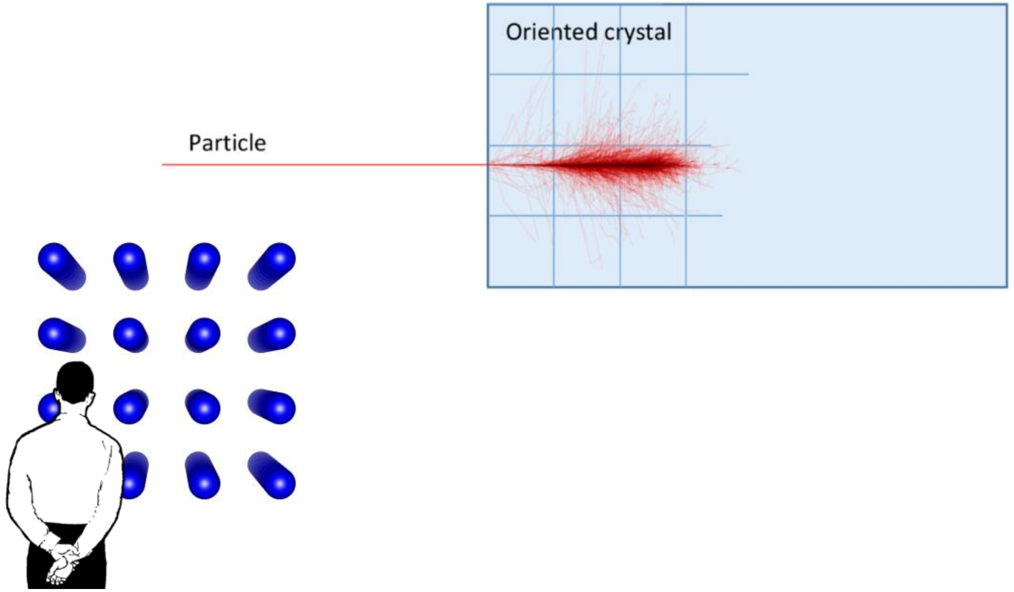
Novel idea: ultra-compact calorimeter

- Using oriented scintillator crystal one may **containing e.m. showers initiated by particles with energies even above 100 GeV in a reduced volume/weight;**

- **Cost reduction!!!**

- **Interesting application in particle and astroparticle phyiscs!!!!!**

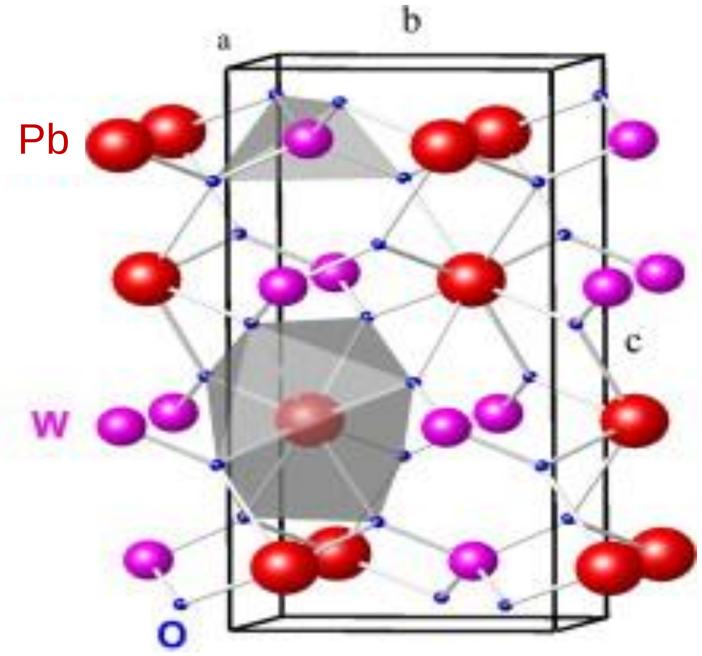


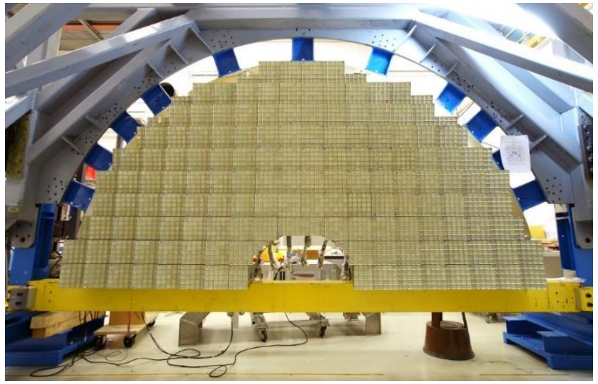


Lead tungstate ($PbWO_4$) – a high-Z crystal scintillator

- scintillator, with well-peaked light emission in the blue
- optically transparent
- exploited by the CMS ECal → well known
- high density, high *Z*
- radiation hard
- cheap fabrication into big samples and with good crystalline quality
- axes properties

	[100]	[001]
interatomic pitch	5.456 Å	12.020 Å
U_0	~700 eV	~500 eV
SF threshold	~30 GeV	





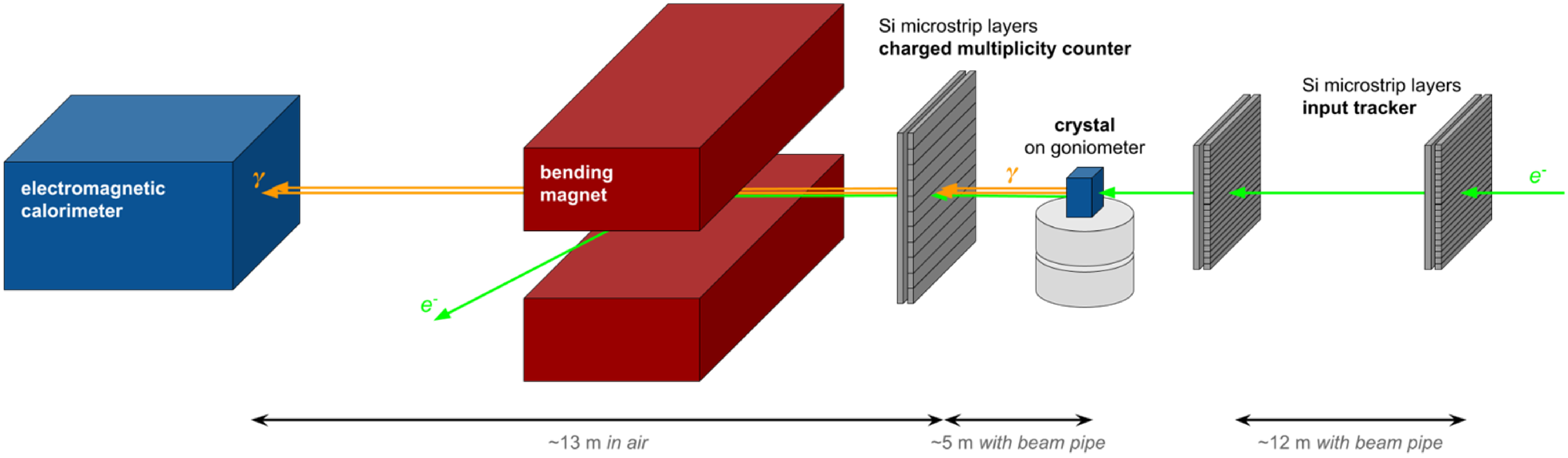
3 sample investigated:
- **A: 4 mm - 0.45 X_0**
- **B: 9 mm – 1 X_0**
- **C: 18 mm – 2 X_0**

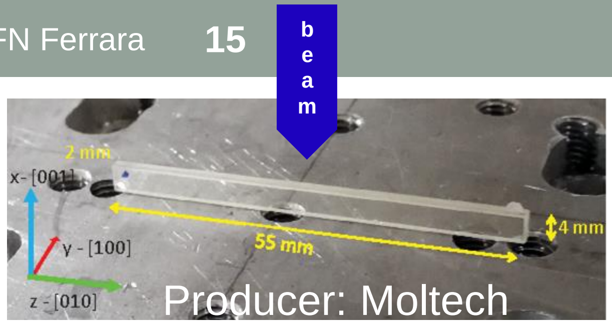
Status of the investigation

Different tests with **electron and positron beams**, in particular at

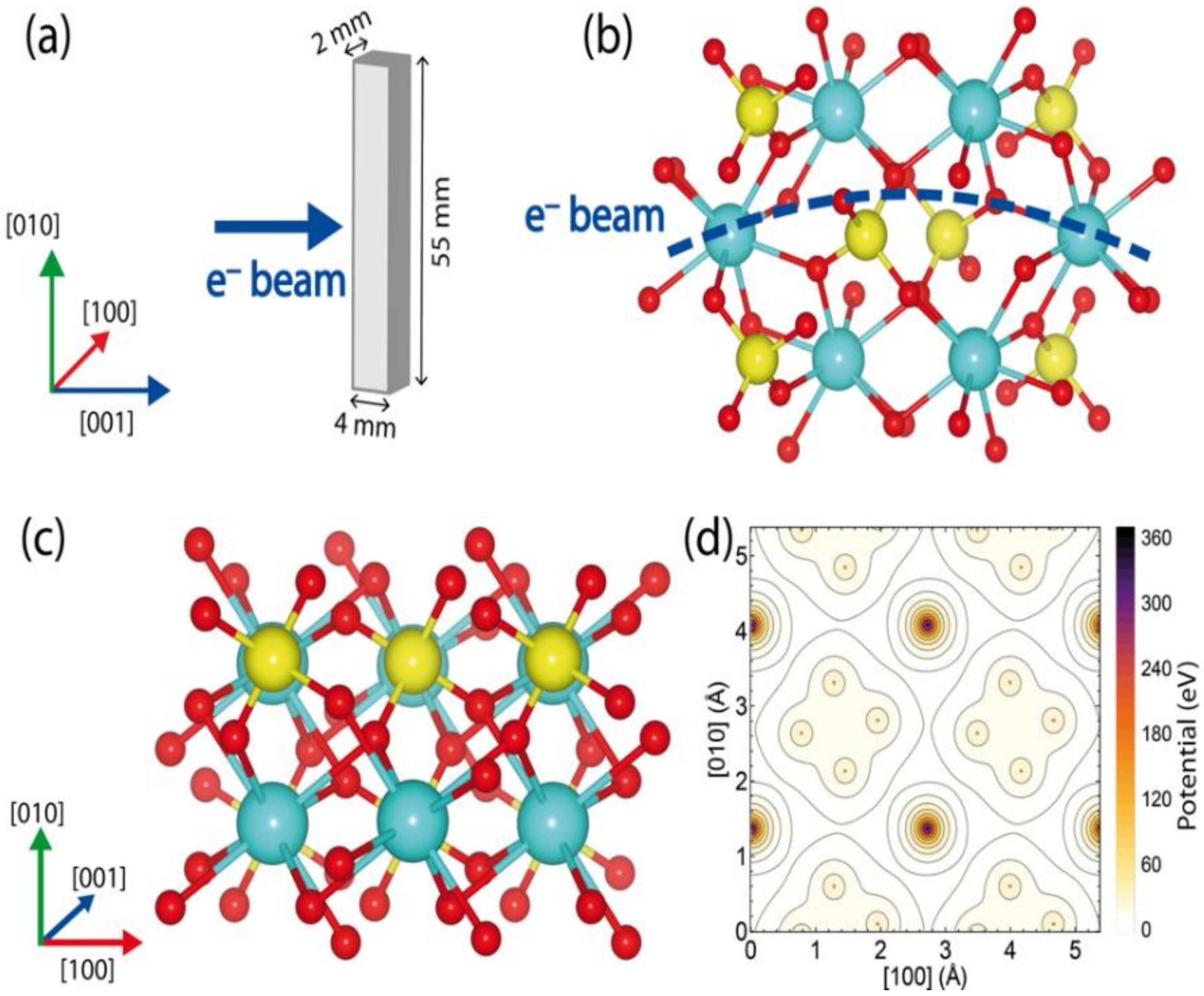
CERN H4/H2 lines e^+ & e^- at **120 GeV/*c***

PWO in full Strong Field regime

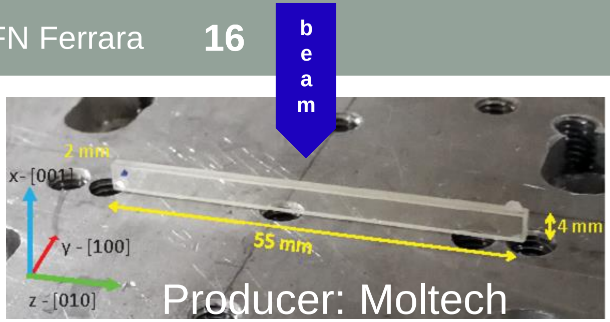


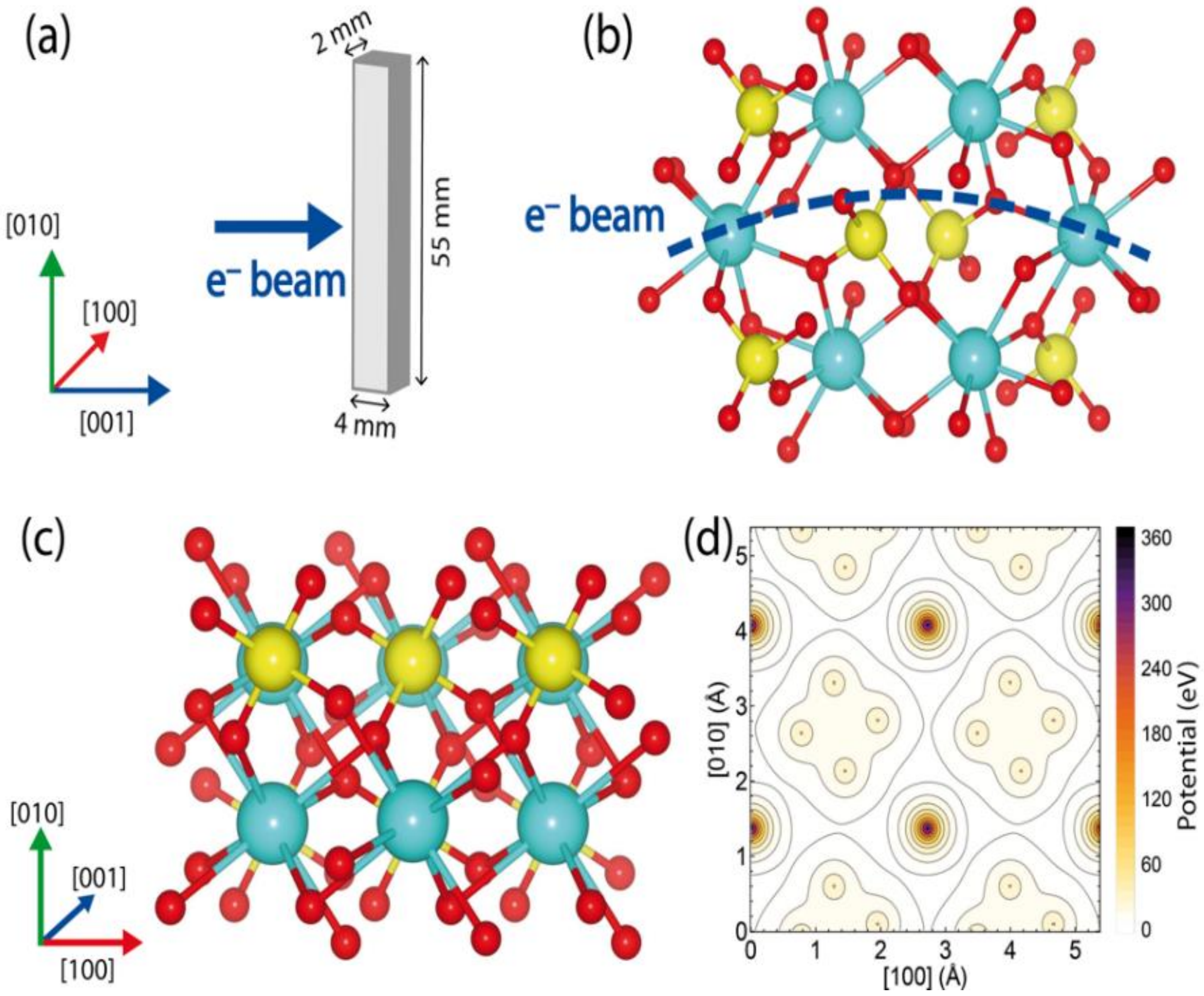


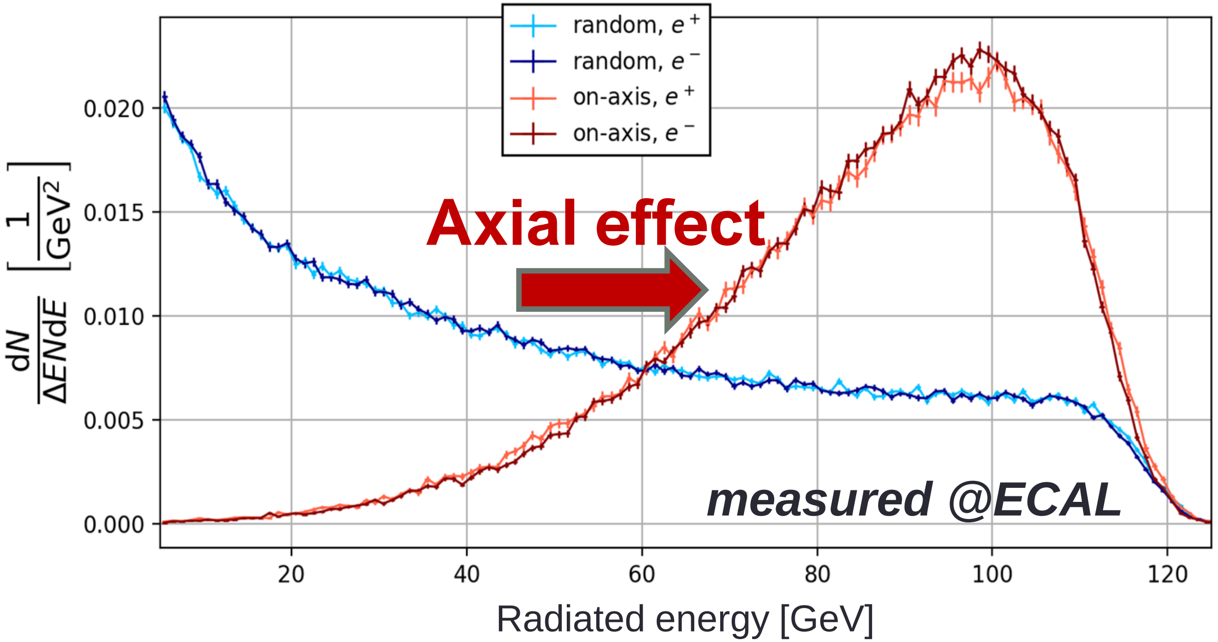
Sample A – 0.45 X_0 & [001] axis



Sample A – 0.45 X_0: radiated energy







random spectra: standard Bremsstrahlung (Bethe-Heitler)

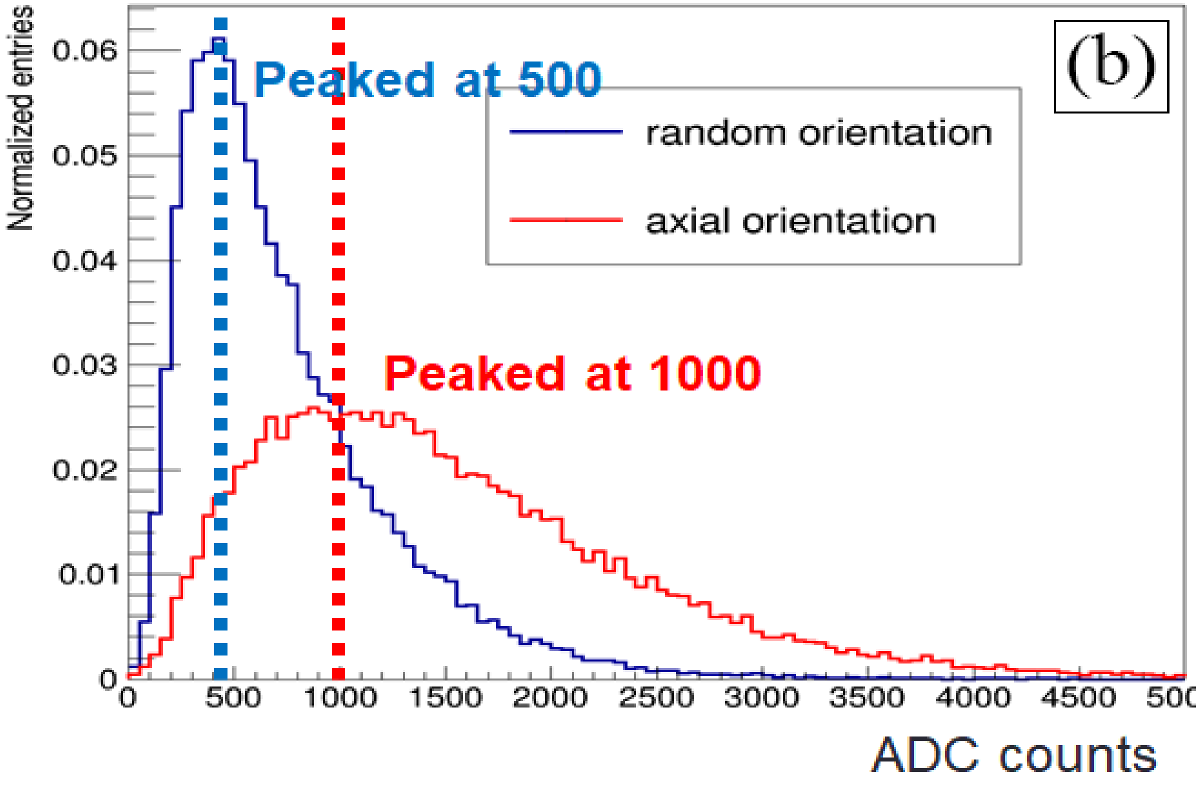
≠

on-axis spectra: <u>enhancement in high-energy component</u>

(peaked @ ~100 GeV)

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

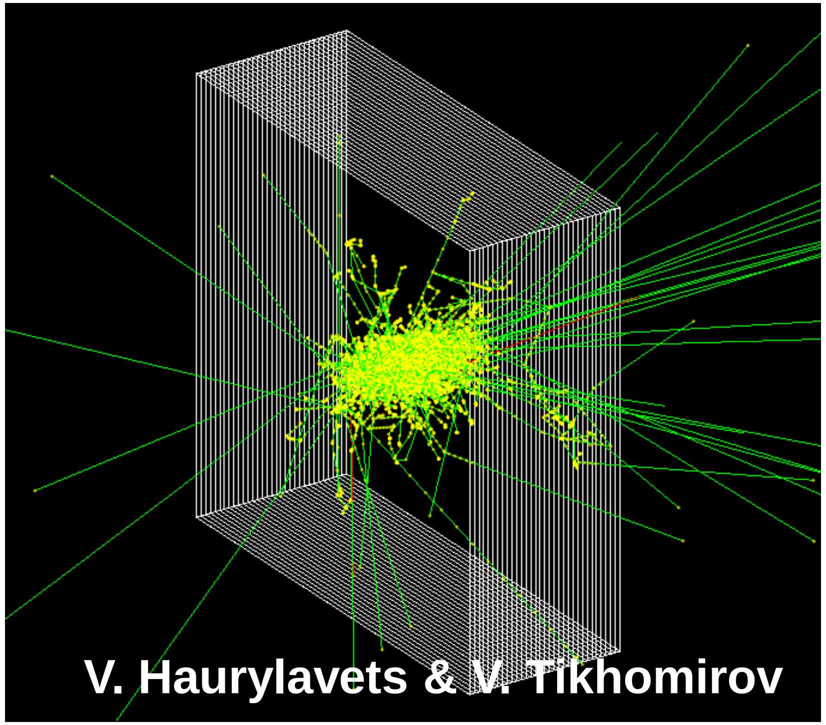
Sample A – 0.45 X_0: scintillation light



The crystal was coupled to a commercially available silicon photomultiplier (SiPM), the ASD-NUV4S-P by AdvanSID, whose 44 mm^2 active surface matches the sample 4x2 mm2 face and whose photodetection efficiency (PDE) is well-peaked around the PWO emission spectrum maximum at 420 nm.

- Light output depends on crystal orientation (and on crystal quality)
- Demonstration of electromagnetic shower acceleration in case of axial orientation

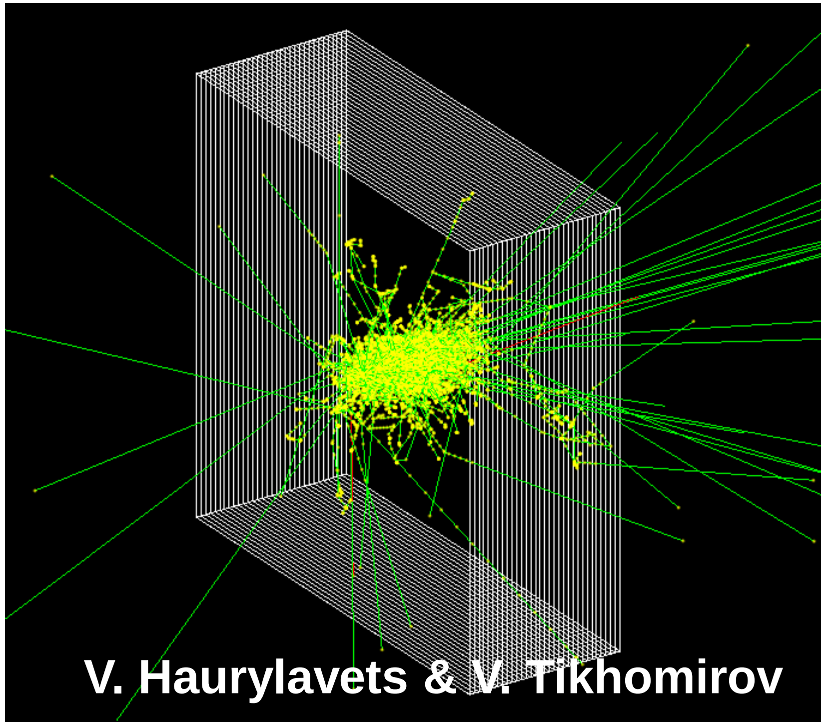
Comparison with simulations

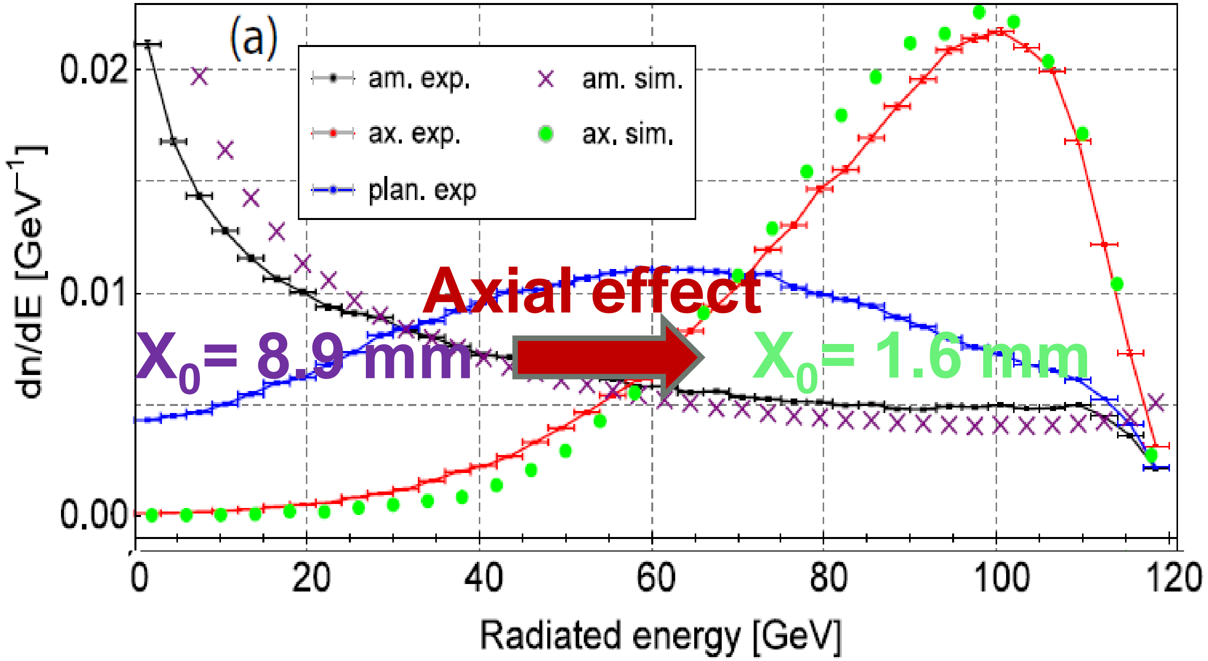


The electromagnetic shower is simulated using the **Geant4** toolkit in which the cross sections for **bremsstrahlung and pair production are rescaled** in agreement with full Monte Carlo*.

***L. Bandiera, V. Haurylavets and V. Tikhomirov Nucl. Instrum. Methods Phys. Res. A 936 (2019) p.124-126**

Comparison with simulations



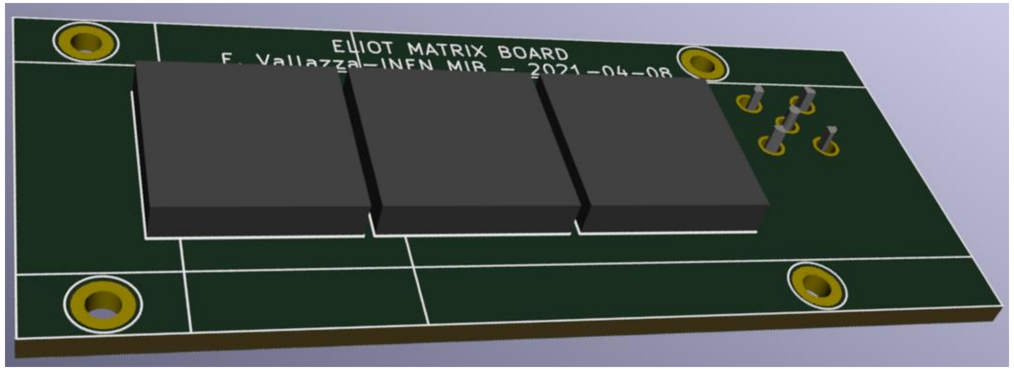


✓ **The simulated axial-to-random ratio for the light output is 2.2** -> fully compatible with the measured SiPM signal enhancement.

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*.

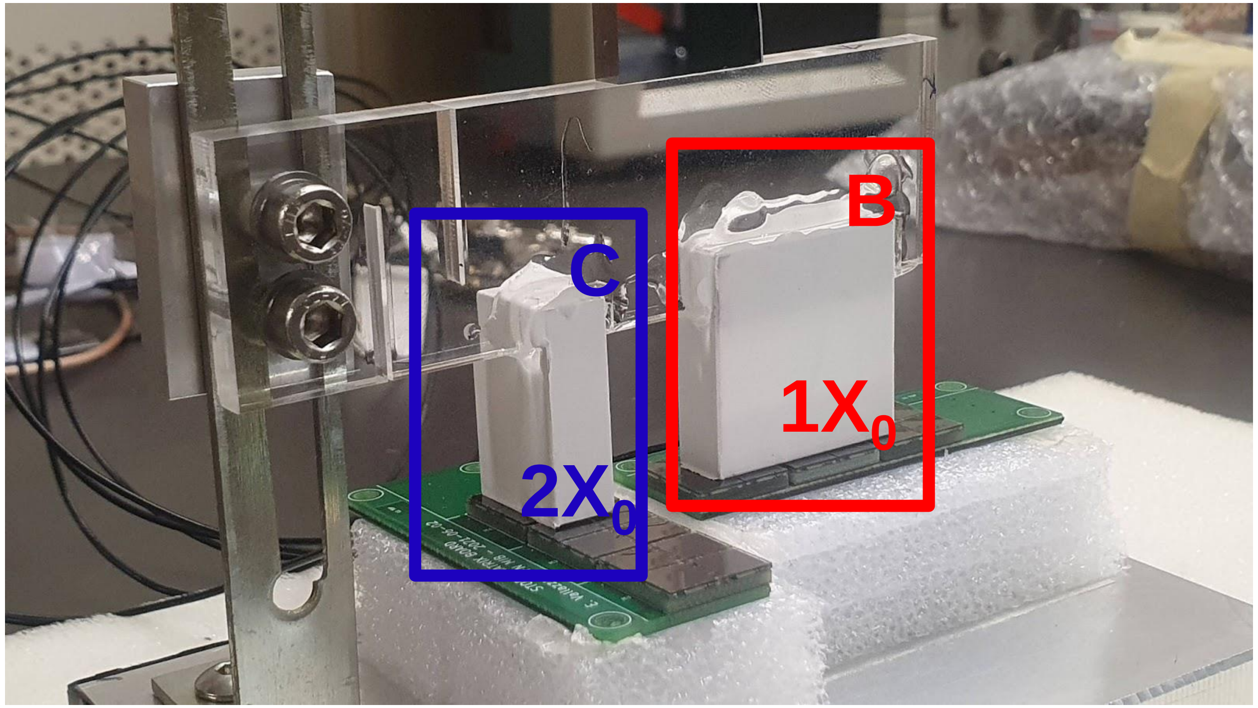
***L. Bandiera, V. Haurylavets and V. Tikhomirov Nucl. Instrum. Methods Phys. Res. A 936 (2019) p.124-126**

Sample B and C – 1 and 2 X_0 & [100] axis



Developed @INSULAB & INFN Bicocca

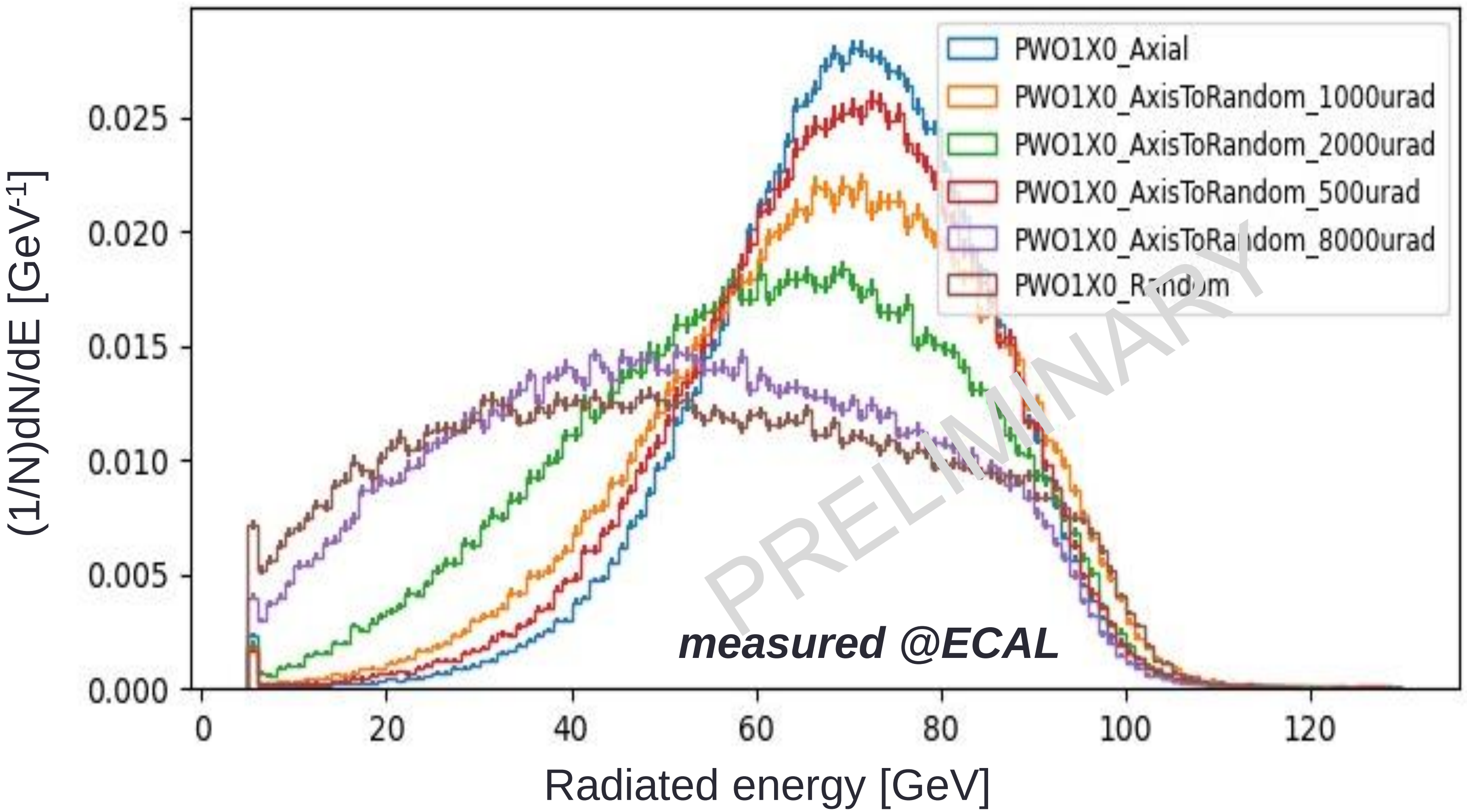
Photodetection board based on silicon photomultipliers (SiPM). In particular, each board mounts three 2×2 matrices model ArrayC-60035-4P-BGA from ON Semiconductor, for a total active surface of ~ 15×45 cm2.



- $1X_0$ along the beam & transversal face 3x3 cm^2
- producer: INP Minsk (Courtesy of M. Korjik & A. Lobko)
- material: PWO II

- $2X_0$ along the beam & transversal face 1x3 cm^2
- producer: MOLTECH
- material: PWO

Sample B – 1 X_0: radiated energy

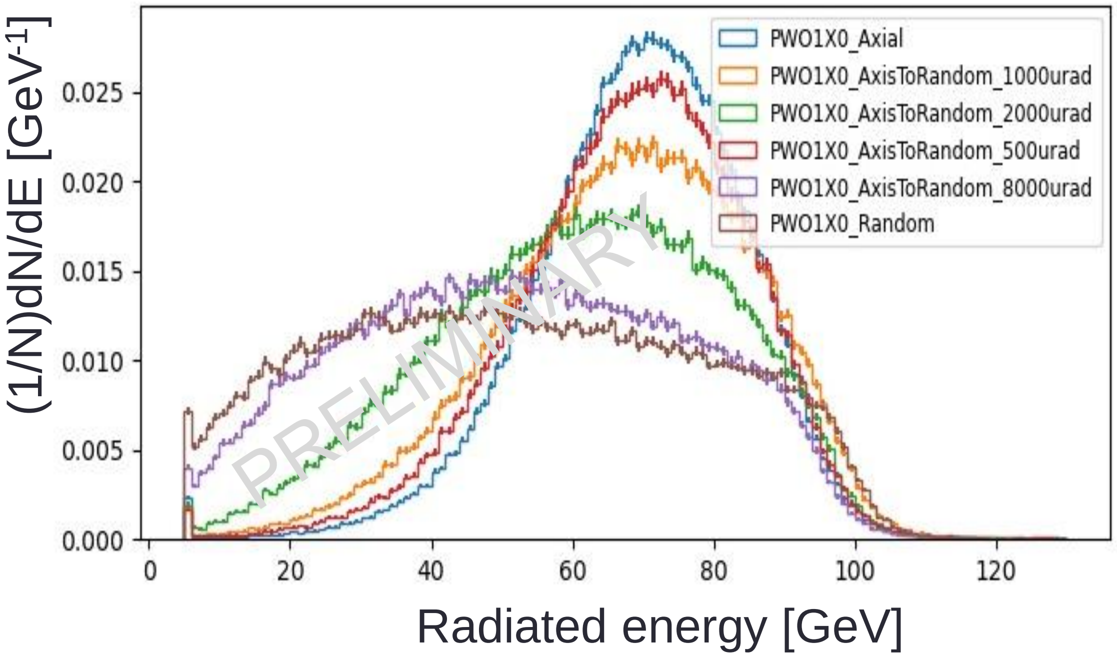


Radiative energy loss measured @ECAL for different crystal-to-beam alignment conditions:

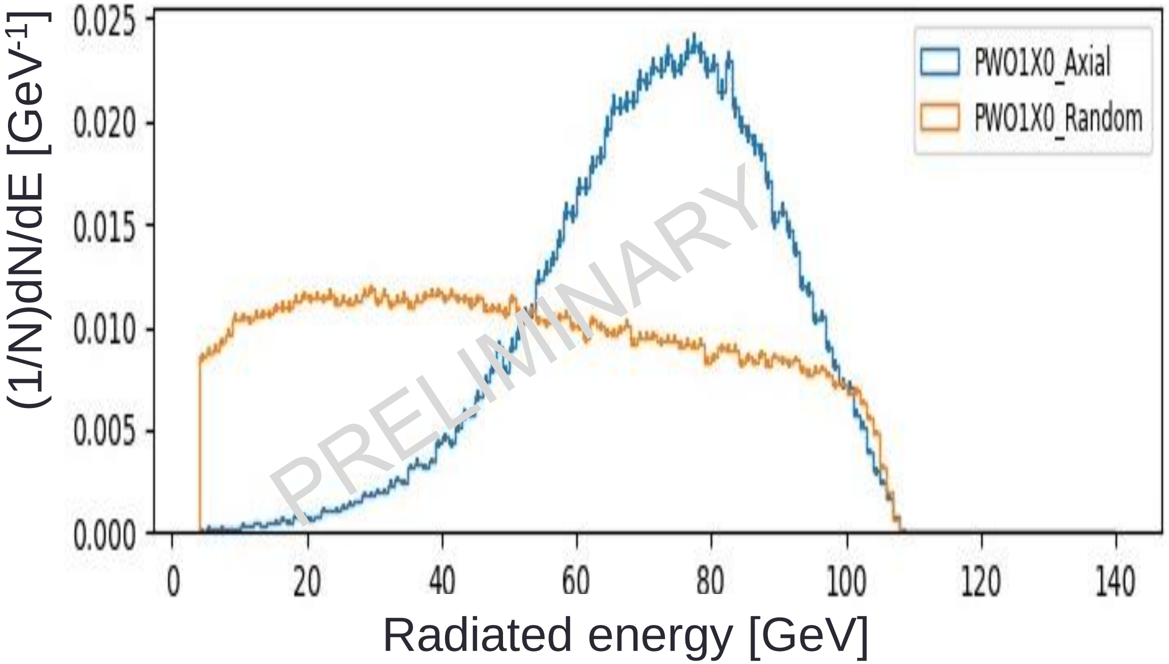
- ✓ **Axial peak @75 GeV**
  Lower energy than for 0.45 X0 case -> more charged pairs produced swept away by the magnet
- ✓ **Enhancement still measurable @8 mrad (0.5°)** from the axis

Sample B – 1 X_0: radiated energy

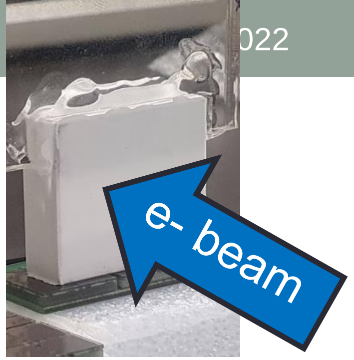
measured @ECAL



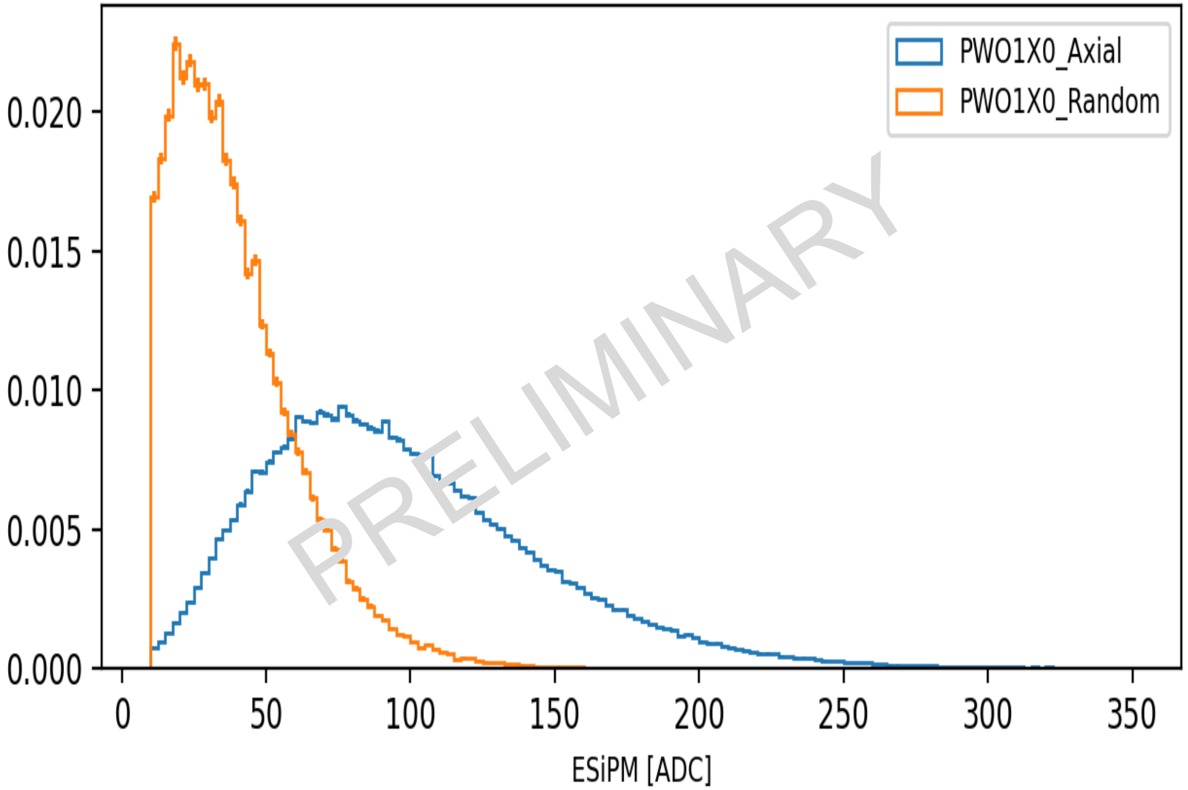
Geant4 simulation



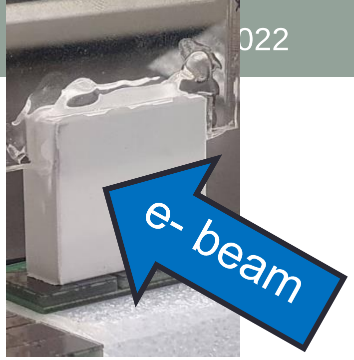
Good agreement with simulations -> prediction capability



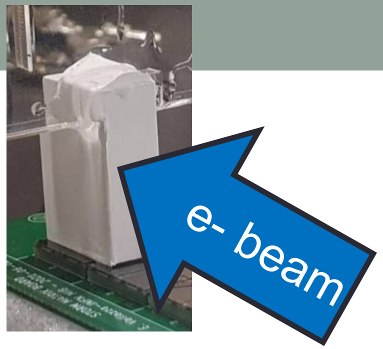
Sample B – 1 X_0 : scintillation light

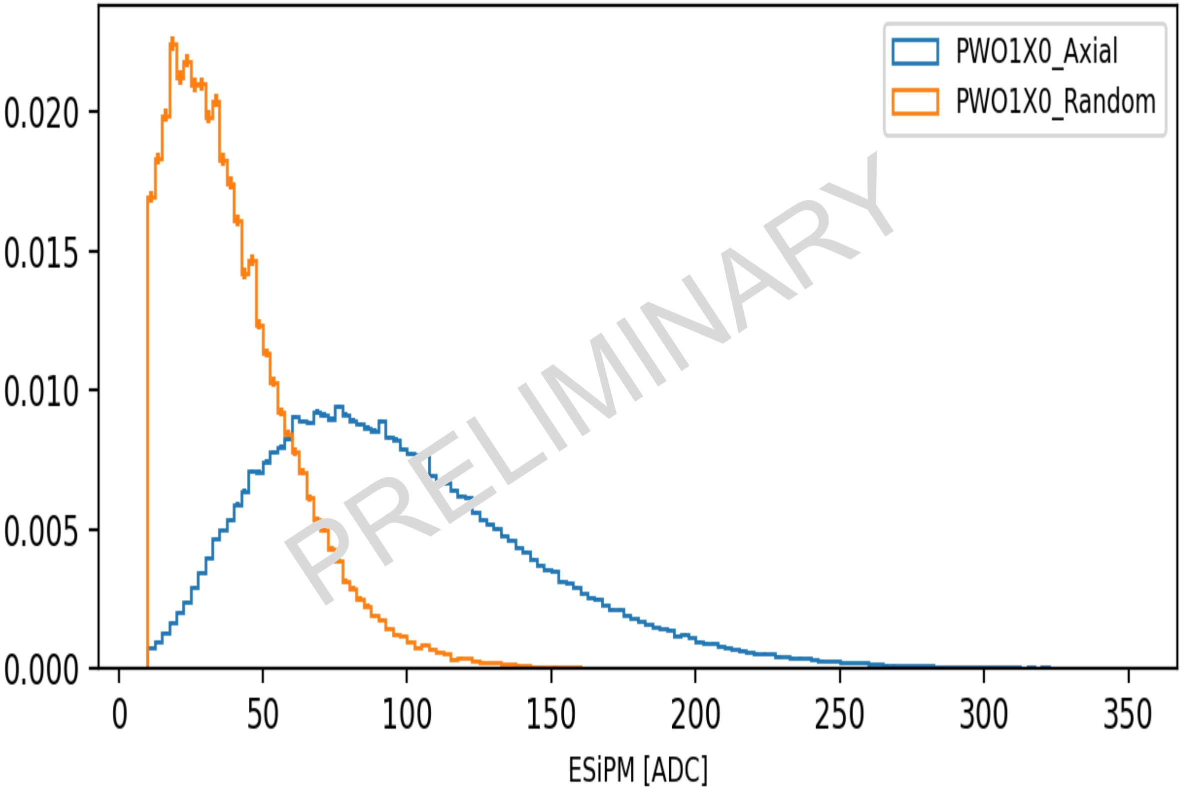


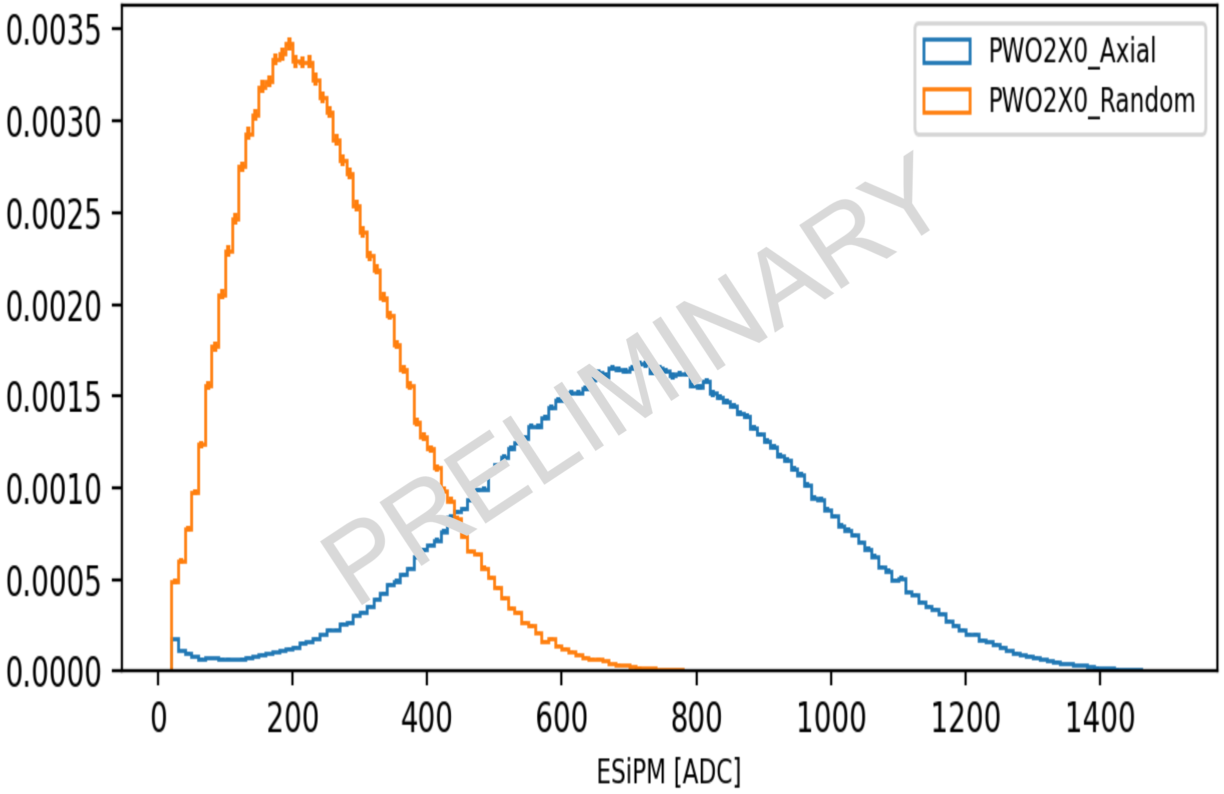
axial / random ratio ≈ 2.5



Sample B and C – 1 and 2 X_0 : scintillation light







axial / random ratio ≈ 2.5

axial / random ratio ≈ 3

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

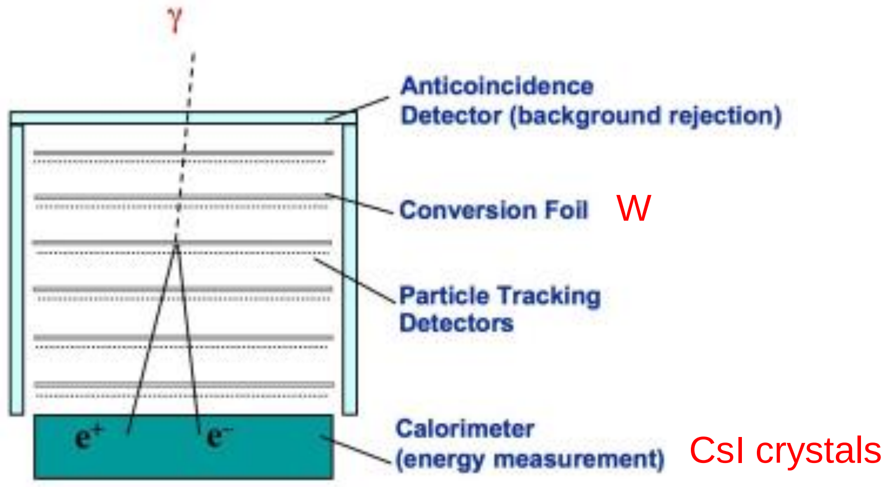
Particle Physics

- 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…

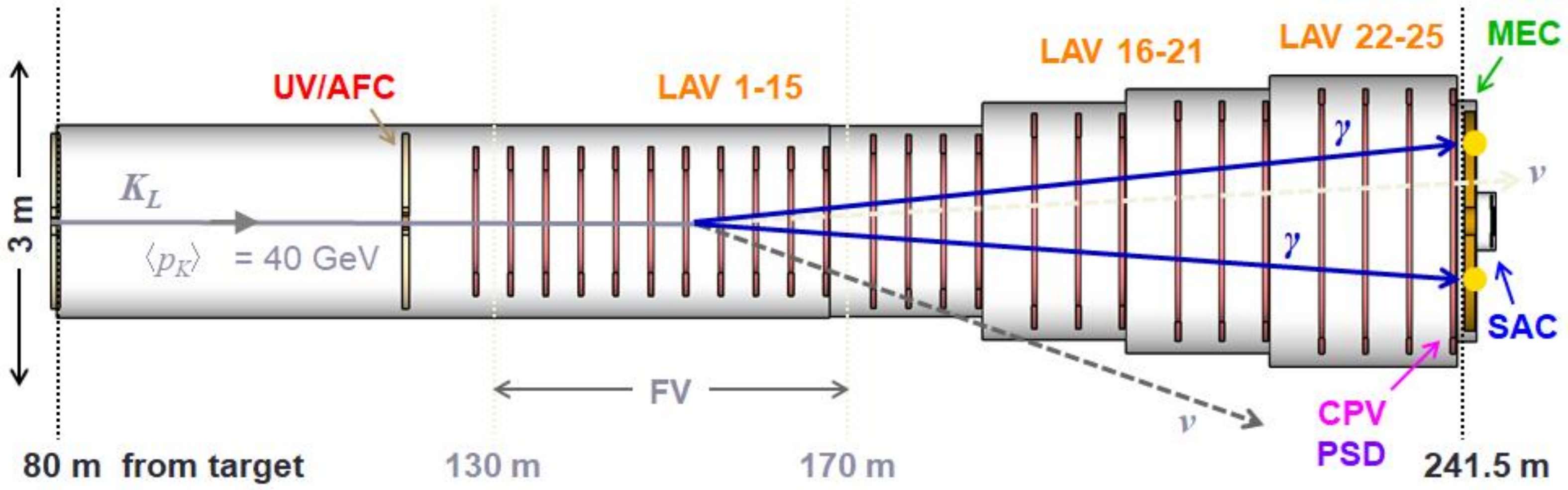
Astroparticle

- **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



Possible successor of NA62 in NA @CERN



KLEVER

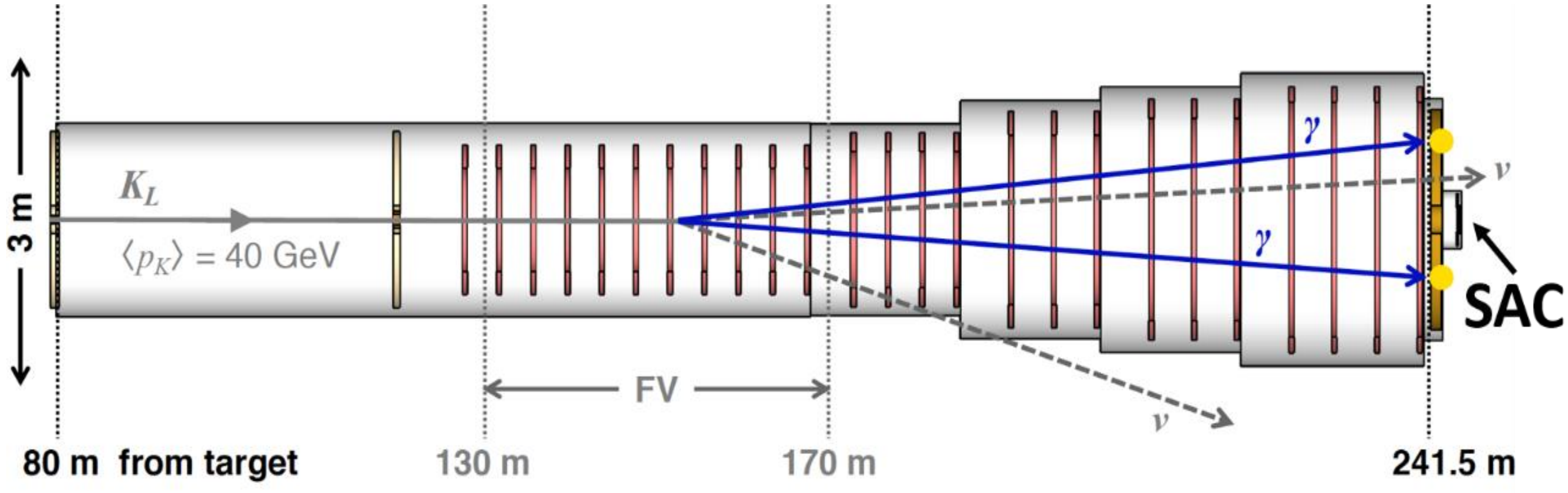
$K_L \rightarrow \pi^0 \nu\nu$

from K^+ (charged) to K_L (neutral) → new challenges: background control, beam characterisation, …

in order to get **~60 $K_L \rightarrow \pi^0 \nu\nu$ events** one will need ~5 × 10^{19} protons on primary target, i.e. **~5 years**!

Courtesy of M. Moulson

KLEVER SMALL ANGLE CALORIMETER



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

Courtesy of M. Moulson

A compact SAC for KLEVER based on oriented crystal

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**

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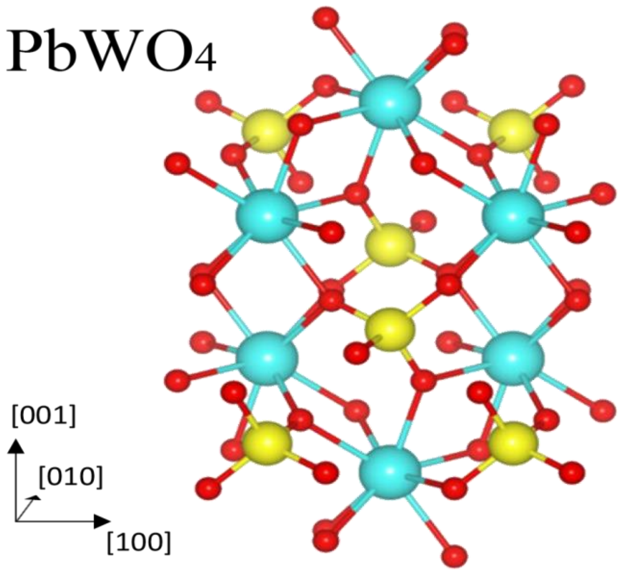

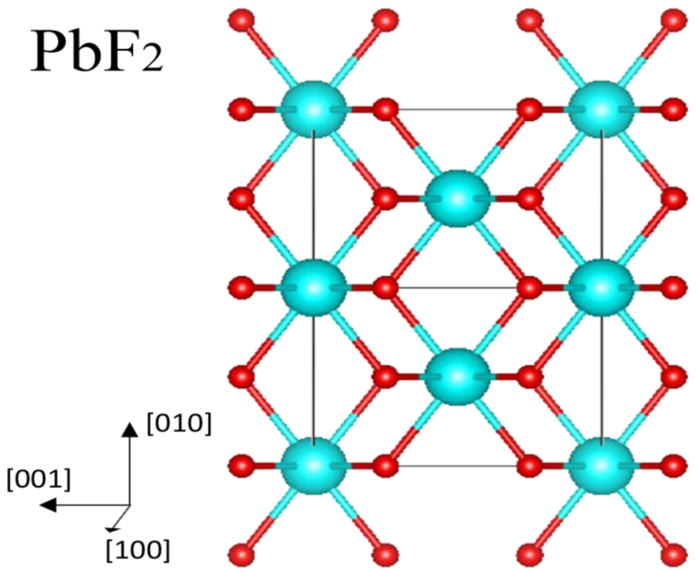

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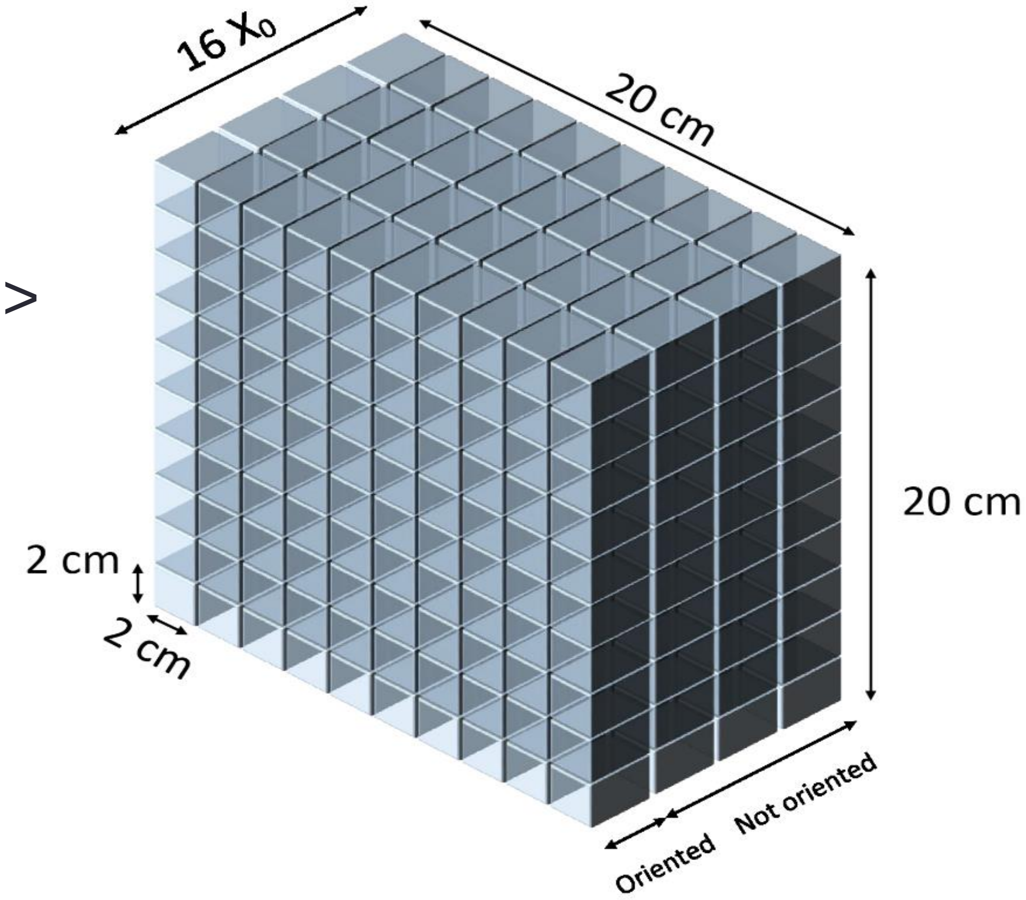
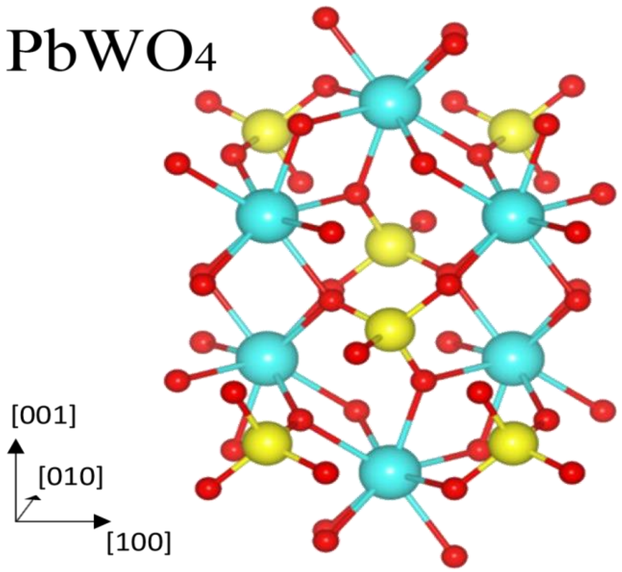
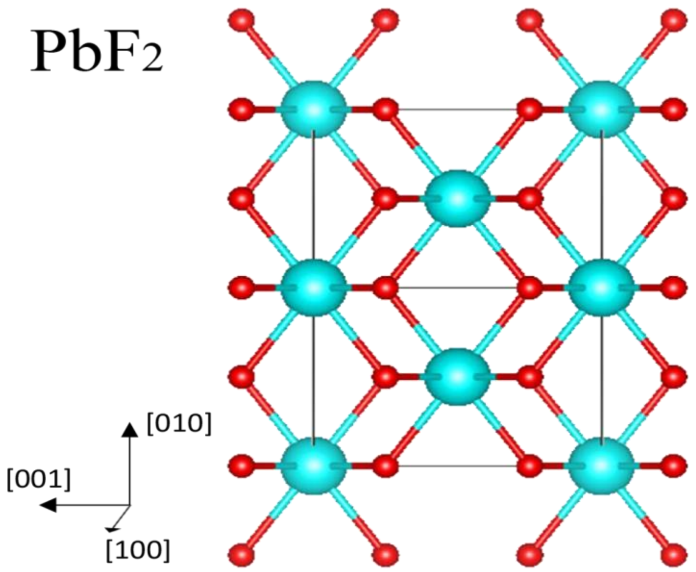


Transverse and longitudinal segmentation for a better n/γ discrimination





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 -> KLEVER Small Angle Calorimeter

Future work

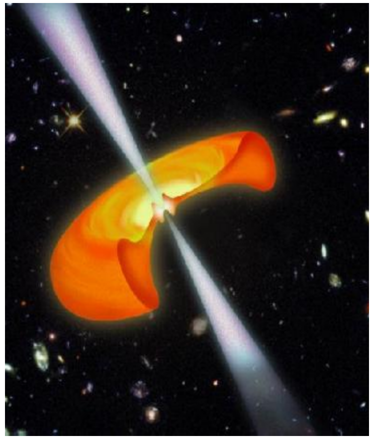
- Test of Cerenkov materials (PbF2) and readout
- Assembly and test of the performances in terms of X_0 reduction and Moliere radius of a full calorimeter prototype based on oriented crystals
- Full development of a Geant4 package dedicated to the e.m. physics modification in oriented crystals – H2020 MSCA IF Global TRILLION
- … and then **ultra-compact** (and ultra-fast) **e.m. calorimeters** could realistically become fundamental detectors for future high-intense & high-energy physics experiments

THANK YOU FOR THE ATTENTION!

Strong field in nature and labs

Such fields are generally only seen in astrophysical phenomena, such as highly magnetized neutron stars, black holes (where the gravitational field is strong)….

Magnetars
$B \approx 10^{10}$ T



Beamstrahlung in future linear colliders
ILC/CLIC

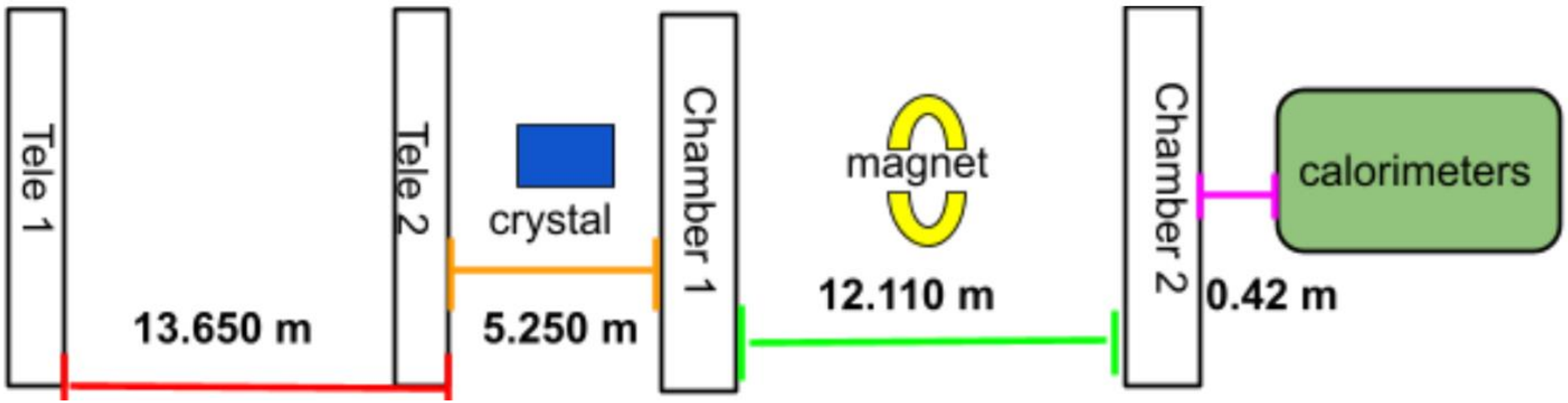
It is the radiation from one beam of charged particles in a collider, emitted due to the electromagnetic field of the opposing beam

Heavy ion collider

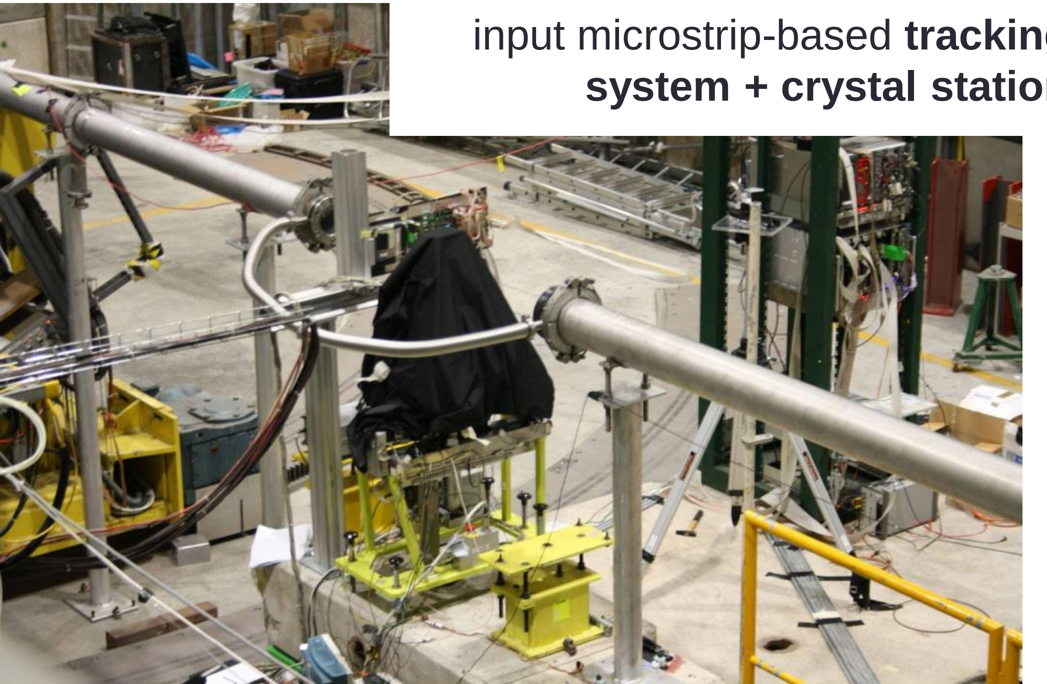
During bunch crossing, the peripheral interactions of the heavy ions generate a sufficiently large electromagnetic field that spontaneous e^+, e^- pair creations will occur.

Strong lasers

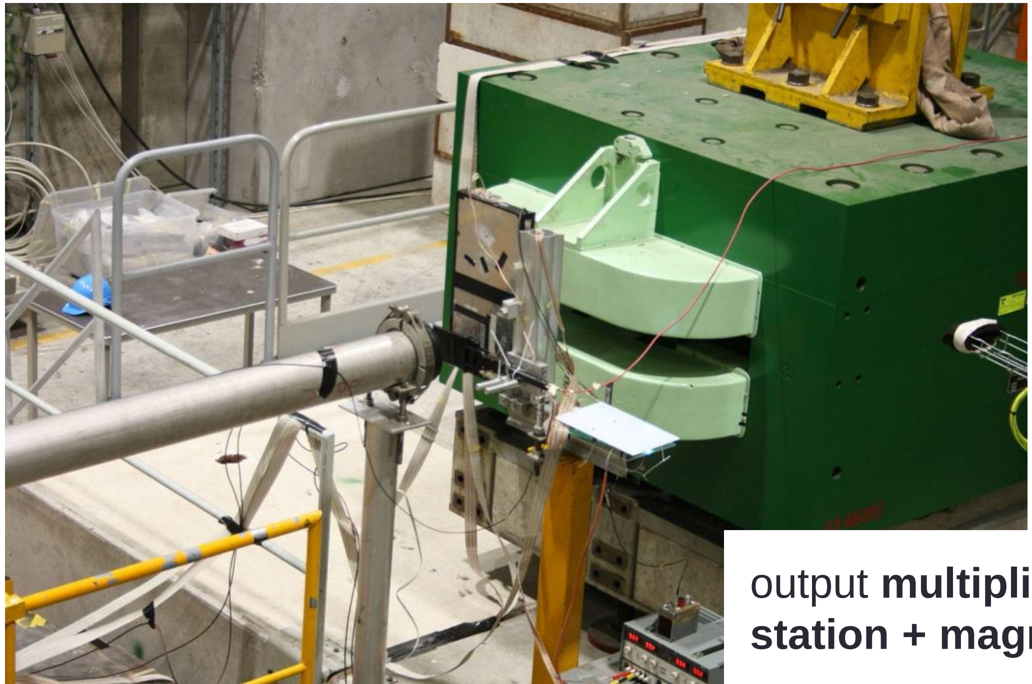
-Non-linear Compton scattering where multiple laser photons are absorbed and a single photon radiated.
- Produced photon interacts with laser field to produce electron−positron pair (Breit−Wheeler)



BGO-based **electromagnetic calorimeter**

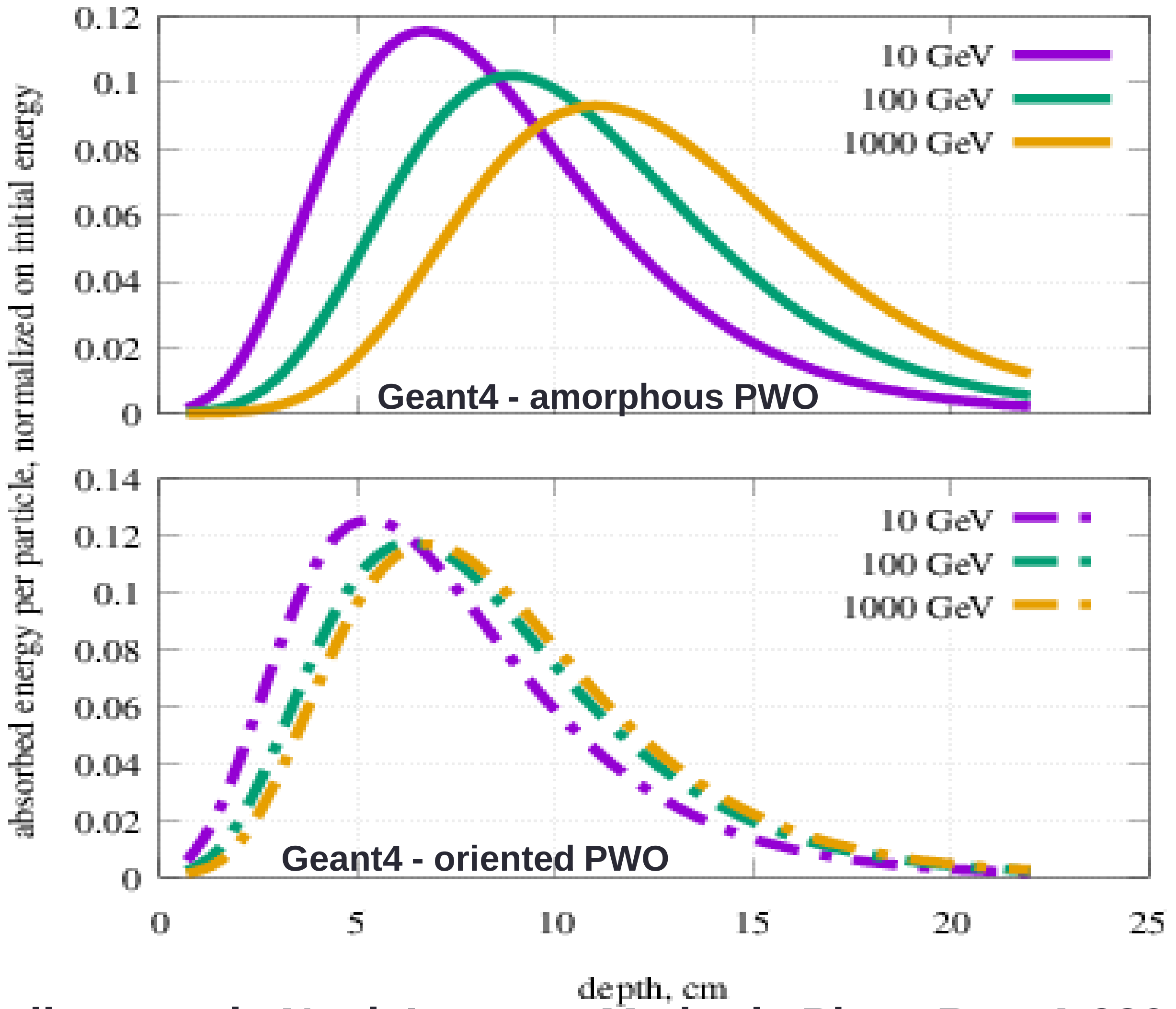


input microstrip-based **tracking system + crystal station**



output **multiplicity counting station + magnet**

Fast e.m. shower development in oriented PWO



Electromagnetic shower longitudinal development vs. e$^-$ beam energy simulated via Geant4 with modified Physics List for oriented crystals

In case of the axially oriented scintillator, the shower maximum is shifted to the entry surface of the crystal.

L. Bandiera, et al., Nucl. Instrum. Methods Phys. Res. A 936 (2019) p.124-126