Compact Calorimeters with Oriented Crystals

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Motivation

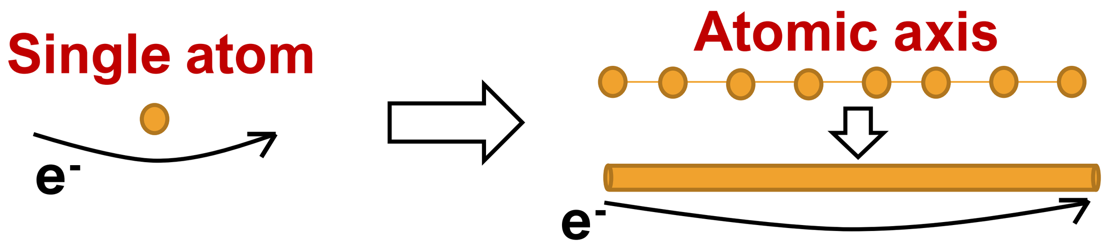
Despite high-Z scintillators are largely used to build e.m. calorimeters, the influence of their crystal lattice on the e.m. shower formation is usually completely ignored both in the detector design and simulations. Nevertheless, it has been known since decades that the lattice structure of a crystal may strongly influence the e.m. processes, which may results in a strong decrease of the shower length. The usage of oriented scintillator crystals in e.m. calorimeters would permit thus to reduce the amount of material necessary to build the detector, a possibility from which HEP and astrophysics experiments could benefit from.

Strong electromagnetic field in crystals

For small angle between charged particle trajectory and crystal axes/planes direction, it is possible to replace the Coulomb potential of each atom with an average continuous potential of the whole plane/string (see Fig. 1), corresponding to a strong electrostatic field $E \sim 10^{10} - 10^{12}$ V/cm [1].

At energies of some GeV, **the continuous axial field** felt by a particle in its rest frame is enhanced by a factor γ because of the Lorentz contraction, thus **becoming comparable to the Schwinger critical field of QED, $E_0 = m^2c^3/e\hbar = 1.32 \cdot 10^{16}$V/cm**, which can be reached for instance in pulsar atmosphere.

Figure 1



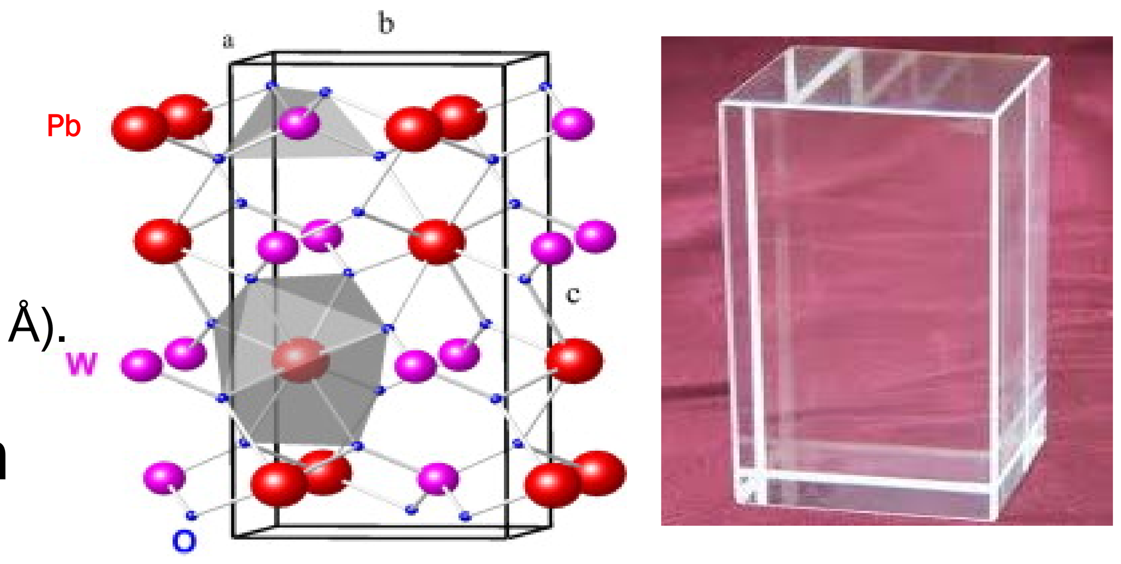
The interaction with the strong field of a crystal axis leads to enhancement of pair production and bremsstrahlung, thus reducing X_0 and thereby the e.m shower length as compared to a randomly oriented crystal or amorphous material.

Radiation Length Reduction in an axially oriented PWO crystal

L. Bandiera et al, ArXiv: 1803.10005

Figure 2
$PbWO_4$ scintillator crystal lattice: Scheelite type structure (tetragonal, a=b=5.456, c=12.020 Å).

X_0 standard = 8.9 mm



Experiment at CERN SPS H4 beamline with 120 GeV/c electrons

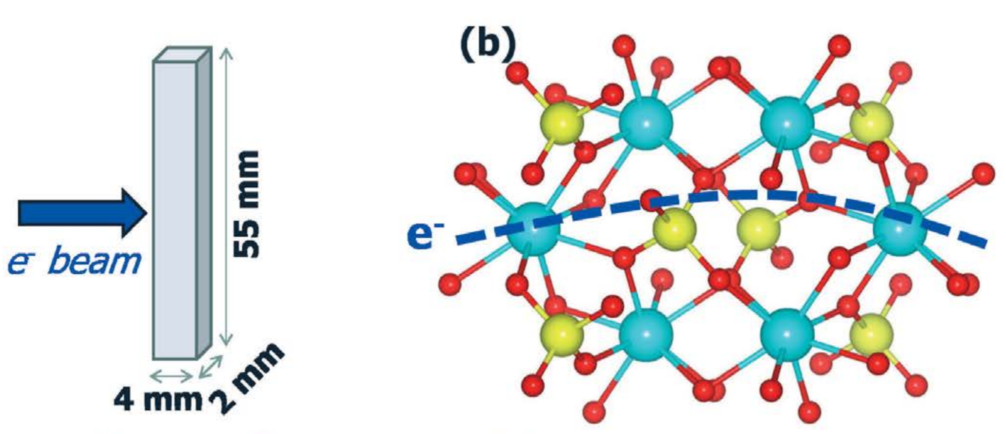
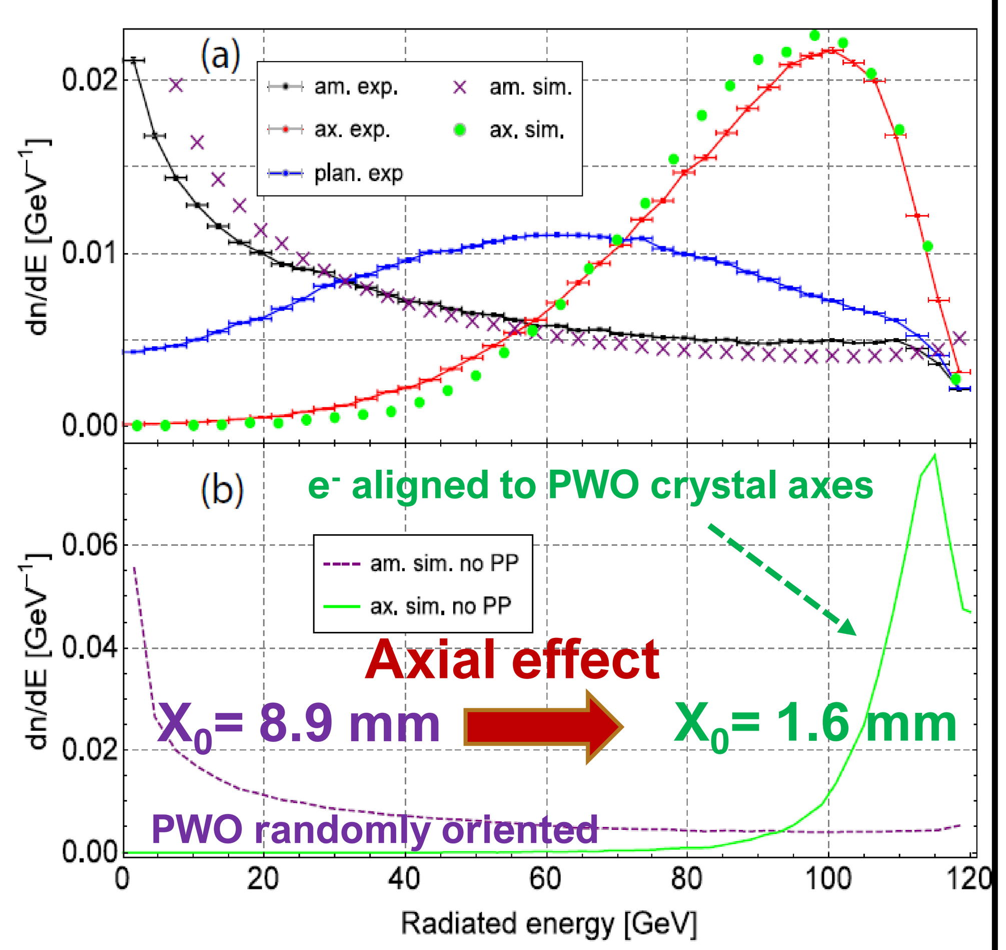


Figure 3
Orientation of the crystal with respect to the 120 GeV/c electron beam. The used crystal was 4 mm (0.45 X_0) along the beam direction and parallel to [001] axes.

Figure 4

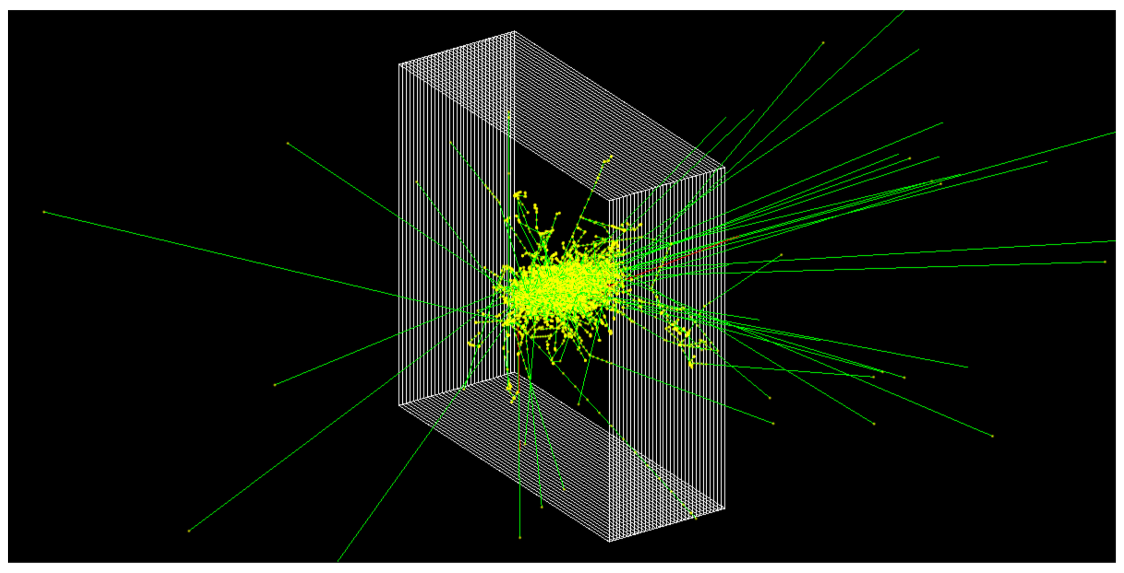
(a) The experimental [1] and simulated radiated energy distributions under axial **alignment within some mrad** (ax. exp and sim.) and when the beam is misaligned (am. exp and sim) with respect to the [001] axes, i.e. as for an *amorphous* material. **The radiated energy is much harder for axial than for random orientation.**

(b) Simulation [2] for pure bremsstrahlung in amorphous (purple) and axial (green) orientation. **In axial case, X_0 is decreased from 8.9 to 1.6 mm.**



GEANT4 modified simulation for a PWO crystal with X_0 reduced vs E beam

Figure 5
The electromagnetic shower is simulated using the **Geant4** toolkit in which the cross sections for **bremsstrahlung and pair production are rescaled** [3] in agreement with full Monte Carlo and experiment with axially oriented PWO [1].



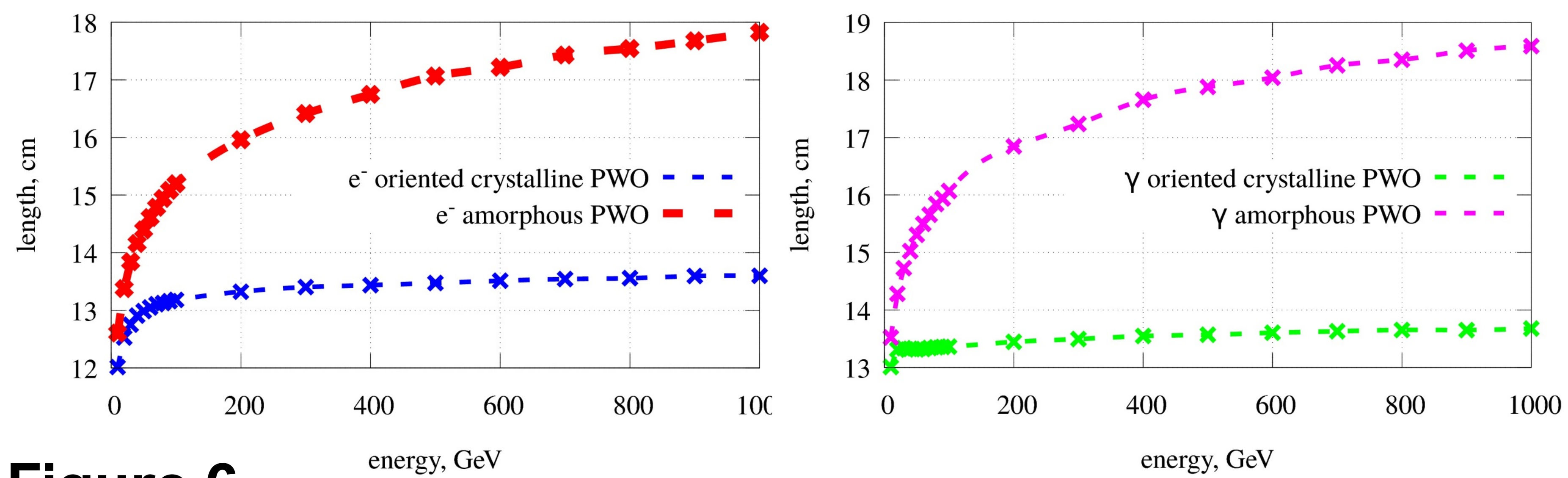


Figure 6
Electromagnetic shower length (defined as 90% of deposited energy) **vs. beam energy**, for both primary e⁻ and γ. Since the crystalline strong field increases with beam energy with a consequent X_0 decreasing, the **shower length is almost constant with primary energy**.

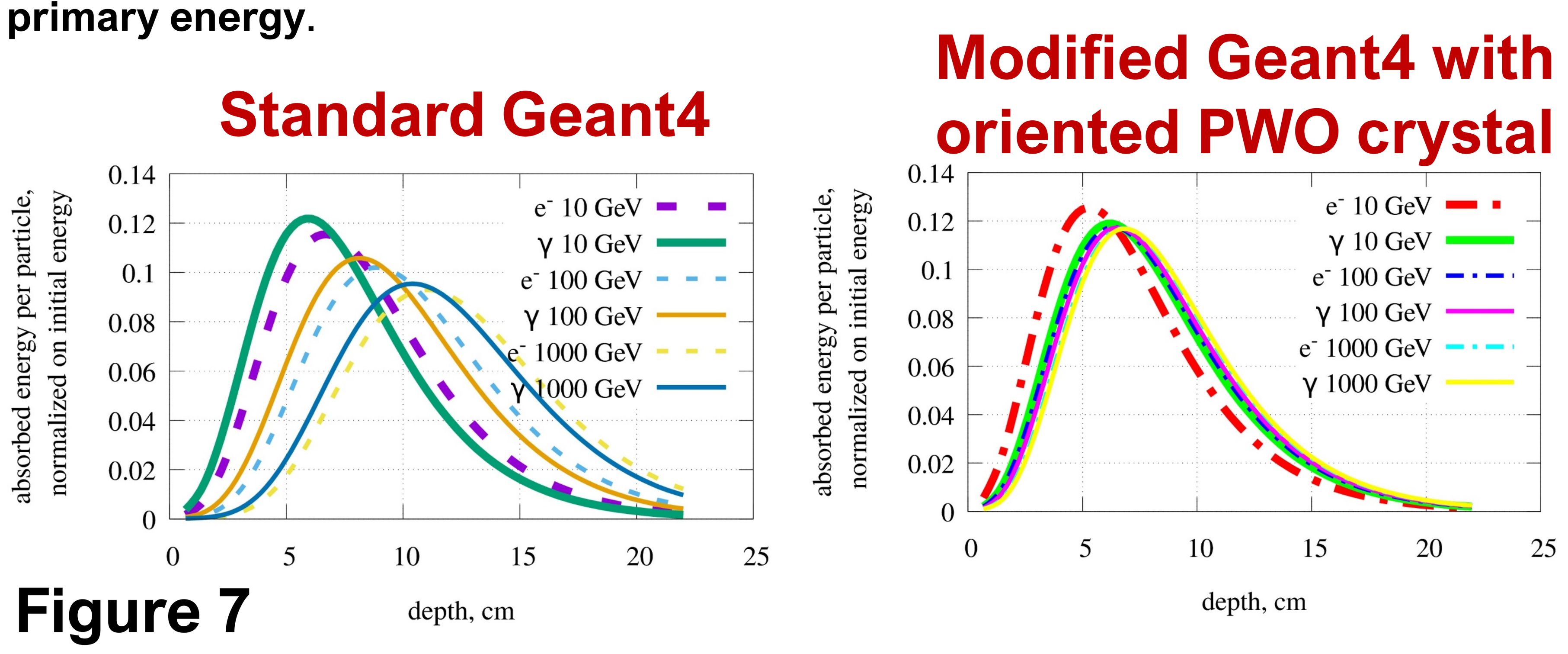


Figure 7
Electromagnetic shower longitudinal development vs. beam energy. The maximum is shifted to the entry surface of the crystal and is almost at the same position for energies from tens GeV to 1 TeV.

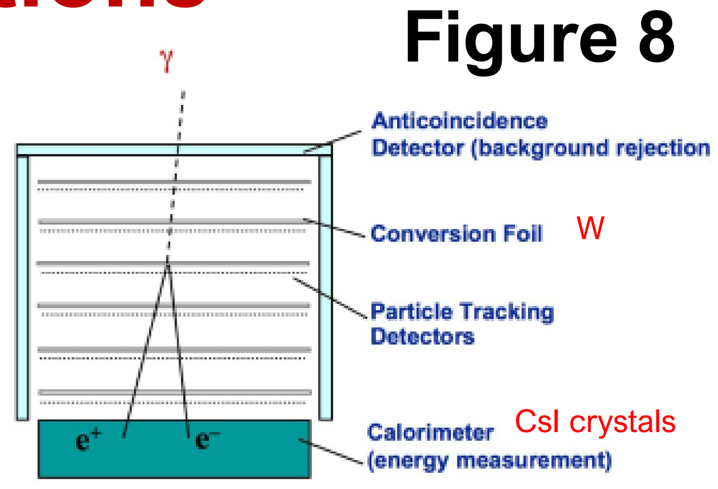
Possible Applications

X_0 reduction is possible if the crystal axes are aligned with the beam direction within 1°. Thereby, elective application can be in:

HIGH-ENERGY PHYSICS:
1. **Fixed-target Experiments**: forward e.m. **calorimeters/preshower with reduced volume.**
2. **Beam Dump**: compact active beam dump with an **increased sensitivity to dark photons.**

ASTROPARTICLE PHYSICS:
1. **Satellite borne gamma-ray telescopes**: With a gamma module (see Fig. 8) made of oriented crystals, **one may point the telescope towards the source** and **the shower of gamma rays with energy larger than 100 GeV can be completely contained in a quite restrained volume.**

Figure 8



FERMI LAT-like telescope:
- reduce the thickness of the calorimeter
- **reduce the thickness of the photon converters in the tracker**,

Cost reduction; increase of sensitivity, energy and spatial resolution!

References

[1] L. Bandiera et al, ArXiv: 1803.10005, under review on Phys Rev. Lett.
[2] L. Bandiera, et al., Phys. Rev. Lett. 111 (2013) 255502.
[3] V.G.Baryshevsky, V.V.Haurylavets, et al., Nucl. Instrum. Methods Phys. Res. B, 402 (2017) 35.