Ultracompact space-borne telescope for VHE gamma rays detection

ASAPP 2023
Perugia, 21st June 2023

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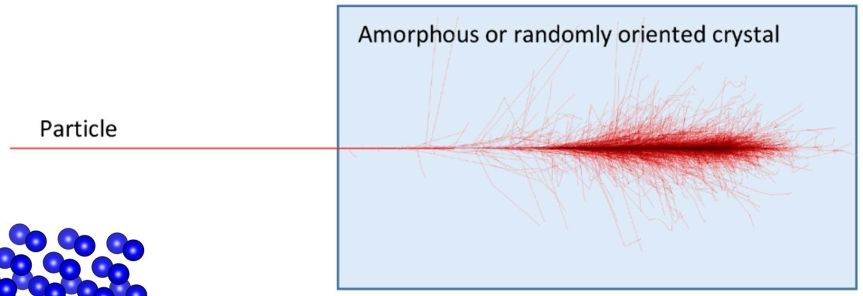
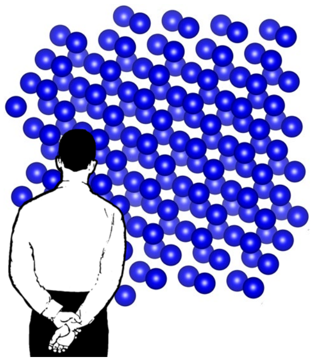
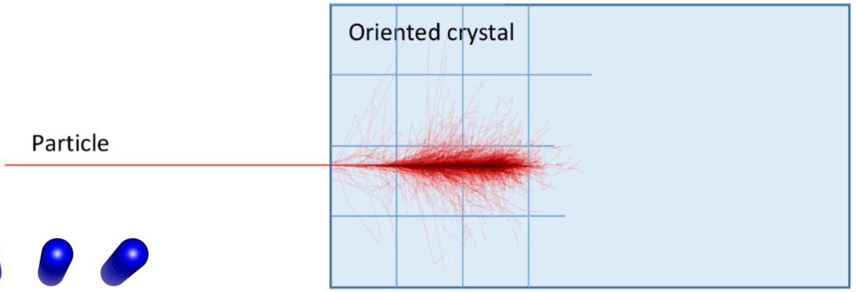
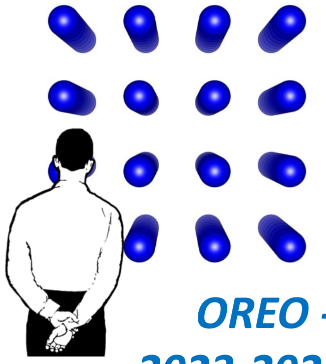
Istituto Nazionale di Fisica Nucleare
Sezione di Ferrara









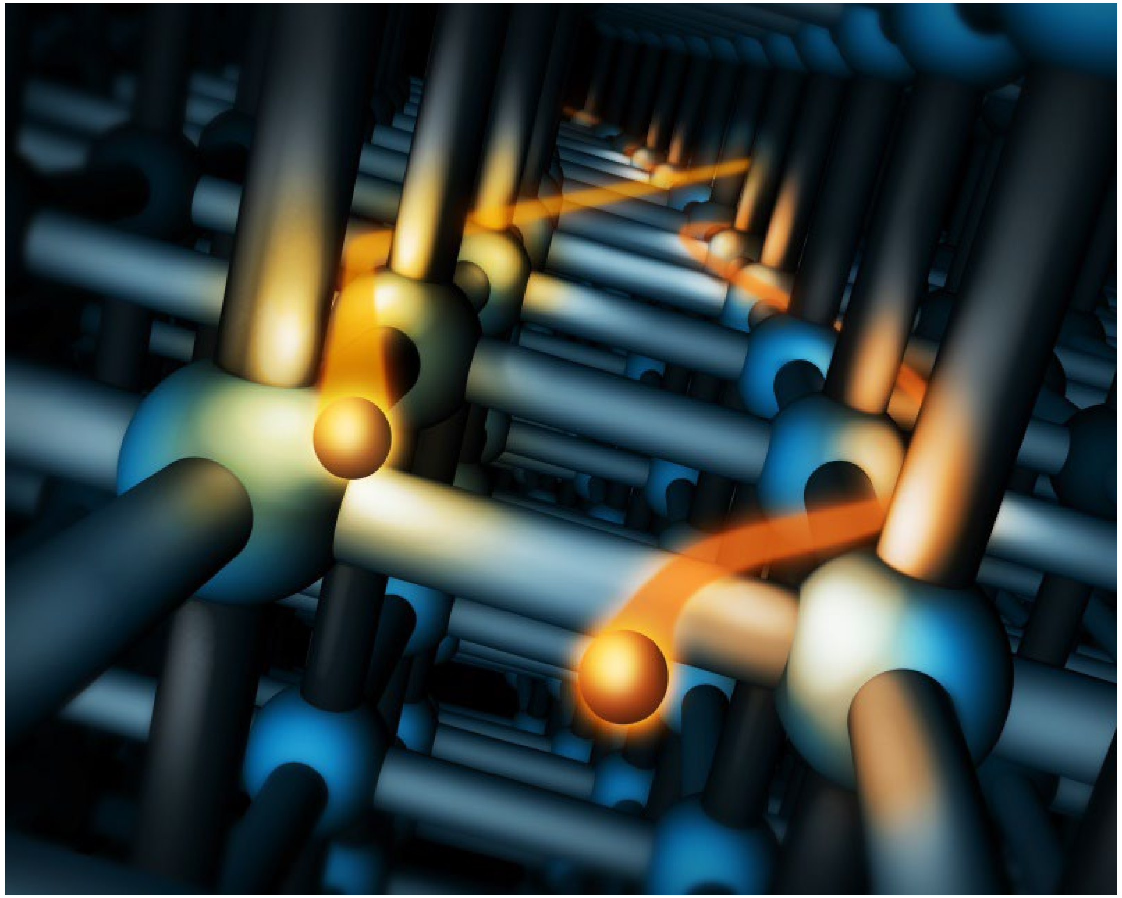
OREO - ORiEnted calOrimeter
2023-2024 project financed by INFN

CSN5 Ricerca Tecnologica

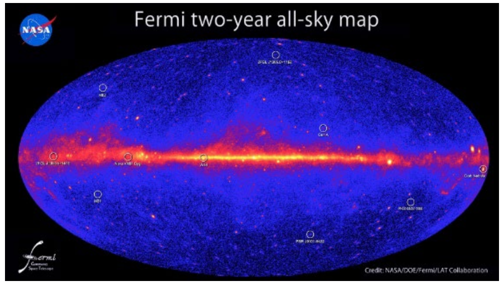
OREO

Outlook

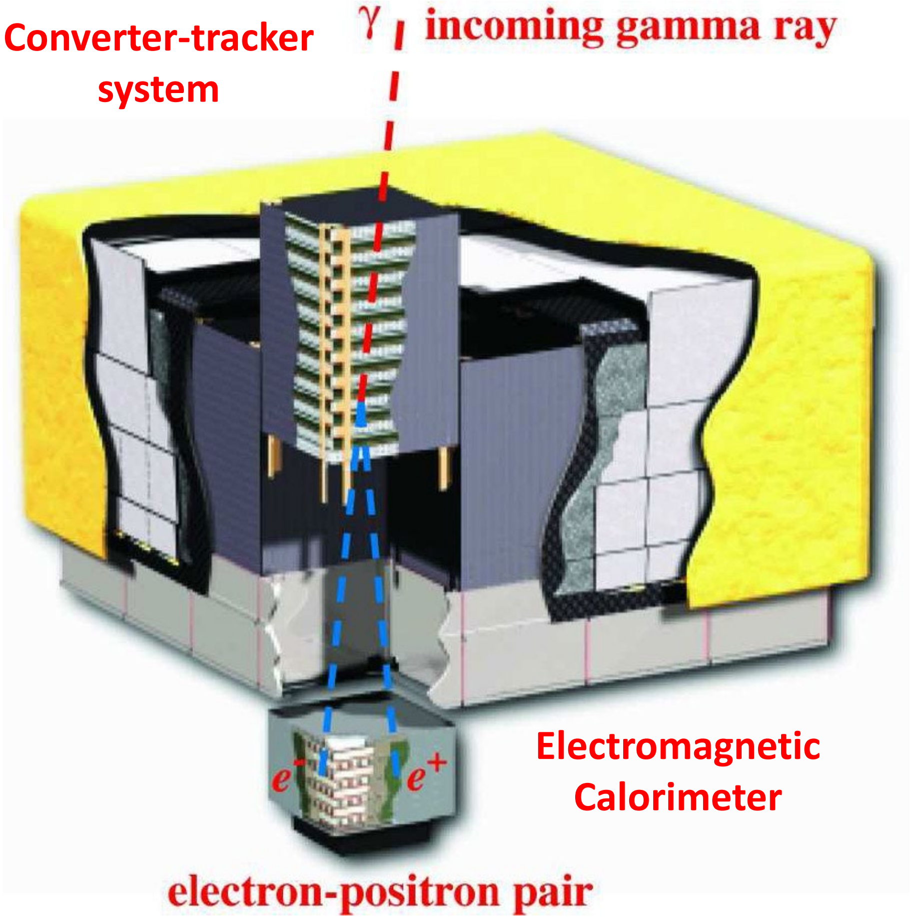
- Electromagnetic shower modification in oriented crystals
- Experimental tests on PWO scintillators with multi-GeV electrons and photons at CERN SPS
- Orienting the crystals for an ultra-compact telescope for VHE gamma-rays
- Possible application



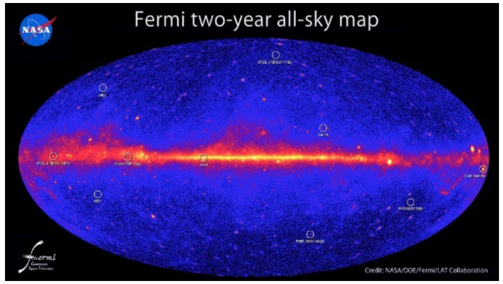
VHE gamma detectors in space ….



Take the FERMI-LAT tower …

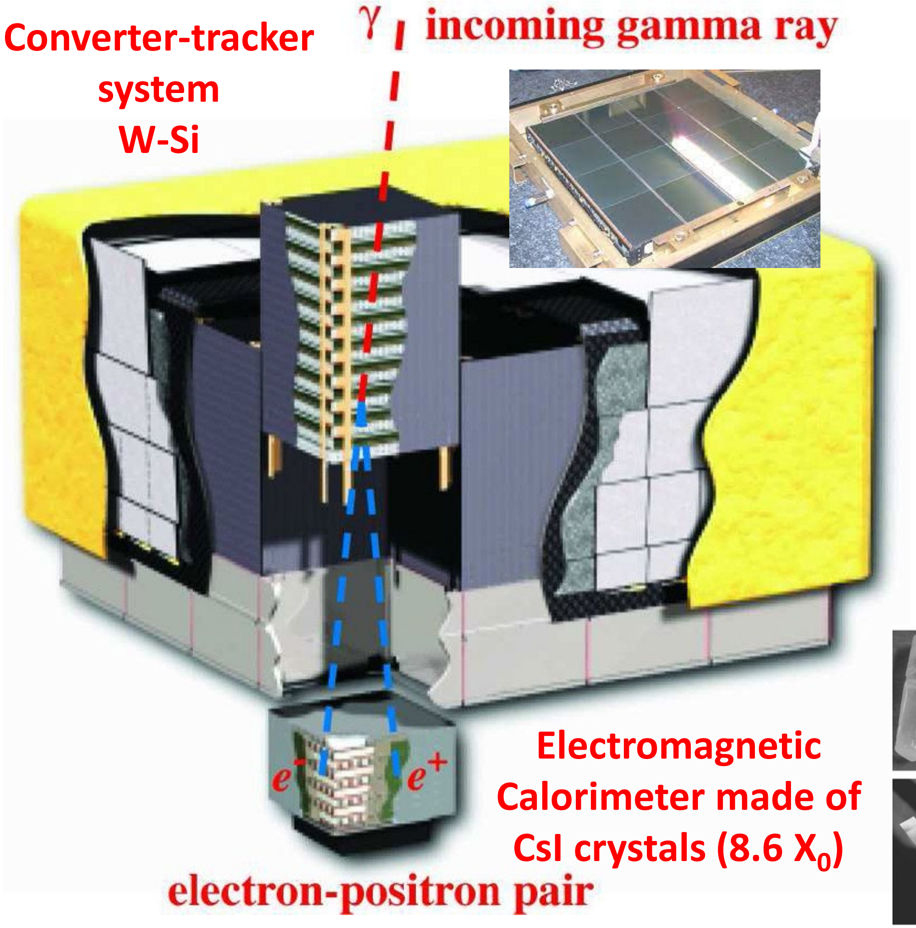


…. are made of crystals….

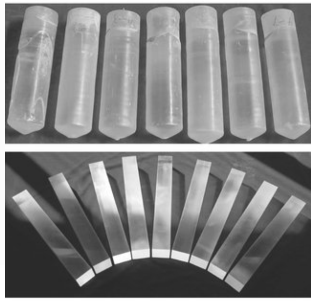


Take the FERMI-LAT tower …

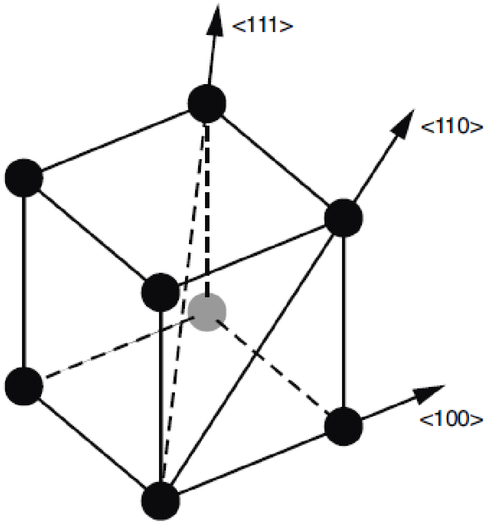
Converter-tracker system W-Si



Electromagnetic Calorimeter made of CsI crystals (8.6 X_0)

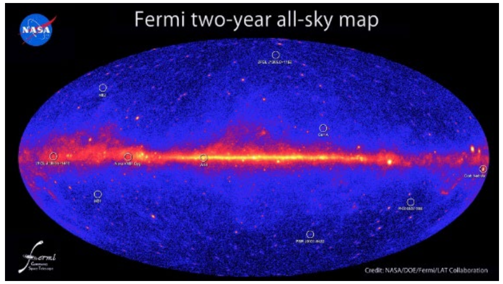


Most of the detector materials have a crystalline structure, i.e., a lattice structure, which can be highly anisotropic for some orientation!



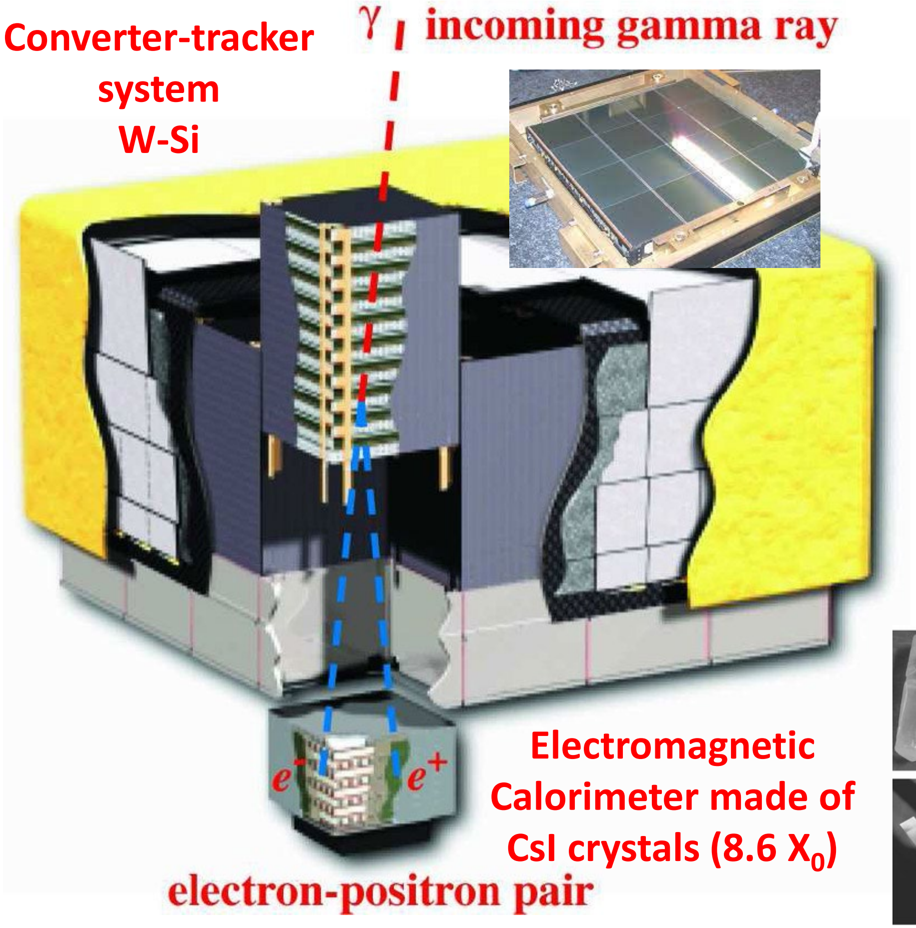
Main lattice directions of a cubic crystal

.. that can be oriented along lattice directions



Take the FERMI-LAT tower …

Converter-tracker system W-Si



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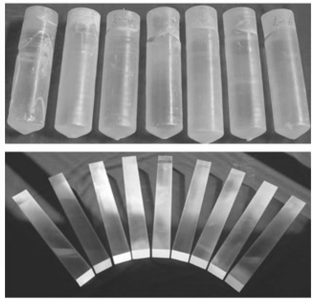
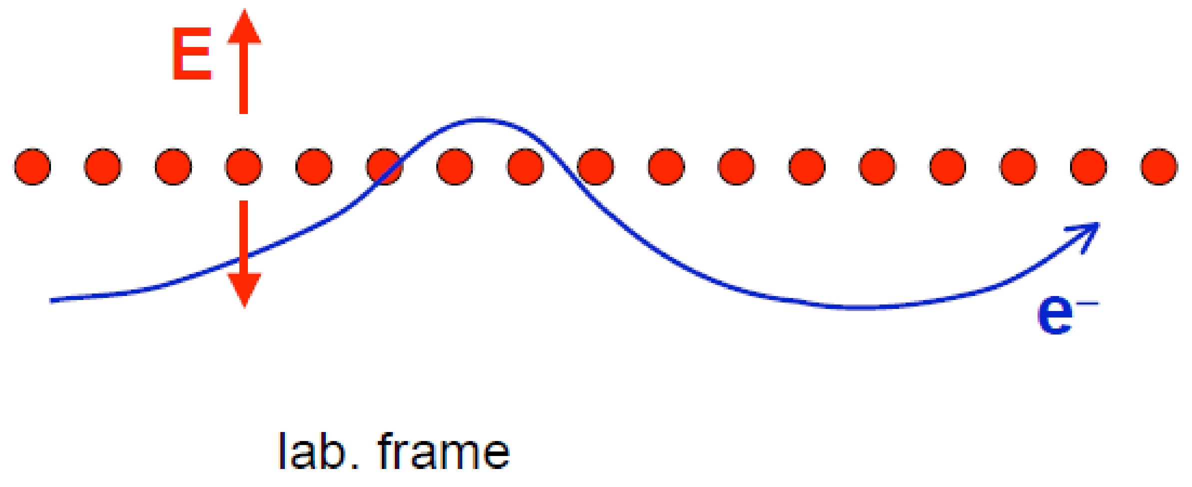
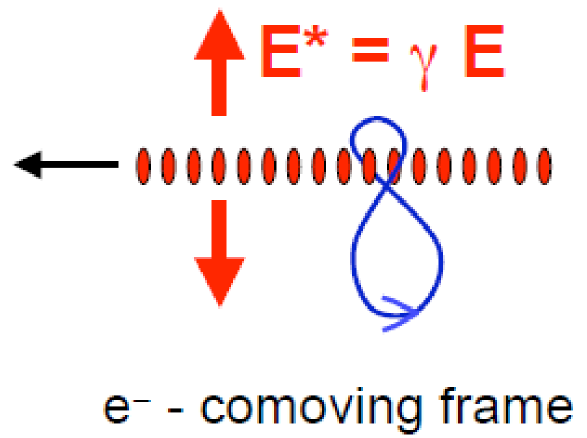


All of these materials have a crystalline structure and can be oriented along some preferred lattice direction

Electromagnetic processes of VHE particles (e.g., bremsstrahlung and pair production) are strongly dependent on crystal orientation!

Strong electromagnetic field in oriented crystals



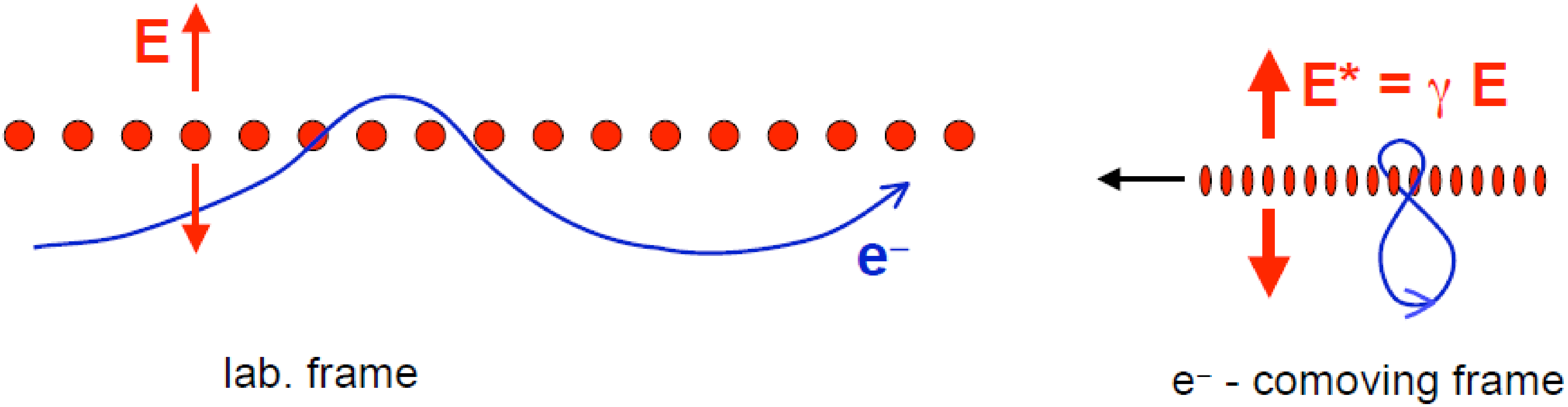


In the comoving frame, the **Lorentz contracted Electric field** can be computed as:

$$E^* = \gamma E$$

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:

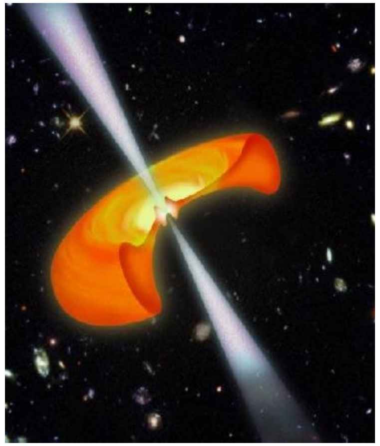
$$E^* = \gamma E$$

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

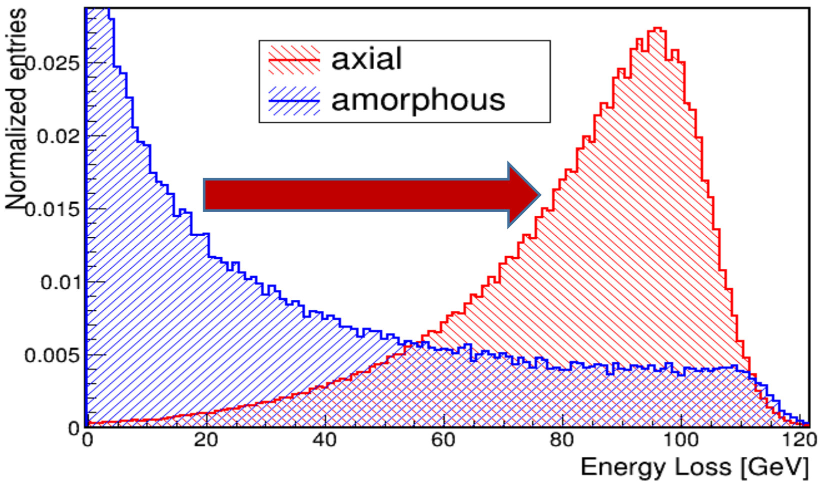


Magnetars
$B \approx 10^{10}$ T

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

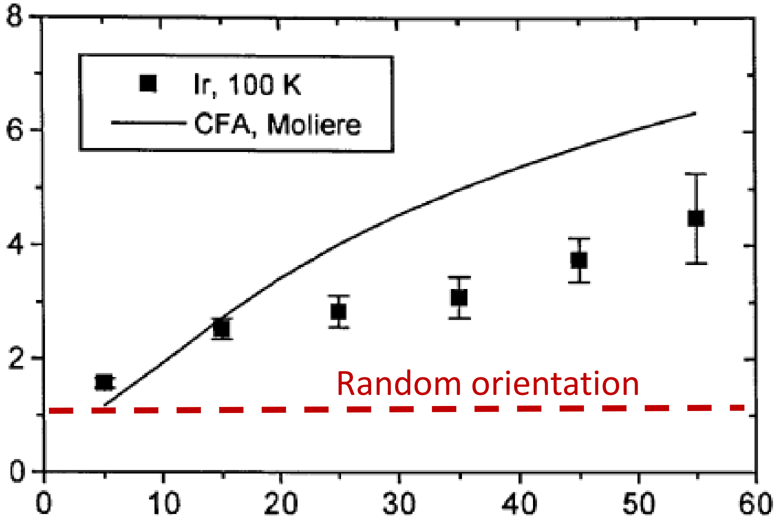
Radiation and pair production in axial alignment

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;
  - Does **NOT** depend on particle energy.

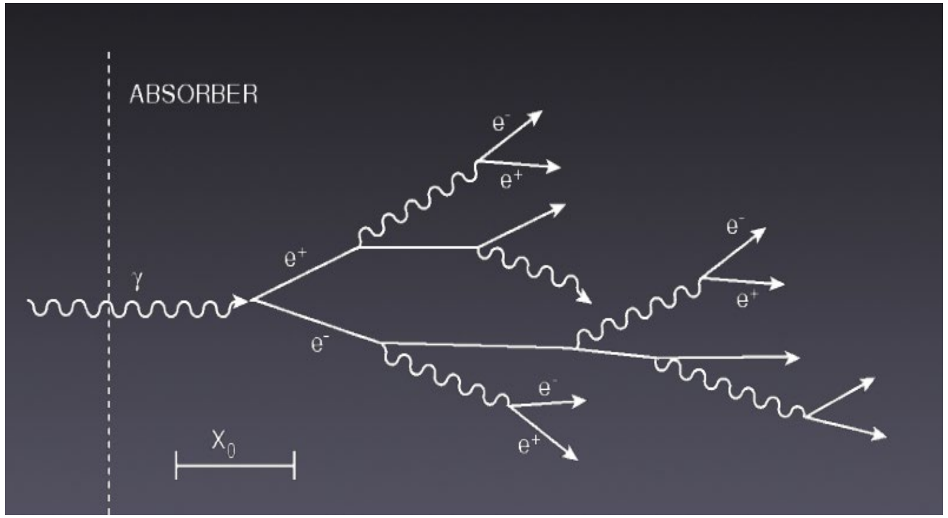
Strong increase in the energy radiated by the electrons and in the pair production probability by high-energy photons!

Electromagnetic shower acceleration

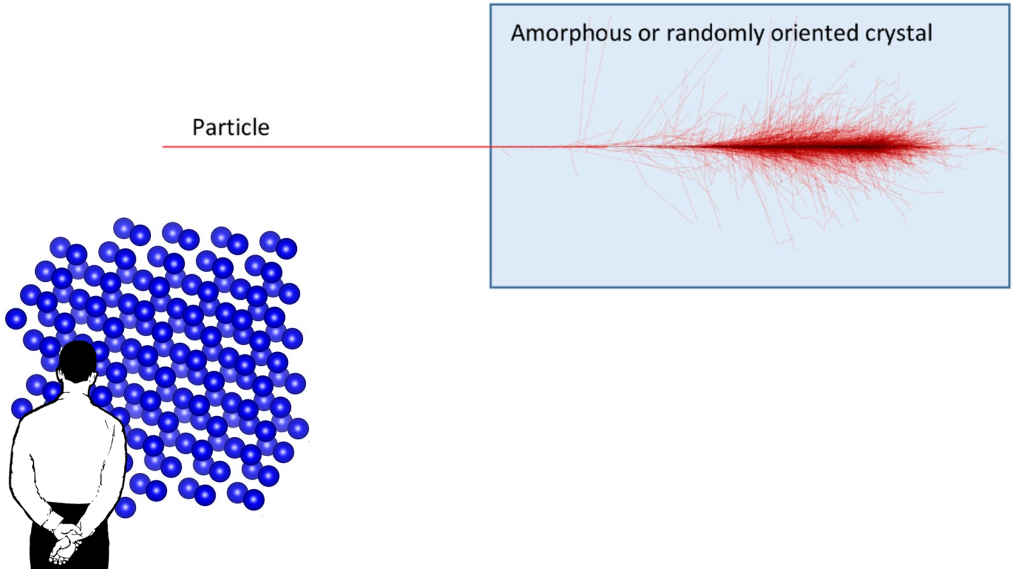
electromagnetic shower is way more compact

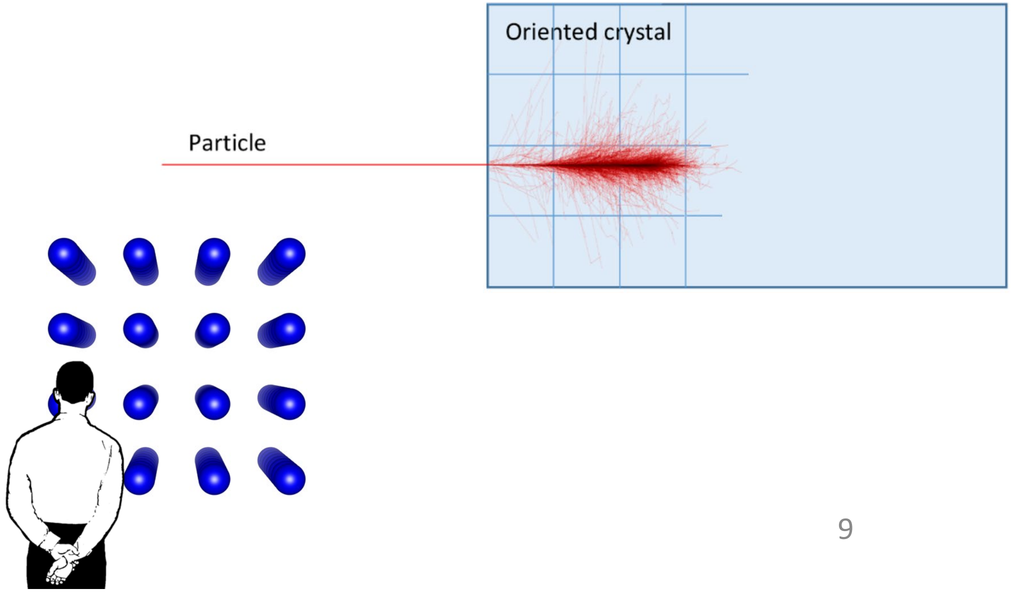
or equivalently

effective radiation length X_0 is much shorter

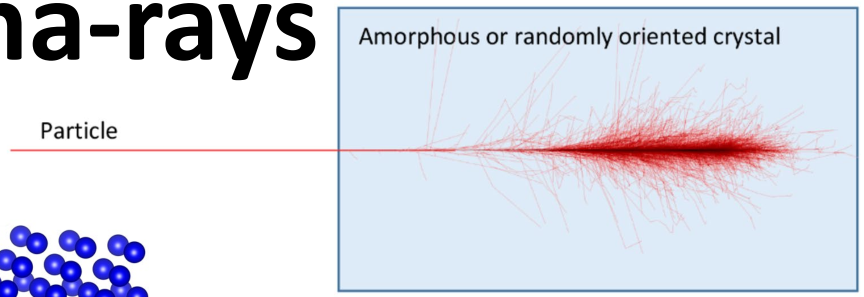


L. Bandiera et al., Phys. Rev. Lett. 121 (2018) 021603

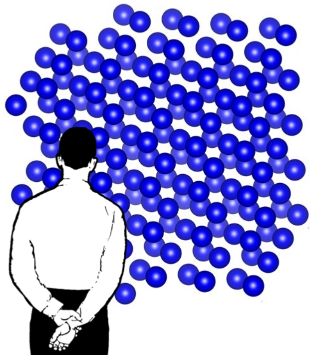




Novel idea: ultra-compact space-borne satellite to detect VHE gamma-rays

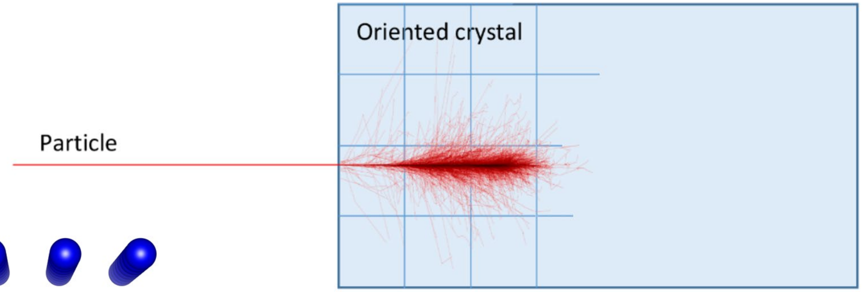


If we point the telescope toward a gamma-ray source, we could exploit the X_0 reduction in oriented crystals to…

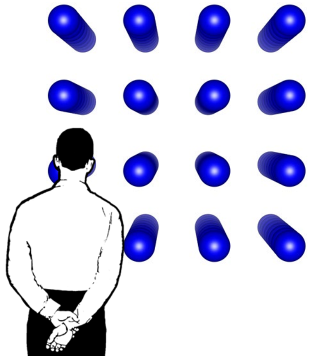


- **enhance the sensitivity of the telescope above few GeV;**

- **containing e.m. showers initiated by particles with energies even above 100 GeV in a reduced volume/weight ->**
  - ***huge cost reduction!!!***
  - ***could improve the energy resolution!***



- **increase the signal-to-background discrimination when the gamma direction is within one or few mrad (0.05°-0.01°).**



N.B. the system would continue to operate in a standard way in the absence of pointing!

Orienting the 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

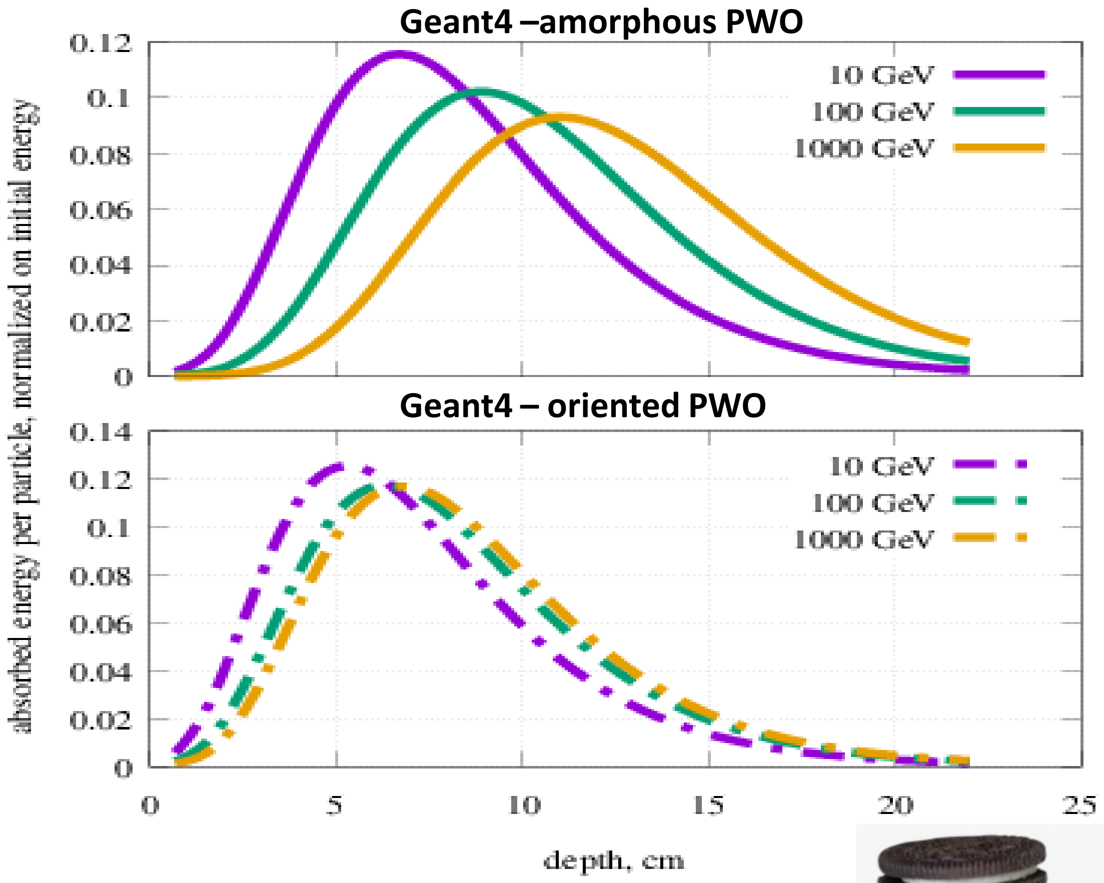
→ enhanced compactness

→ budget-saver

→ 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

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

CSN5 Ricerca Tecnologica

STORM – STrOng cRystalline electroMagentic field
2021-2022 project financed by INFN

OREO - ORiEnted calOrimeter
2023-2024 project financed by INFN

CSN5 Ricerca Tecnologica

The INFN STORM/OREO team

- ✓ **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

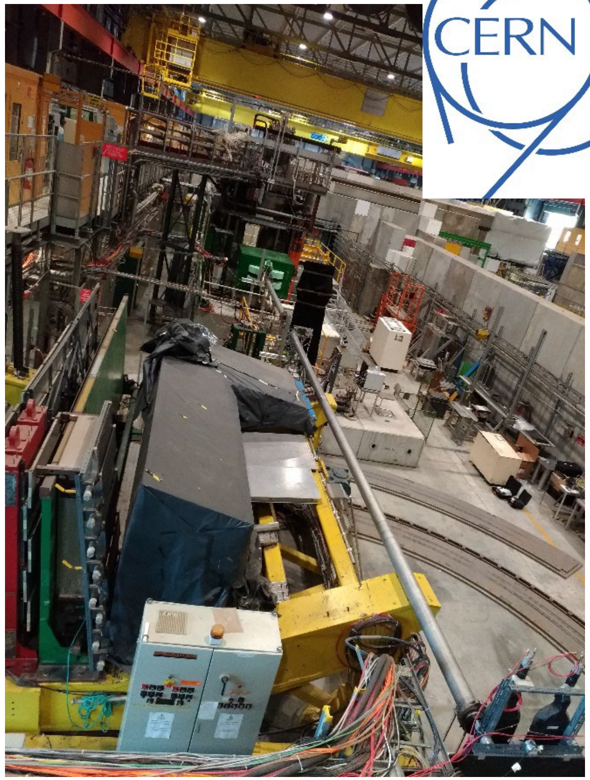
- ✓ **INFN Legnaro Labs and University of Padua**

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

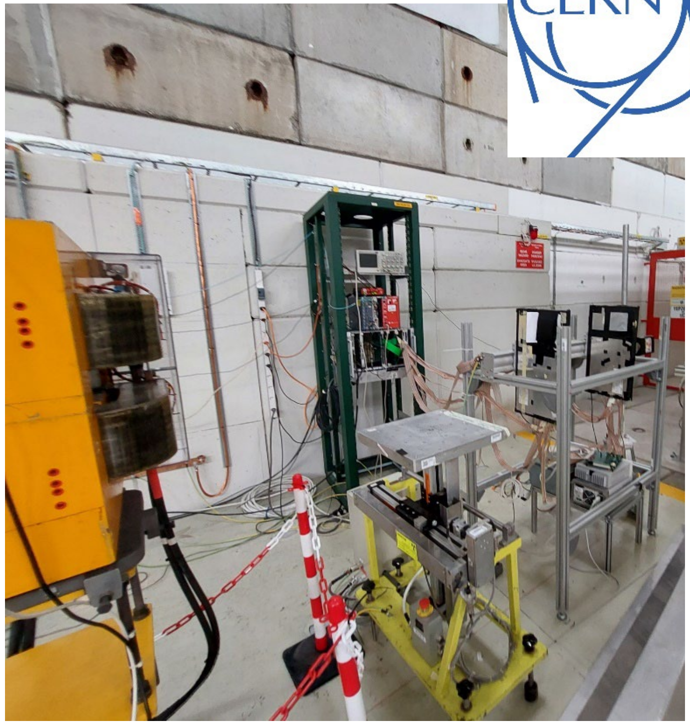
- ✓ **INFN Milan Bicocca and Insubria University**

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

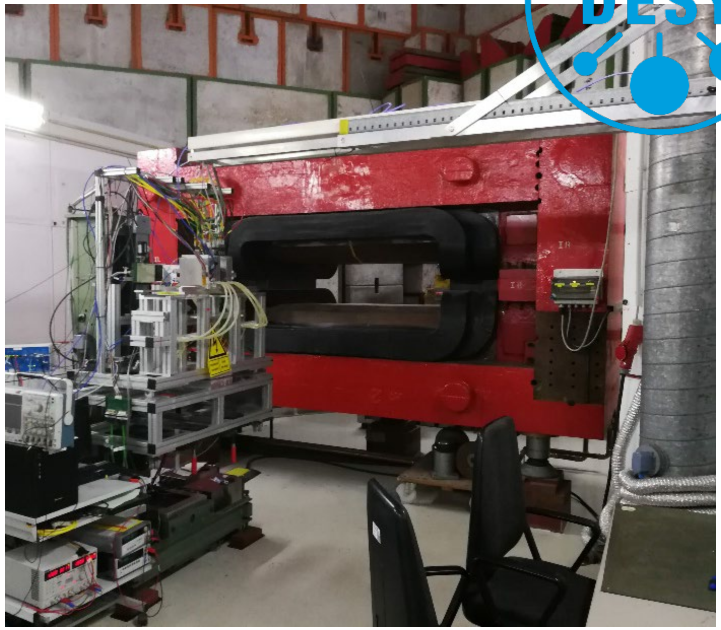
Experimental tests…



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

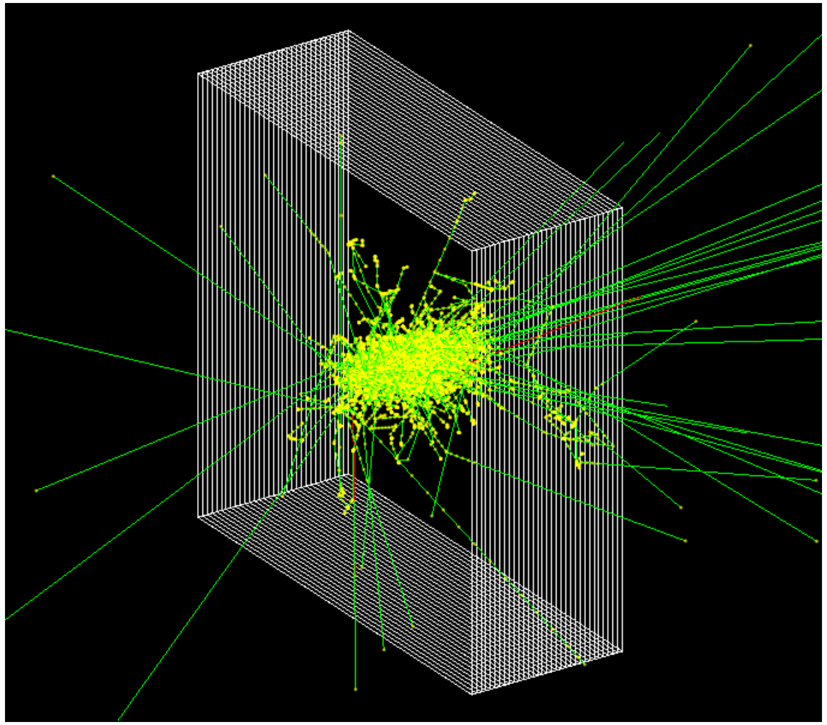


e^- @ 6 GeV
CERN PS EA T9
(Geneve, Switzerland)

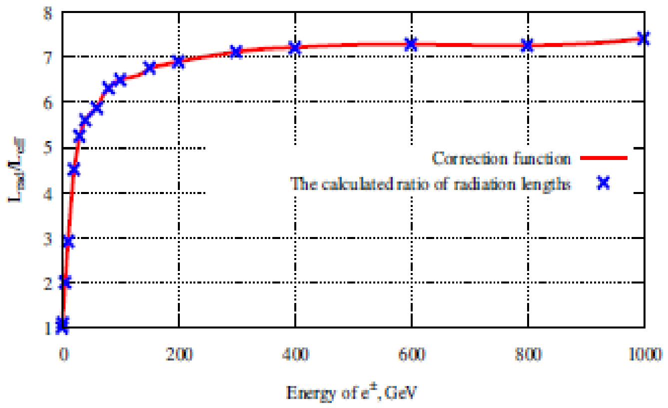


e^- @5.6 GeV
DESY TB (Hamburg, Germany)

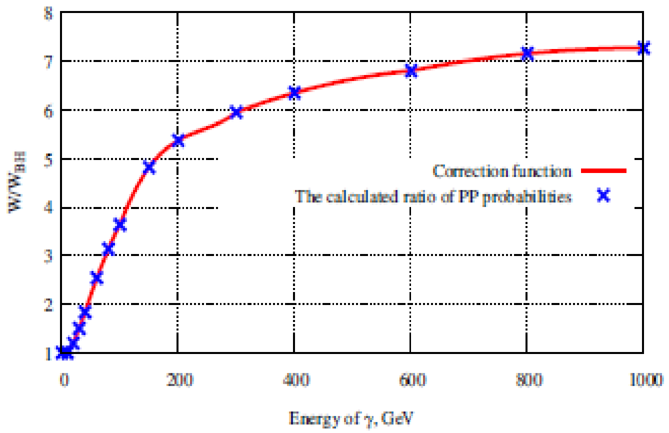
…and Monte Carlo simulations



bremsstrahlung



Pair production



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. Haurylavets and V. Tikhomirov NIM A 936 (2019) p.124-126**

European Commission

Alexei Sytov (INFN-FE)
Marie Curie Individual fellow
TRILLION coordinator
https://www.fe.infn.it/trillion/

The project TRILLION is dedicated to the implementation of electromagnetic processes in oriented crystals into Geant4

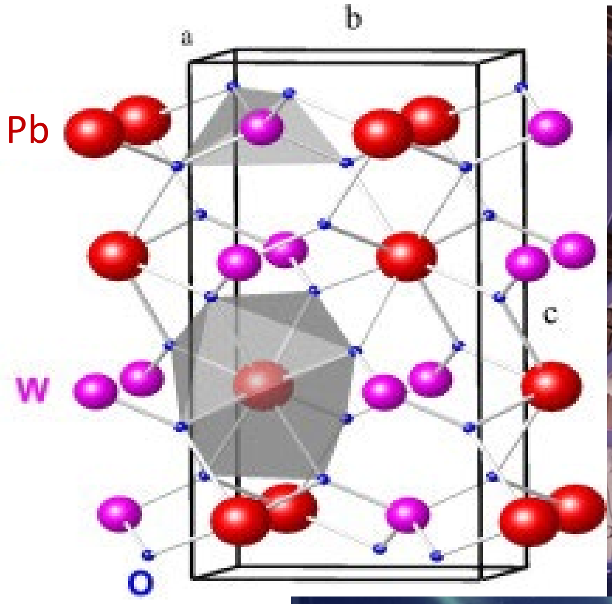
Crystal investigated: Lead tungstate ($PbWO_4$)

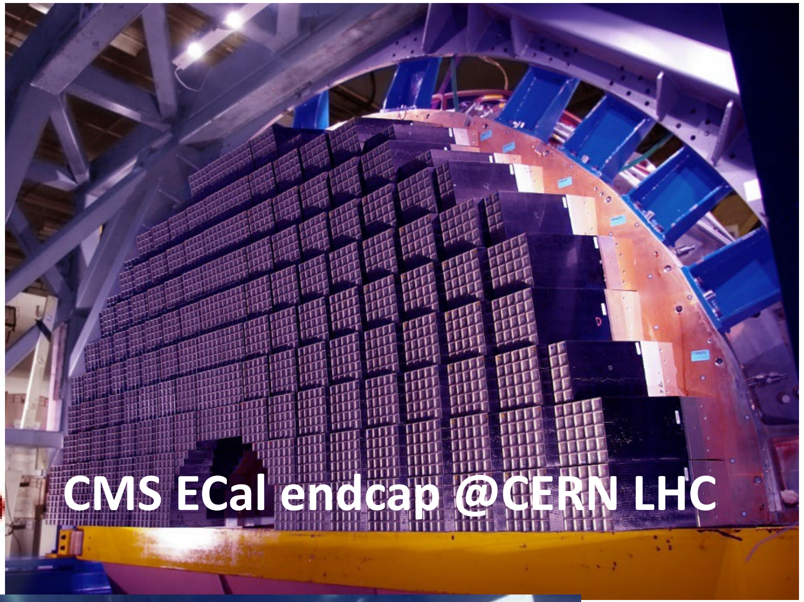
- scintillator, with well-peaked light emission in the blue
- optically transparent
- exploited by the CMS ECal → well known
- high density, high *Z* ***X_0 = 8.9 mm***
- radiation hard
- cheap fabrication into big samples and with good crystalline quality
- axes properties

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

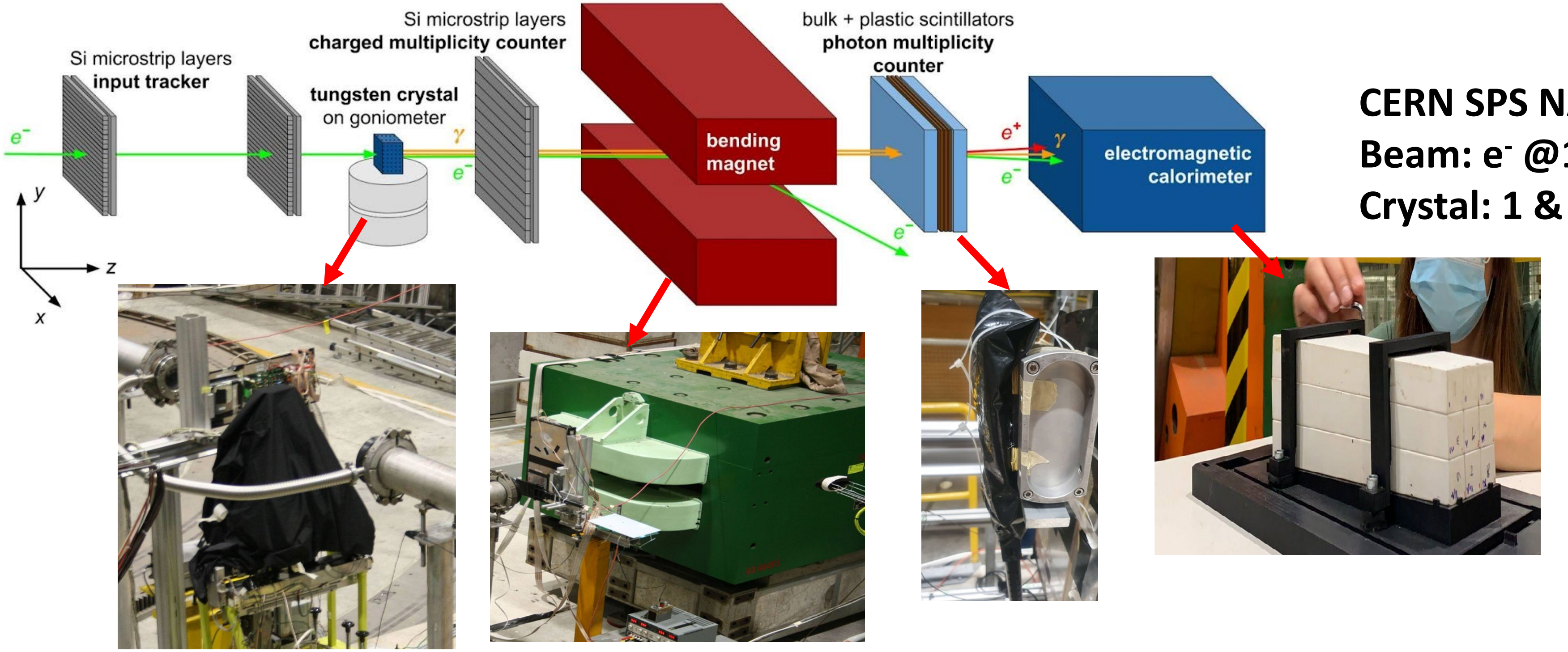
High-Z crystal for compact detectors

Maximum of Strong Field within V_0/m ≈1 mrad

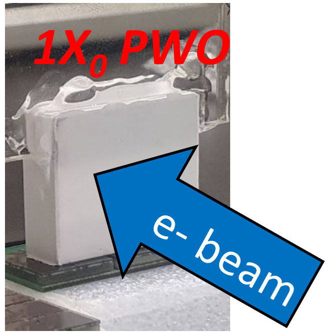


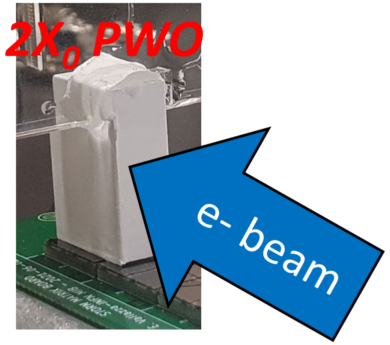


1. Test on single crystals with electrons @CERN SPS

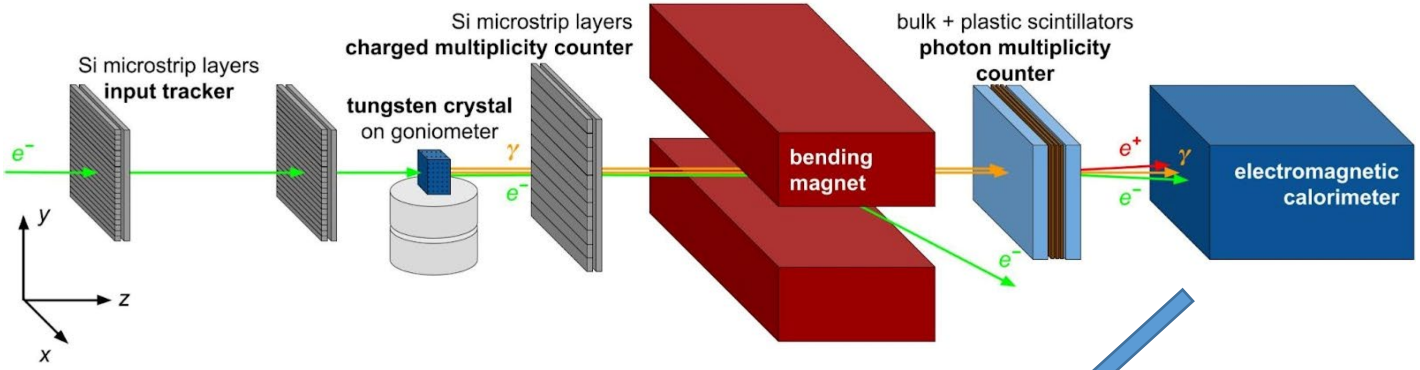


CERN SPS NA H2 beamline
Beam: e^- @120 GeV
Crystal: 1 & 2 X_0 PWO





1. Experiment & MC – calorimeter data



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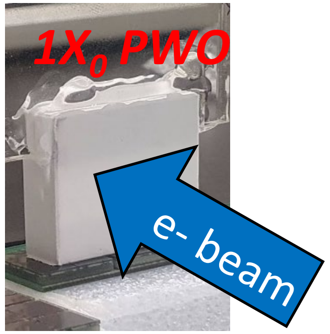
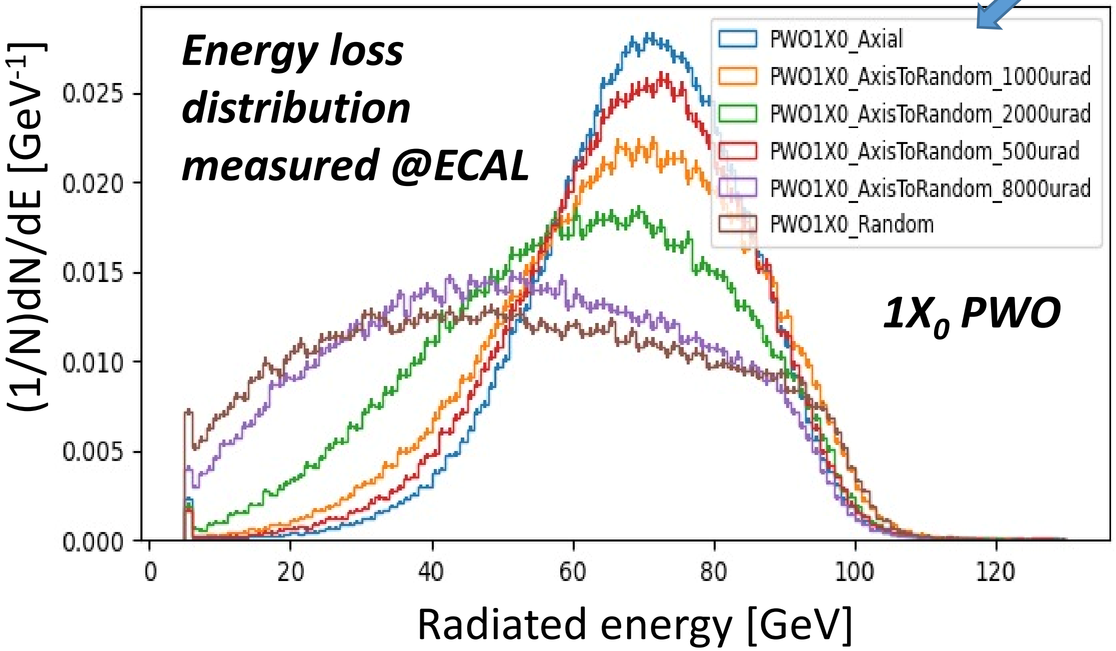
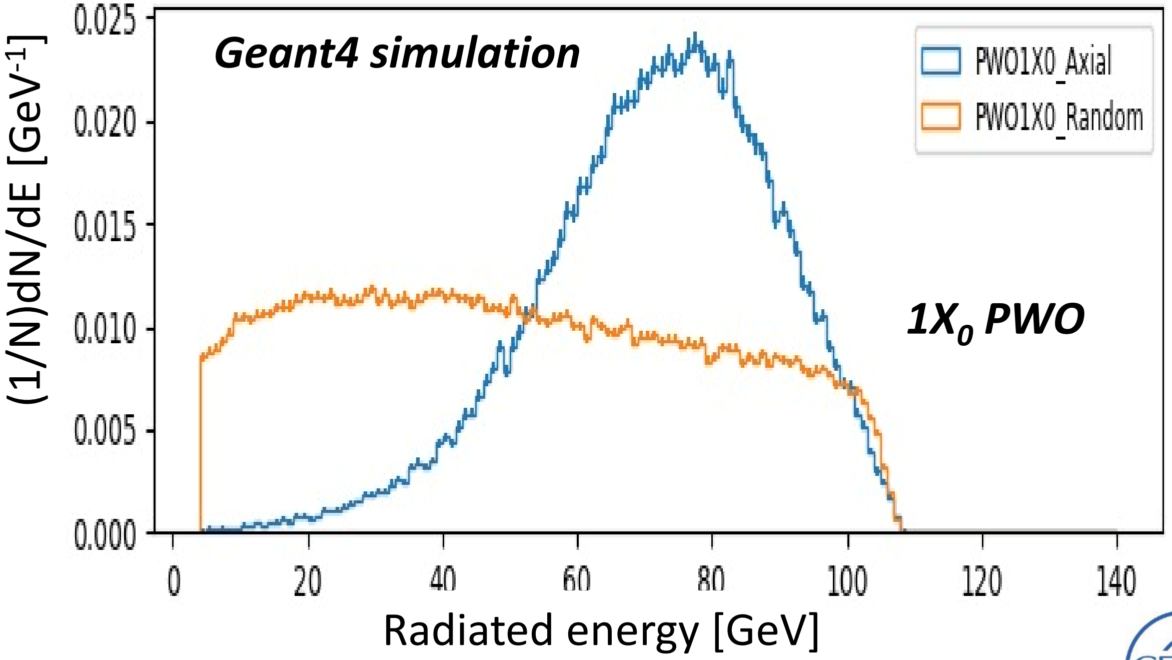


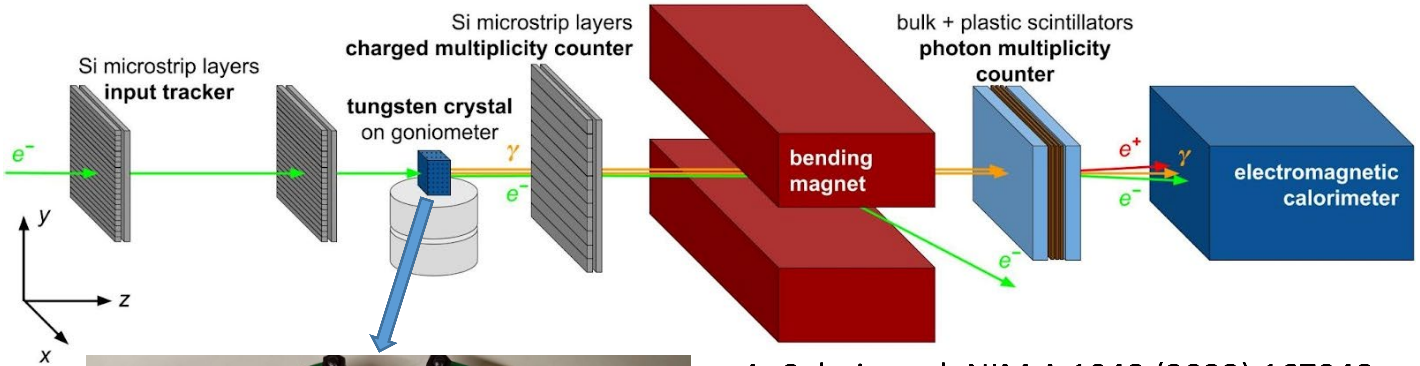


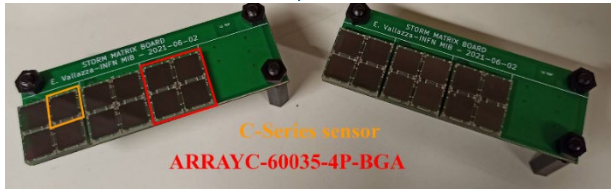


North Area H2 line

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

1. Experiment & MC – scintillation light on axis



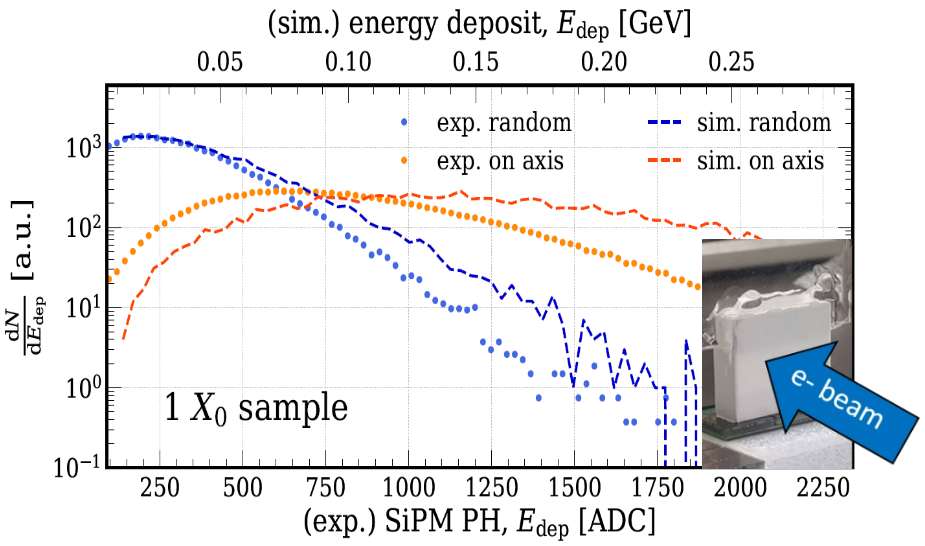


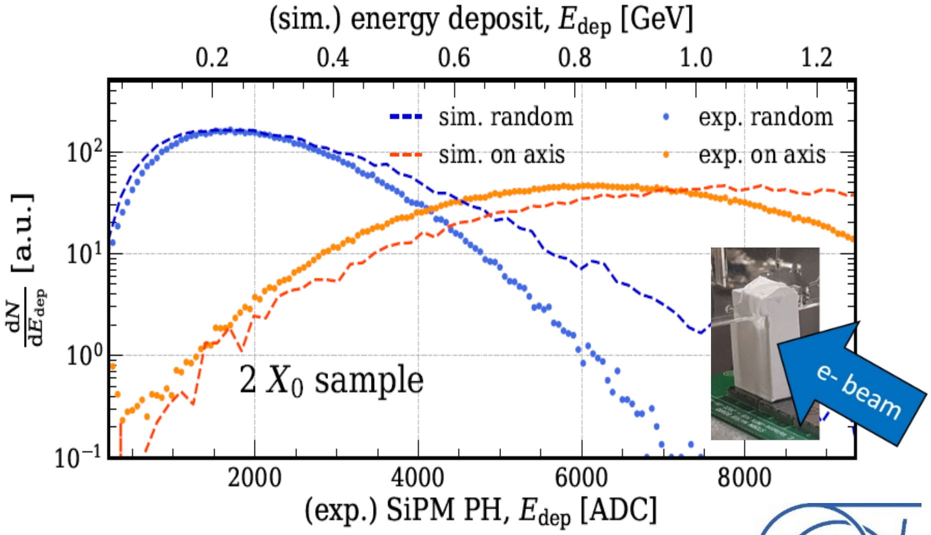
A. Selmi, et al. NIM A 1048 (2023) 167948

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	$2.923^{+0.329}_{-0.397}$	$146.17^{+16.45}_{-19.84}$	$6.091^{+0.957}_{-0.616}$	$0.684^{+0.107}_{-0.069}$

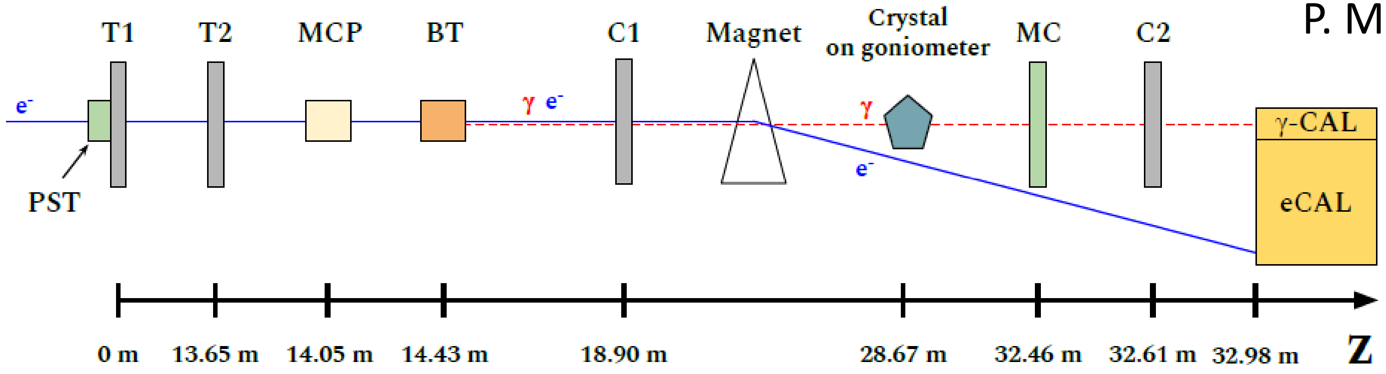
Effective thickness that a randomly oriented crystal should have to make the electrons lose the same amount of energy deposited on axis.





North Area H2 line

2. Experimental measurement with a VHE gamma beam @CERN SPS



P. Monti-Guarnieri et al., PoS ICHEP2022 (342) 414 (2022)

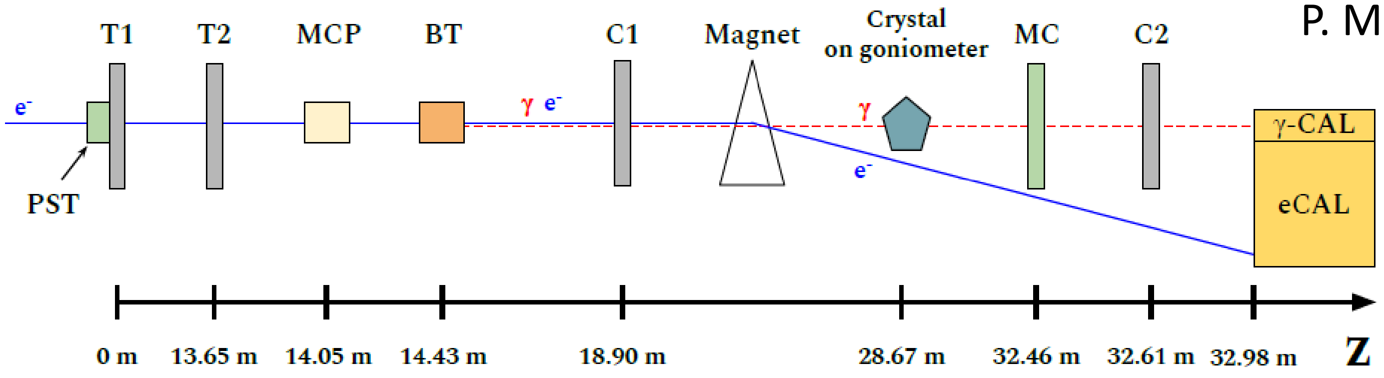
CERN SPS NA H2 beamline
Beam: γ @5-100 GeV
Crystal: 1 X_0 PWO

North Area H2 line

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

2. Experimental measurement with a VHE gamma beam @CERN SPS

P. Monti-Guarnieri et al., PoS ICHEP2022 (342) 414 (2022)



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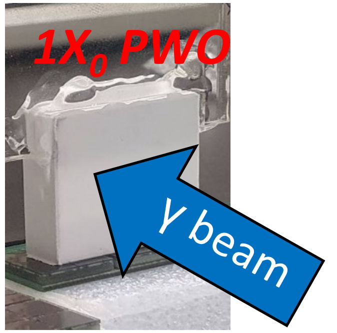
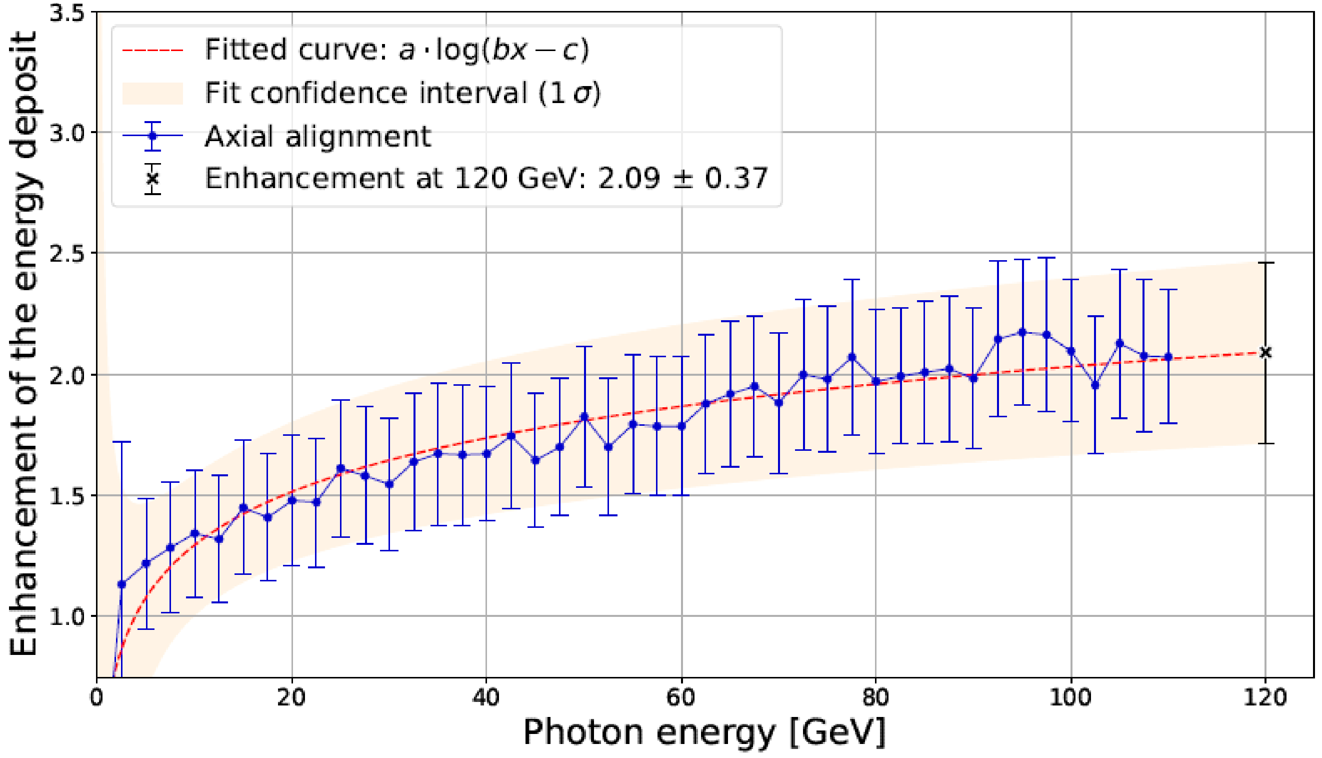




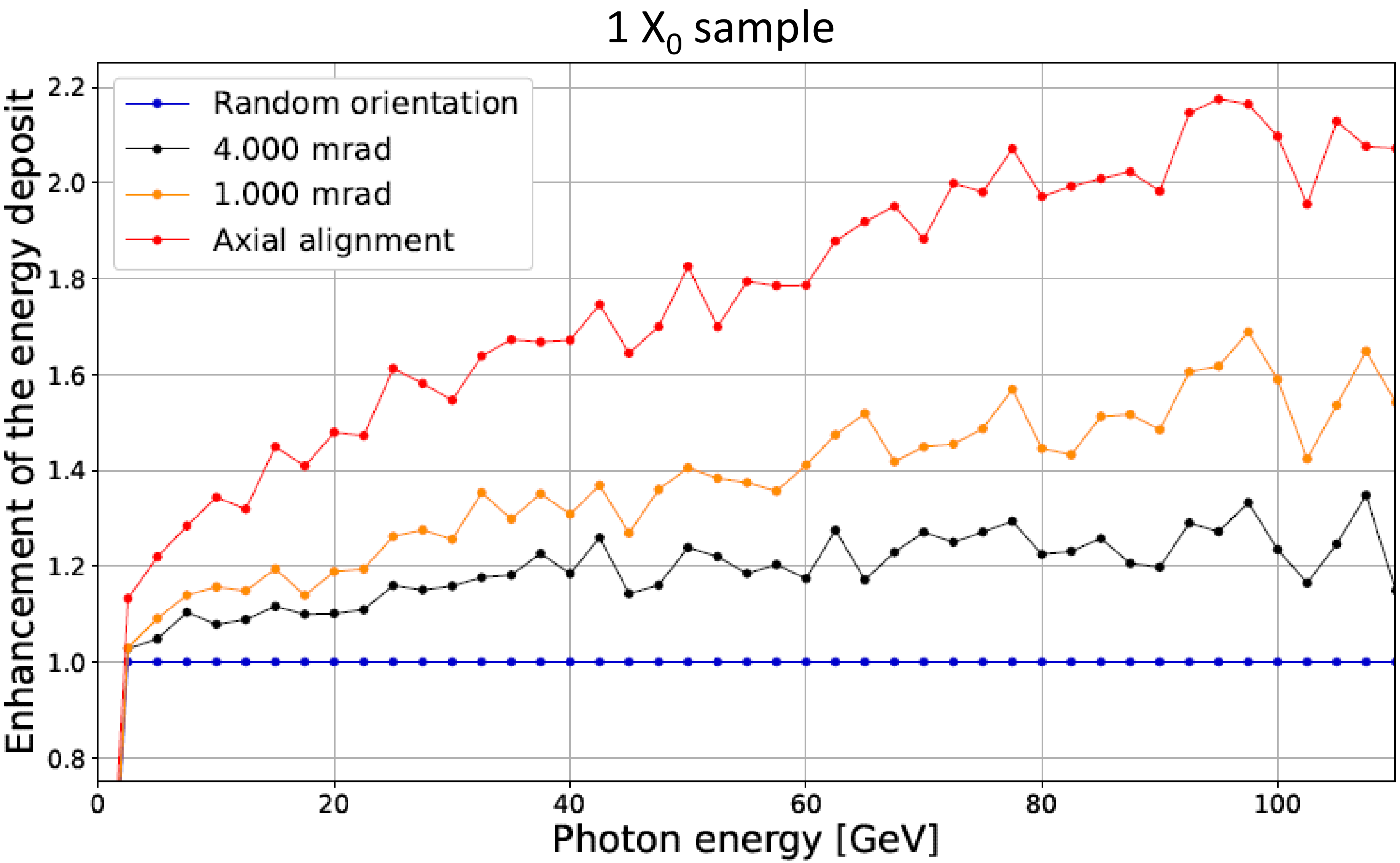
Enhancement of the energy deposited inside the crystal by the photon beam in axial orientation as measured by SiPM vs. the photon energy

Pietro Monti-Guarnieri (UniInsubria) Ms. Thesis

North Area H2 line

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

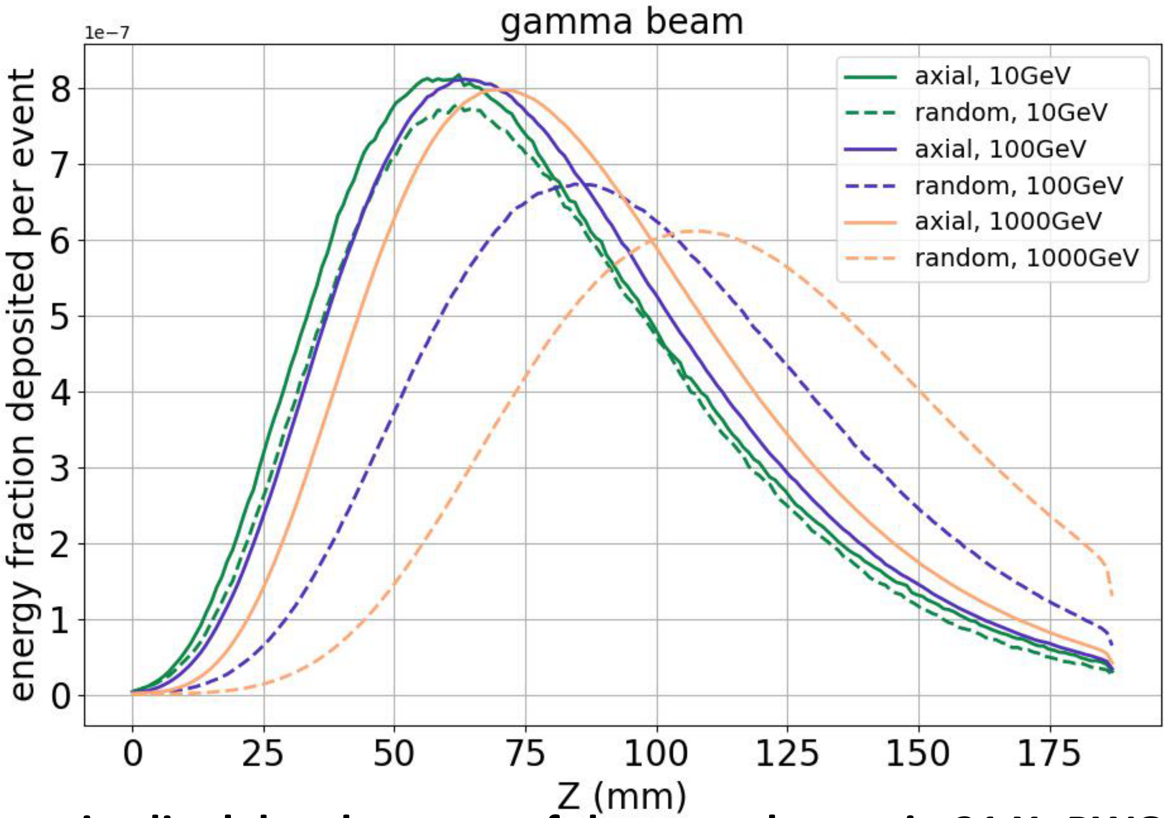
2. Angular sensitivity – Scintillation light vs. orientation & vs. photon energy



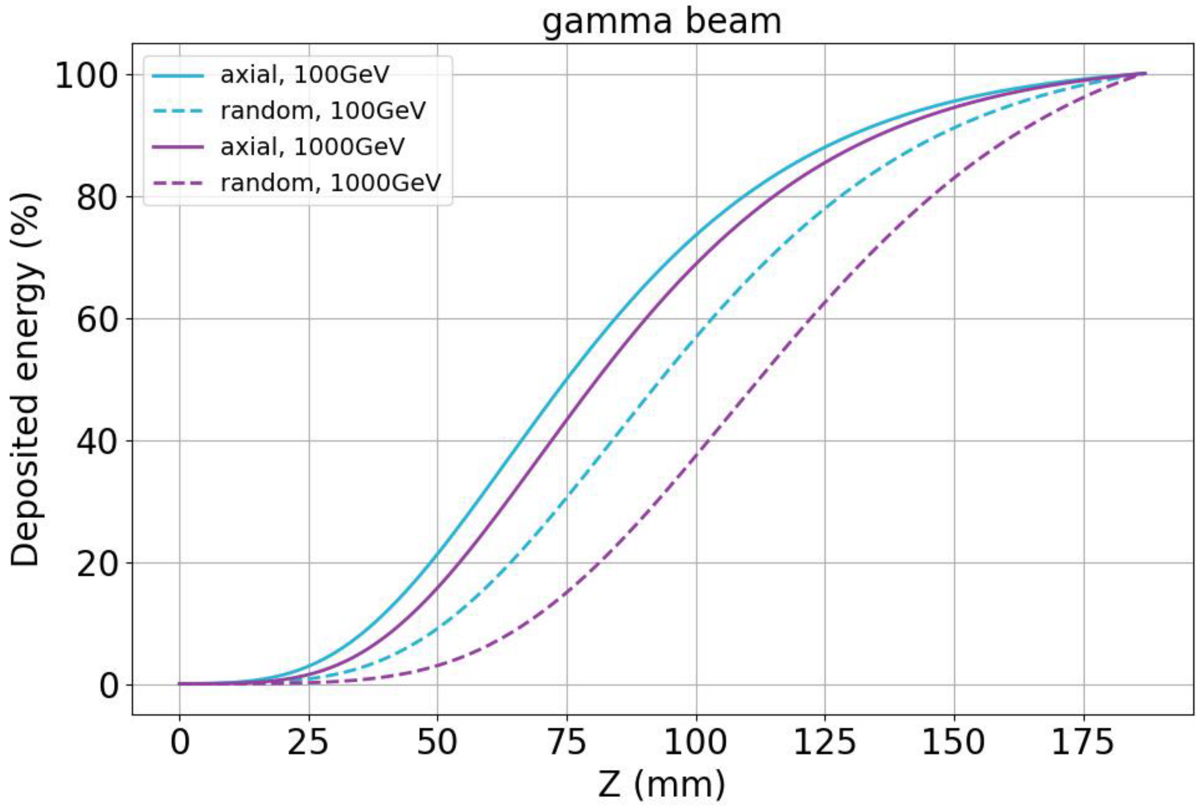
Pietro Monti-Guarnieri (UniInsubria&INFN MiB) Ms. Thesis

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

Geant4 Simulation of VHE gamma-ray e.m. shower



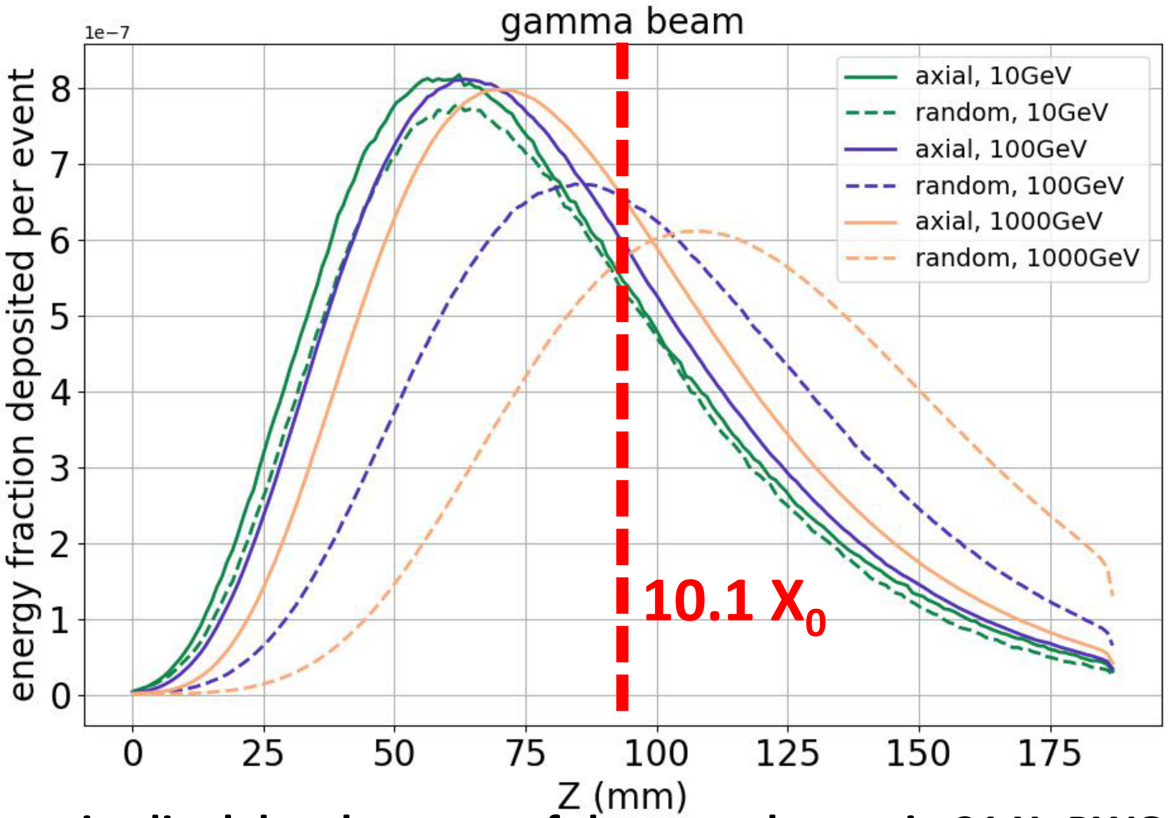
Longitudinal development of the e.m. shower in 21 X_0 PWO axial vs. random



Total energy deposited by the gamma-ray vs. crystal depth axial vs. random

note: the higher the particles energy, the stronger the shower enhancement, →
the shower peak longitudinal position remains closer to the front face of the crystal even at higher energies

Geant4 Simulation of VHE gamma-ray e.m. shower



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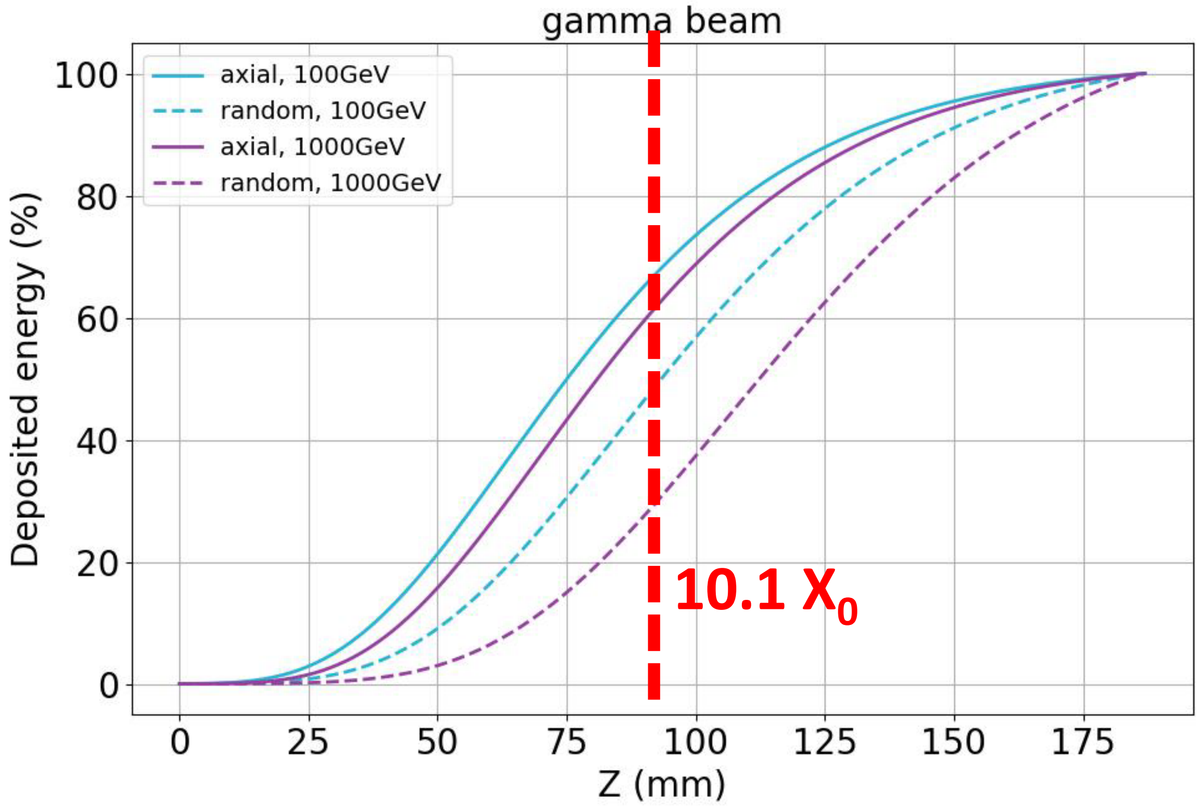
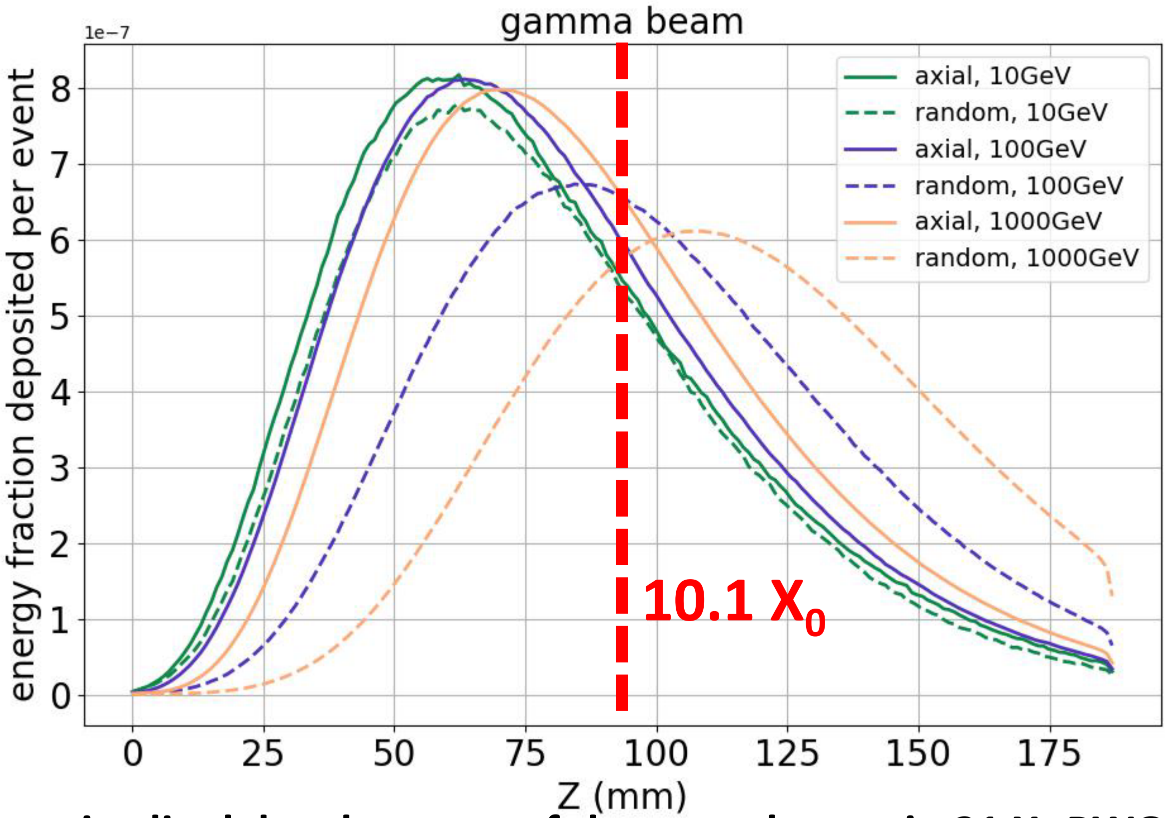


Total energy deposited by the gamma-ray vs. crystal depth axial vs. random

note: The shower maximum is well contained in 10.1 X_0 (total Fermi-LAT length) even for the 1 TeV case, with more than 60% of deposited energy!

Geant4 Simulation of VHE gamma-ray e.m. shower



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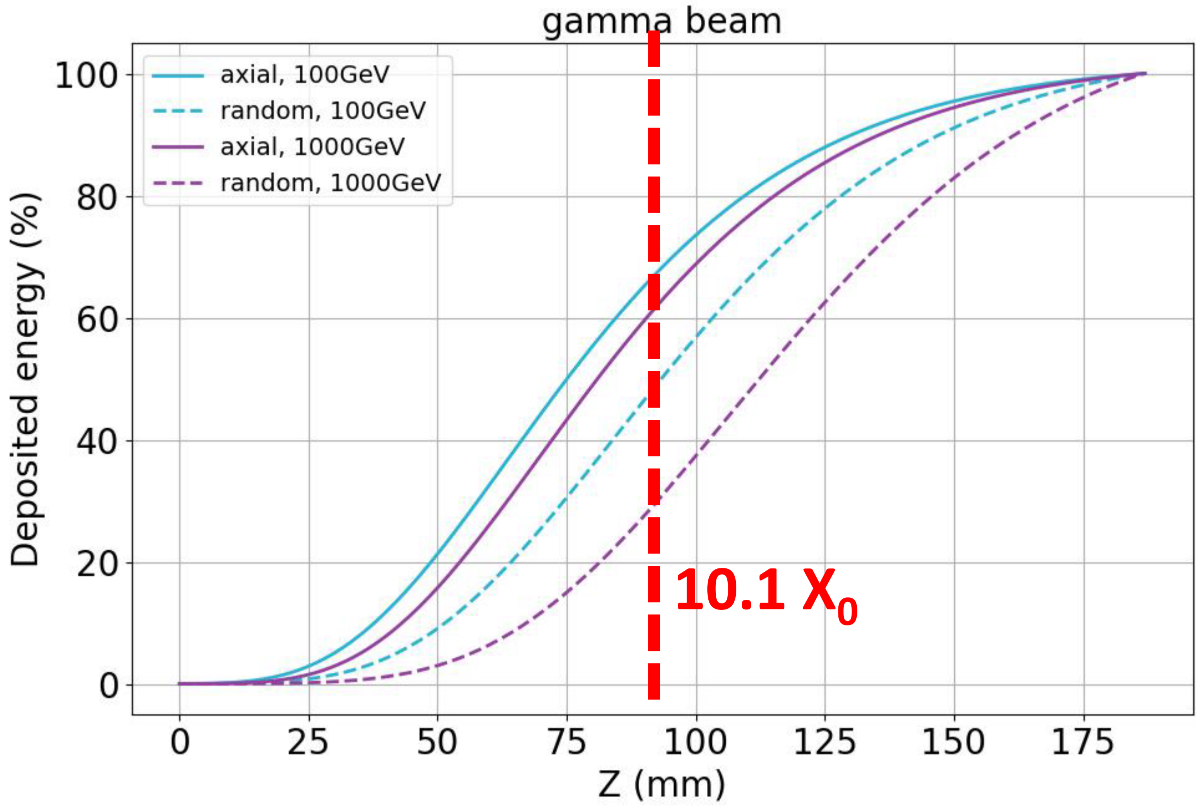

Total energy deposited by the gamma-ray vs. crystal depth axial vs. random

- **A much better containment of the e.m. shower above 100 GeV.** For instance, in the 100-300 GeV range, where either Fermi-LAT or CTAs will not reach their highest performances in energy resolution.
- **Possibility to increase the area of the detector**, while maintaining a **compact volume/weight**!

… And what about the tracker-converter system?

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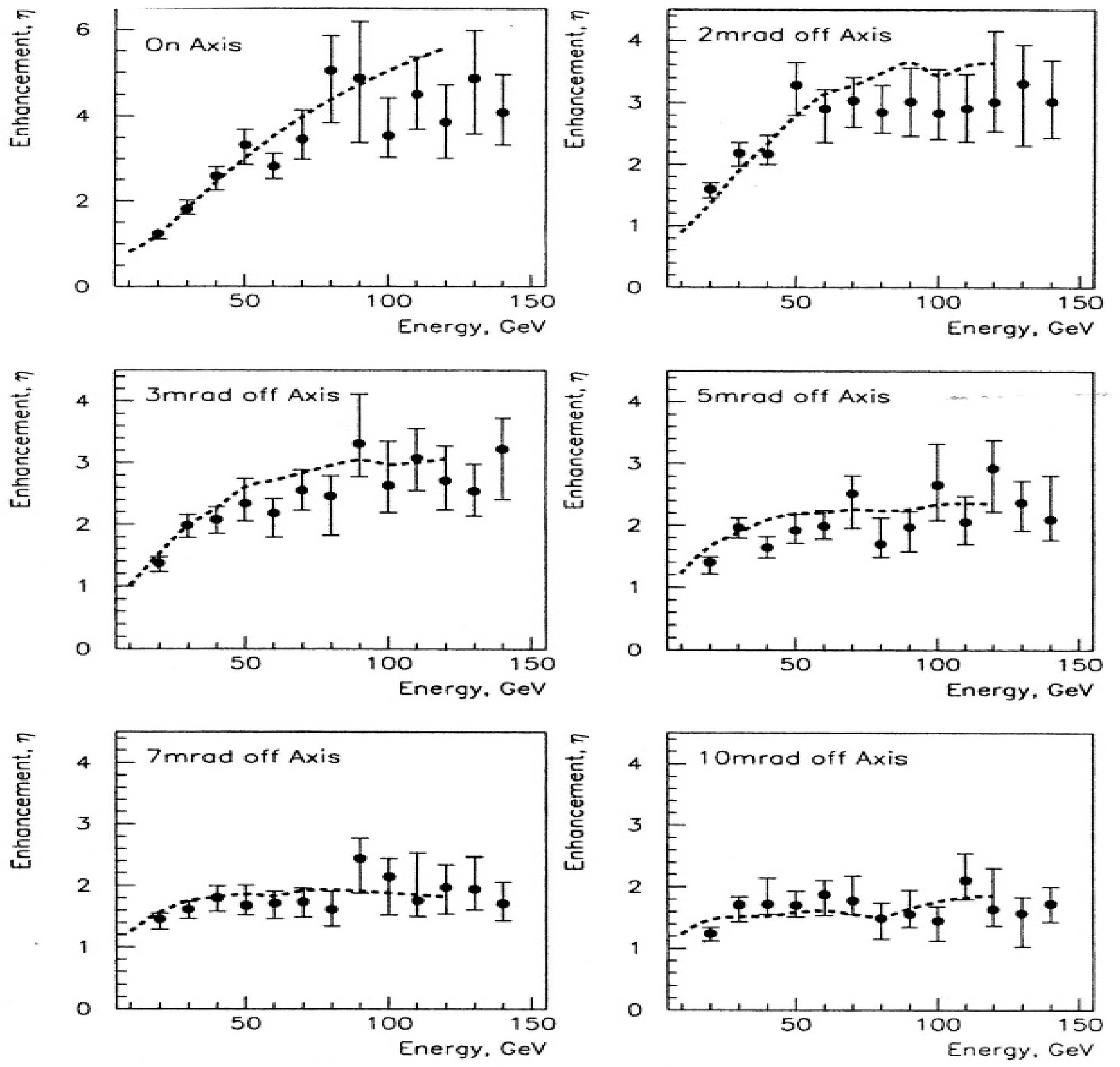


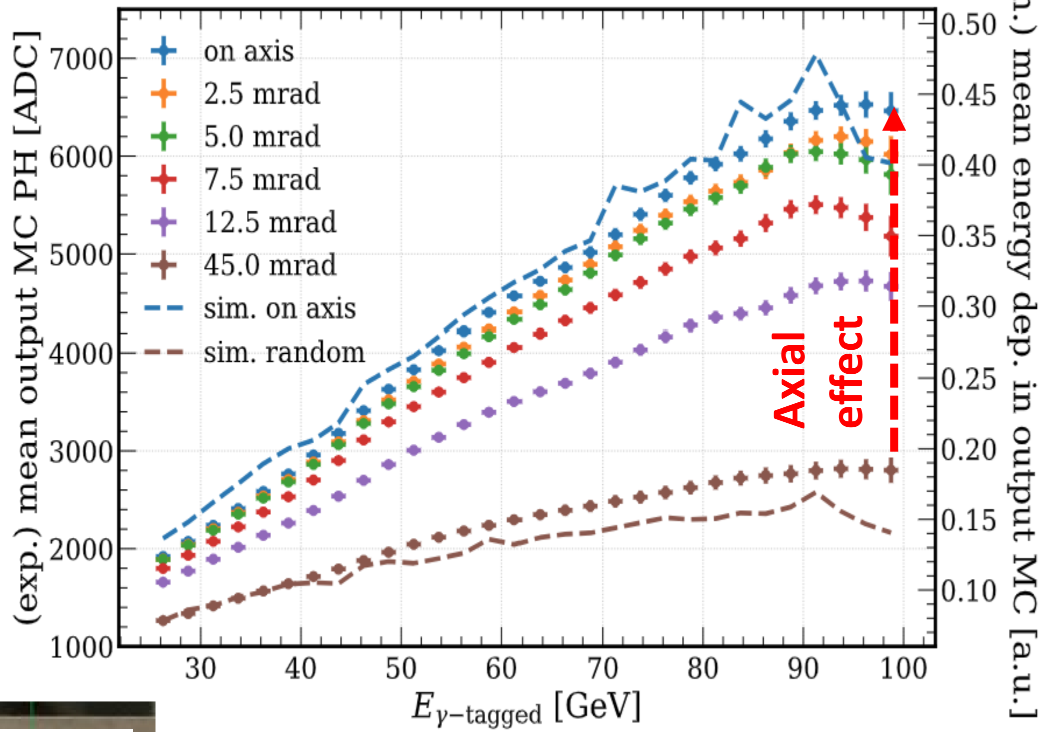
R. Moore et alm Nuclear Instruments and Methods in Physics Research B 119 (1996) 149-155

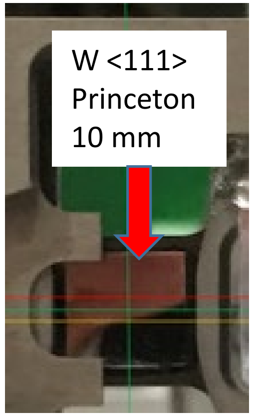
NA48 exp. @CERN with 1 X_0 W <111> crystal

- **The gamma conversion in pairs in an aligned W crystal increases with photon energy**
- The enhancement is maximal in the case of axial alignment and diminishes as the misalignment between the gamma direction and crystal axes increases.
- **A measurable enhancement is visible up to 0.6°**

… And what about the tracker-converter system?

*Energy deposited in a plastic scintillator after the crystal (i.e. **the pair production enhancement**)*





CERN SPS H2
e- beam energy: 120 GeV
Bremsstrahlung photons: 25-100 GeV
Crystal: W <111>, 10 mm long (~2.85 X_0)

INFN STORM experiment vs. Geant4 simulation

- **The gamma conversion in pairs in an aligned W crystal increases with photon energy**
- The enhancement is maximal in the case of axial alignment and diminishes as the misalignment between the gamma direction and crystal axes increases.
- **A measurable enhancement is visible up to 0.7°**

M. Soldani, L. Bandiera, M. Moulson et al., Eur. Phys. J. C 83, 101 (2023)

… Pointing the tracker-converter system?

In case of pointing gamma sources within 0.5°-1°, one may **substitute the W amorphous foils with crystalline W**, leading to:

- **Possible reduction of tracker length**, while maintaining or **even increase the sensitivity to gamma with E > few GeV**

- **Pair production enhancement possible also for Silicon and for lower energy photons (hundreds of MeV) in case of off-axes orientation due to Coherent Pair Production**

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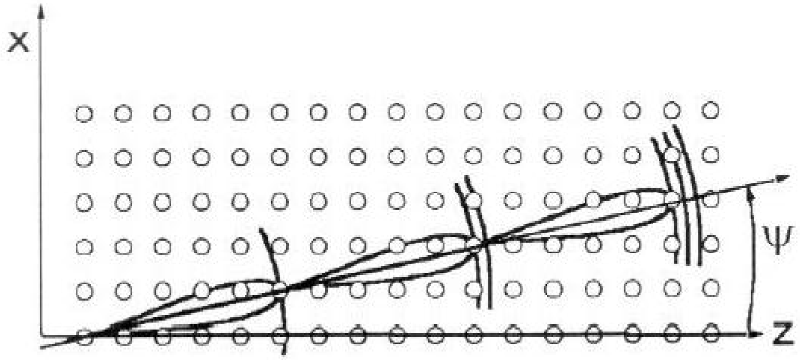
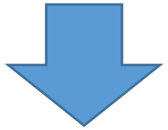
Interference of pair production on different atomic strings gives rise to pair production enhancement.

G. Diambrini Palazzi, Rev. Mod. Phys. 40 (1968) 611





<u>**Possible application in smaller satellites (CubeSat?)**</u>

… Why not using active scintillator crystals also in the tracker-converter system?

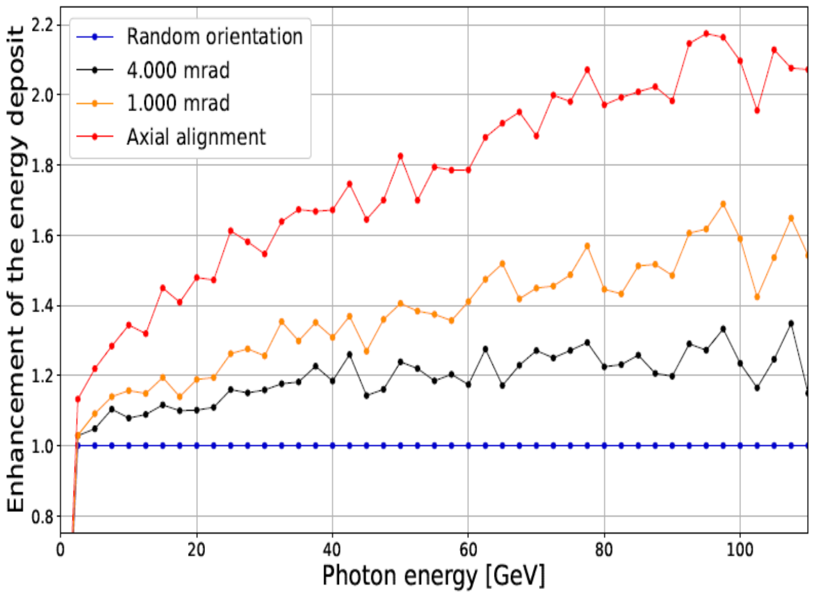
One may exploit the crystal anisotropy to:

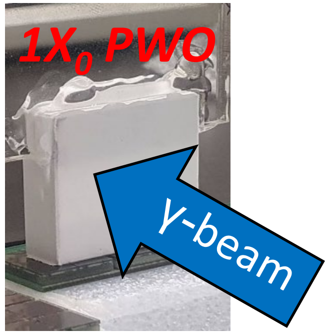
- Increase the sensitivity in one direction (better signal-to-background)
- Improve the e.m. shower containment

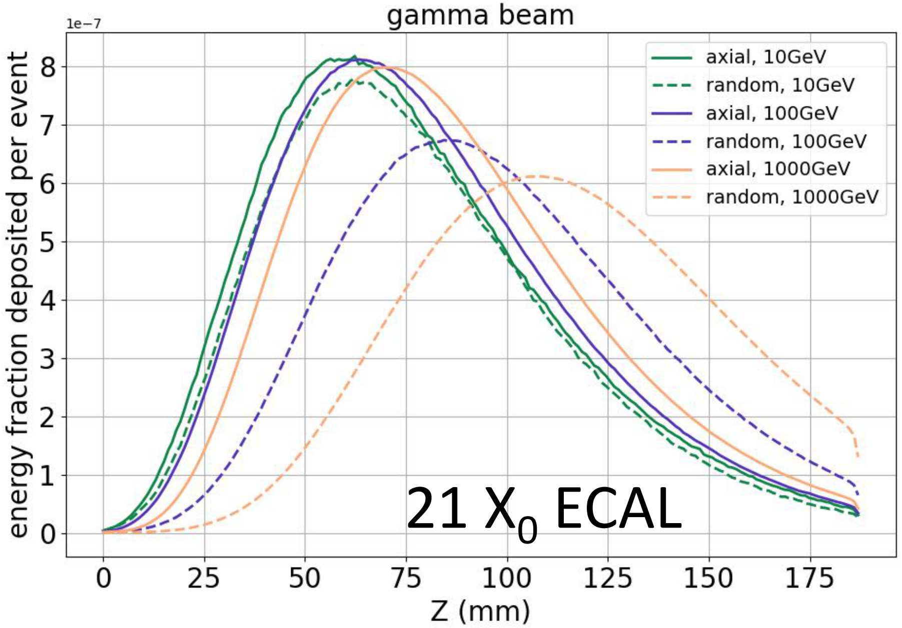
… Why not using active scintillator crystals also in the tracker-converter system?

One may exploit the crystal anisotropy to:

- ➢ Increase the sensitivity in one direction (better signal-to-background)
- ➢ Improve the e.m. shower containment
- ➢ **Have a good angular resolution with no need of a complex system**

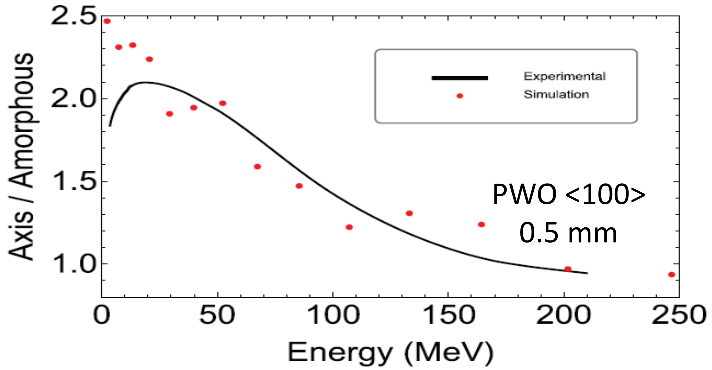


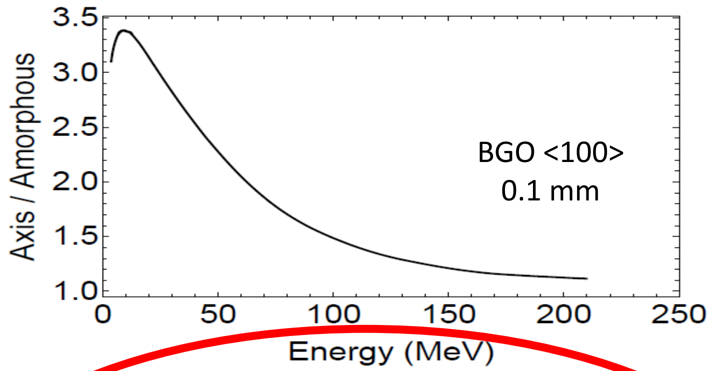


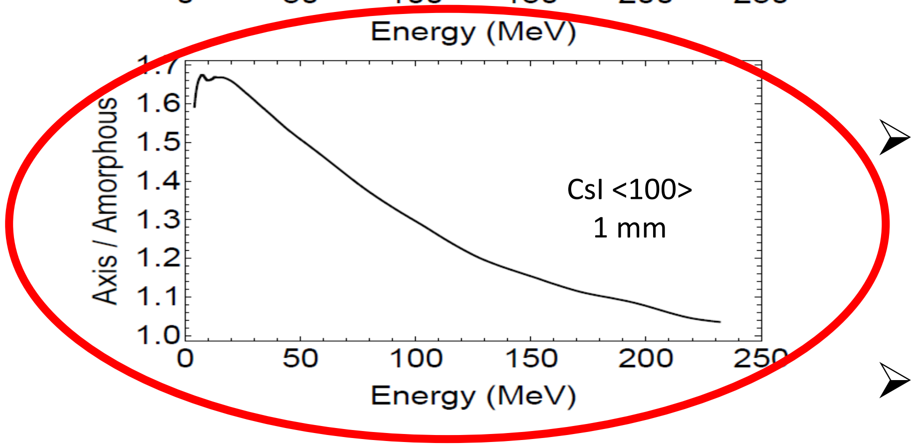


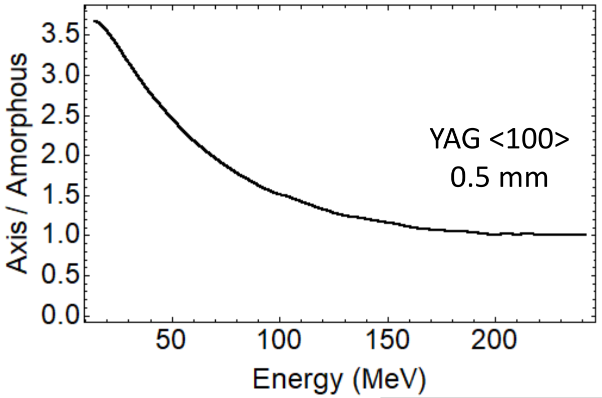
- ➢ **Shower acceleration is maximal within 1 mrad (0.05°) and at tens of GeV the shower longitudinal shape in axial orientation is very different w.r.t random case.**
- ➢ **A segmented ECAL (+ a simple preshower) to know either the energy and the direction of the photon (within 0.05° for PWO).**

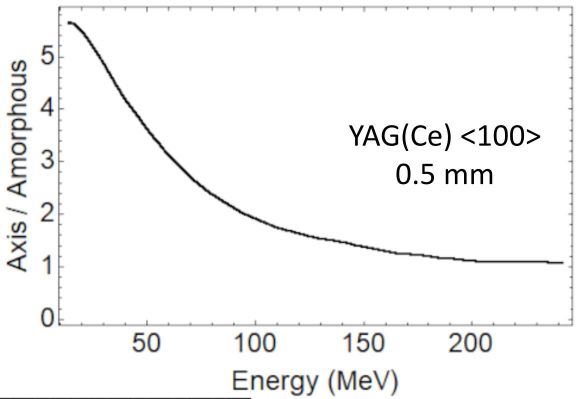
Just to mention: electromagnetic processes are modified not only in PWO..

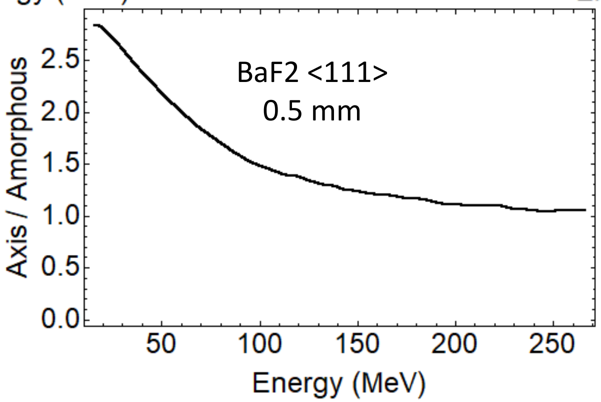












- Bremsstrahlung radiation enhancement in axial orientation in the [0, 150] MeV range (e- beam @855 MeV – below Strong Field threshold), which **indicates an enhancement of the electromagnetic processes inside the axially oriented crystals.**
- **INFN CSN5 ELIOT/STORM experiments: First measurements ever of radiation enhancement** due to coherent orientational effects for all these **scintillator crystals (PWO, BGO, CsI, YAG(Ce), BaF2)**.

Summarizing

The idea of an oriented crystals based satellite may be useful in future missions…

- To **increase the sensitivity** in the pointing direction above few GeV
- To **improve the shower containmen**t up to TeV and more **-> cost reduction!**
- To **increase the detector area** with a reduced volume
- To improve the **angular resolution** exploiting **crystal anisotropy**

N.B. Even if such an apparatus would be preferably designed for pointing strategy, it will continue to operate in the standard way in the absence of pointing

Possible applications in astrophysics

- Several fields of the astrophysics could be explored with such an apparatus:
  - **pointing of the galactic center for the dark matter decay lines** detection (Milky way or dwarf galaxies*).
    - Crystal anisotropy would help to increase signal-to-background and to improve the angular resolution to **discriminate point sources (e.g., pulsars..) from dark matter halo**
  - **observation of unidentified Fermi gamma-ray sources**;
  - **follow-up** of flaring/transient and multimessenger sources;

- The enhancement of pair production efficiency become substantial above few GeV and in the near future with the new IACTs observatories a more efficient coverage in that energy range become fundamental for joint strategy of observation.

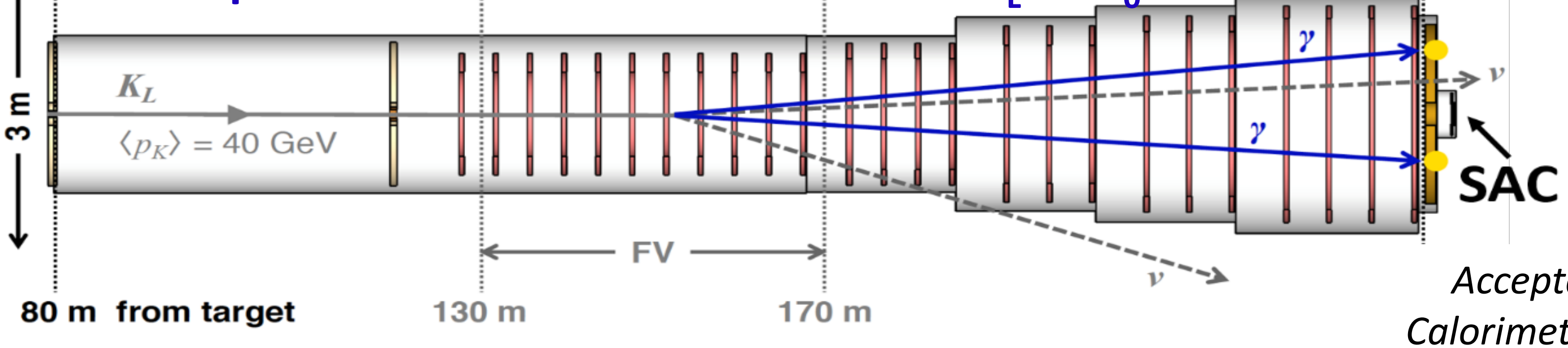
*** See R. Gaitskell's next talk**

…. And much more

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 (e.g. for the HIKE experiment at CERN - ongoing)
- in **dark matter search**, to realize compact active beam dump with an increased sensitivity to light dark matter, such as dark photons etc…

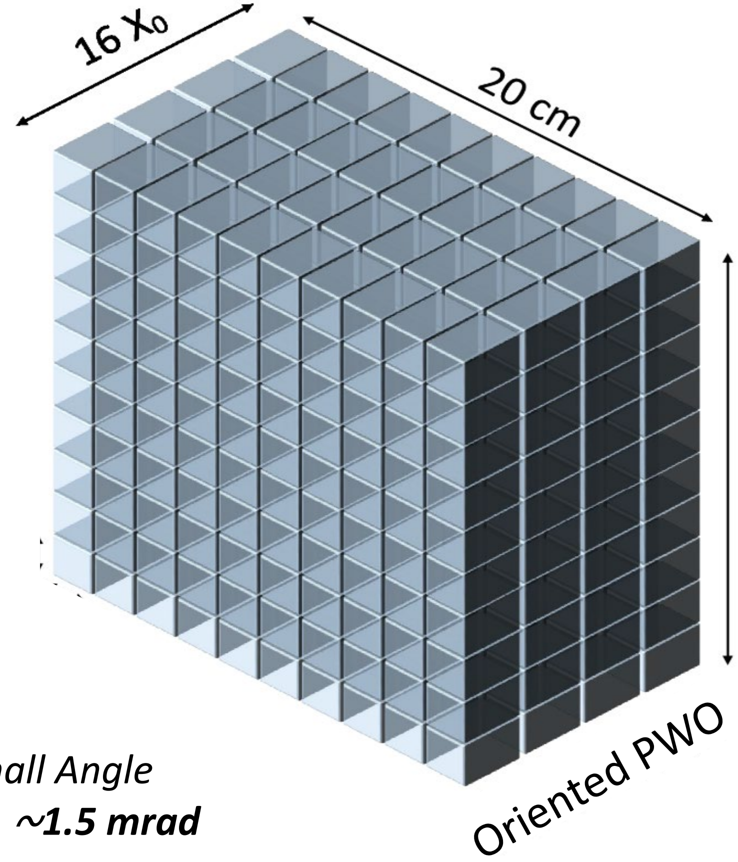
HIKE experiment at CERN SPS to measure $K_L \rightarrow \pi_0 \nu\nu$



Technological fallout

- Our study also envisages **to investigate the variation of the light yield of scintillator crystals as a function of their crystallographic quality and orientation**

High Intensity Kaon Experiments



*Acceptance Small Angle Calorimeter (SAC) ~**1.5 mrad***

…. And much more

Particle Physics

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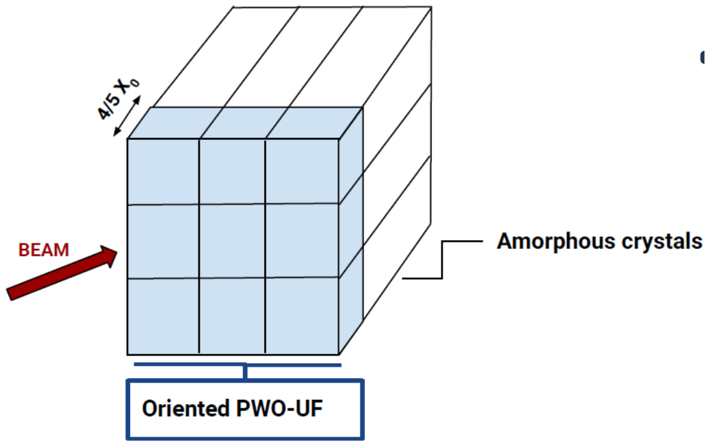

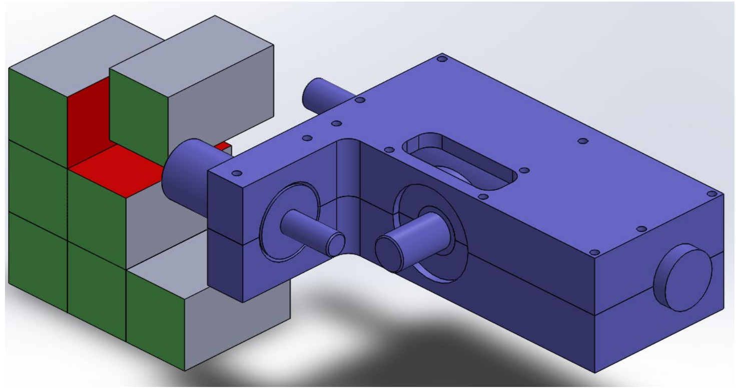

Technological fallout

- Our study also envisages **to investigate the variation of the light yield of scintillator crystals as a function of their crystallographic quality and orientation**

Challenge:
- Construction of an oriented layer of many crystals

- **A prototype for HIKE SAC and HEP calorimeters is under construction**
- **We believe the technology ready for application in gamma-ray astronomy !**

Contribution to the presented ideas

INFN OREO team: L. Bandiera, N. Canale, S. Carsi, V. Guidi, A. Mazzolari, P. Monti Guarnieri, R. Negrello, G. Paternò, M. Prest, M. Romagnoni, A. Selmi, M. Soldani, A. Sytov, E. Vallazza

FERMI-LAT people: S. Cutini, F. Longo, M. Di Mauro

Other: R. Gaitskell and S. Koushiappas (Brown University); Kihyeon Cho (KISTI); V. Haurylavets and V. Tikhomirov

Contact: L. Bandiera, INFN Ferrara – bandiera@fe.infn.it

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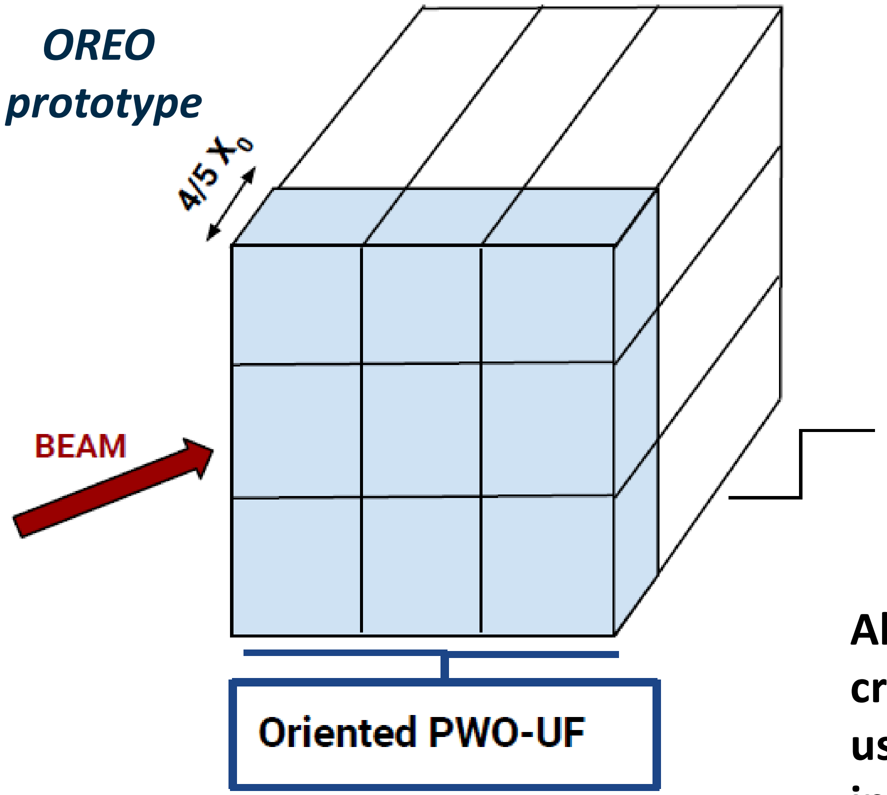
Thank you for your attention!

BACK UP

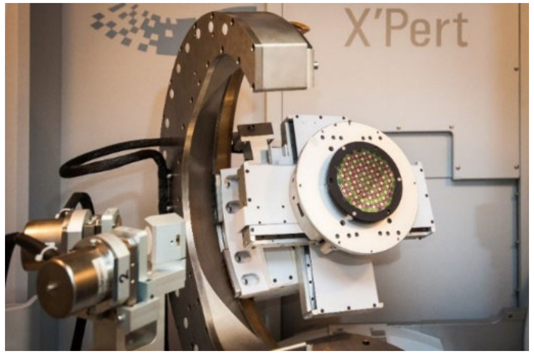
The *OREO* prototype

Challenge:
- Construction of an oriented layer of many crystals

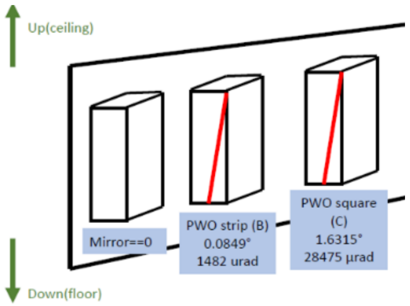
OREO prototype

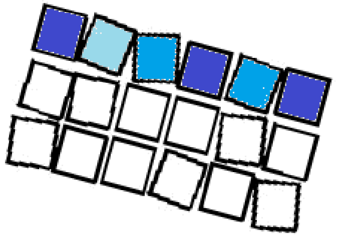


Amorphous crystals

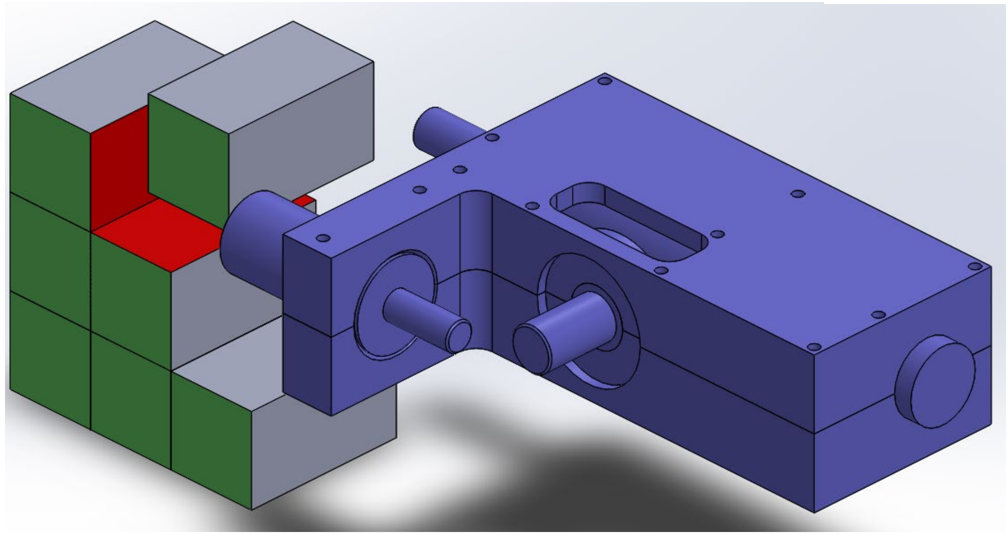


HR-XRD measurement of
- ***Miscut angle***
- ***Crystal mosaicity***

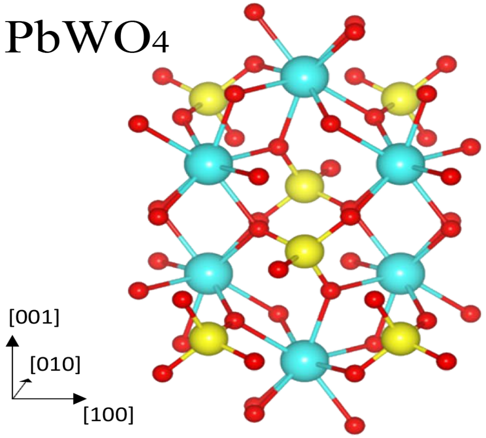


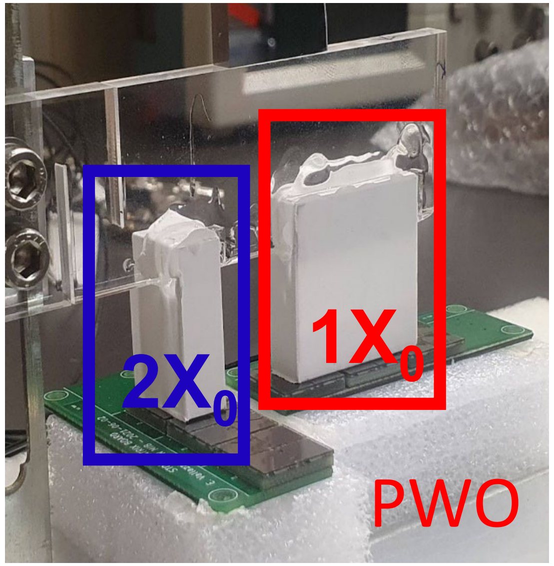


Alignment of one crystal to another using laser interferometry



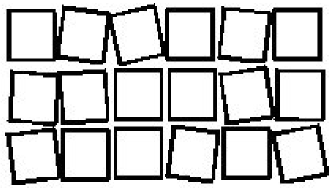
Characterization of Lead tungstate ($PbWO_4$)



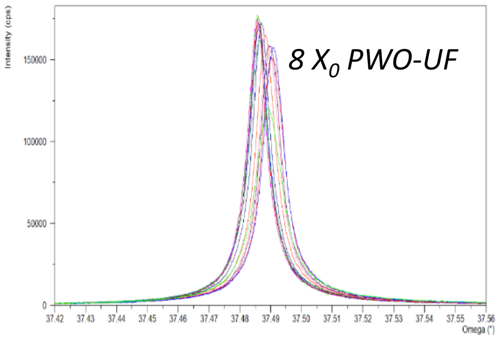


PWO: Superficial X-ray characterization

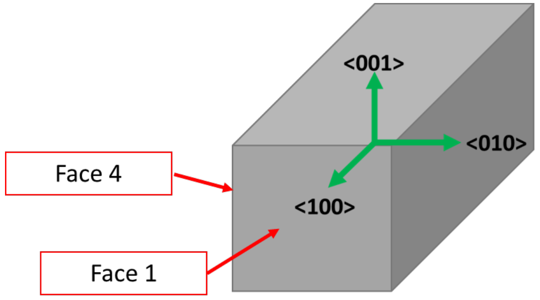
surface mosaicity and crystal orientation

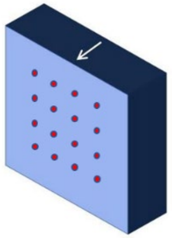


- mosaicity ≤ 0.1 mrad;
- axis alignment on different position changes of < 0.2 mrad << V_0/m



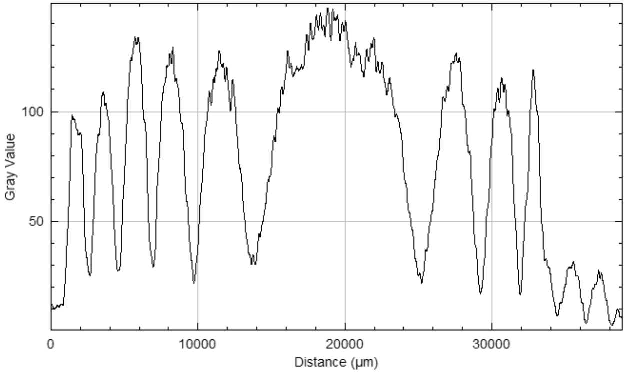
PWO: In depth photoelastic conoscopy





typical fringe patterns are observed and are related to the crystal condition

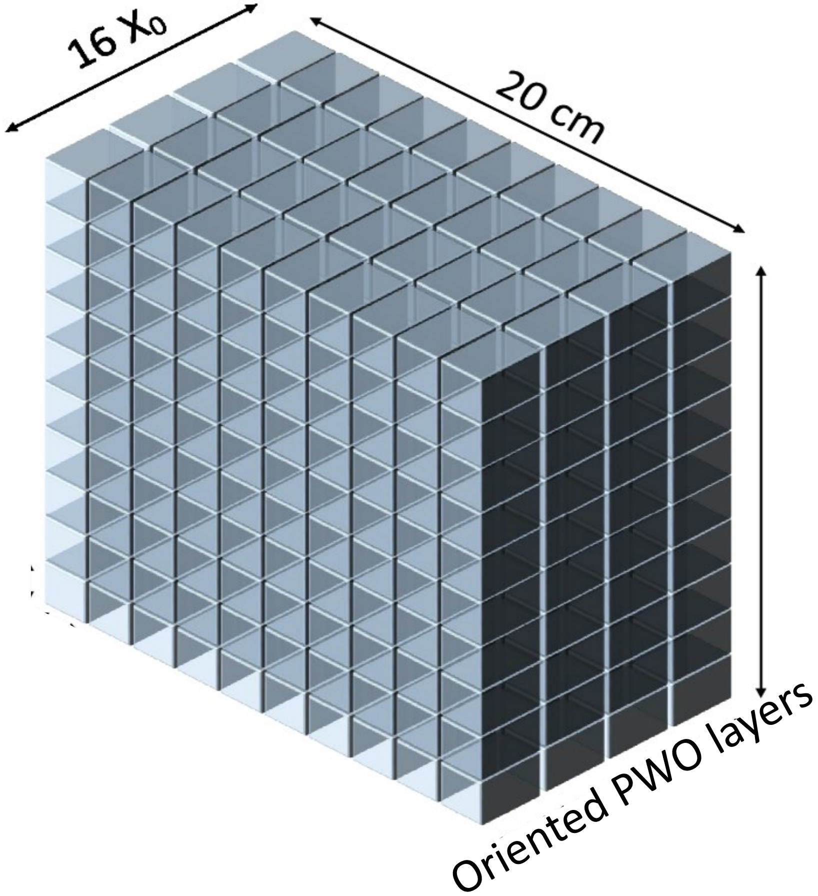
the misalignment on the whole surface is less than about 100 μrad in **agreement with XRD data** !



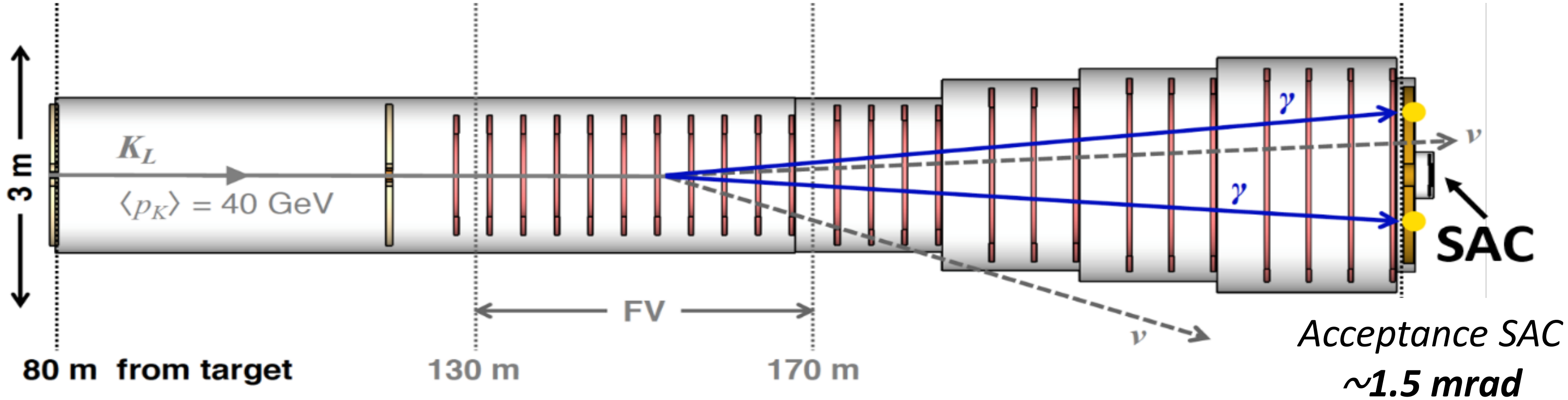
Work done in collaboration with UNIPVM

3. Small Angle E.M. Calorimeter

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



KLEVER is a proposed experiment at **CERN SPS** to measure $K_L \rightarrow \pi_0 \nu\nu$



Acceptance SAC
~1.5 mrad

The SAC should:

- ✓ **reconstruct the 2 γ 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!
- ✓ **insensitivity to more than 500 MHz of neutral hadrons** in the beam.

Best solution for the KLEVER SAC:

- **X_0/λ_{int} smallest possible -> make it ultra-compact!**
- Excellent time resolution: Ultrafast PWO* **->** make it ultra-fast!

*Scintillation decay decreased down to the subnanosecond (0.7 ns)
M. Korjik et al., NIM A, 1034 (2022) 166781

OREO - ORiEnted calOrimeter
2023-2024 project financed by INFN