Application of compact detectors composed of oriented crystals to the observation of VHE γ-rays in space

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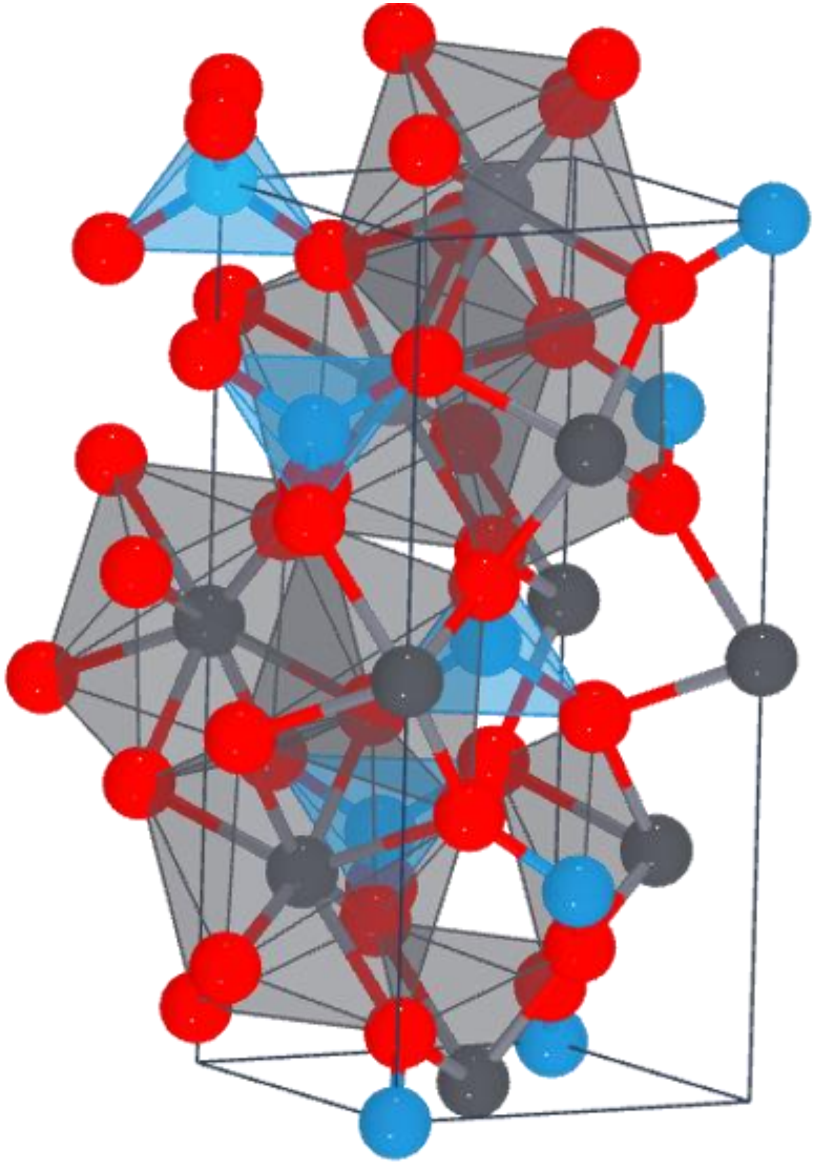
04th September 2024

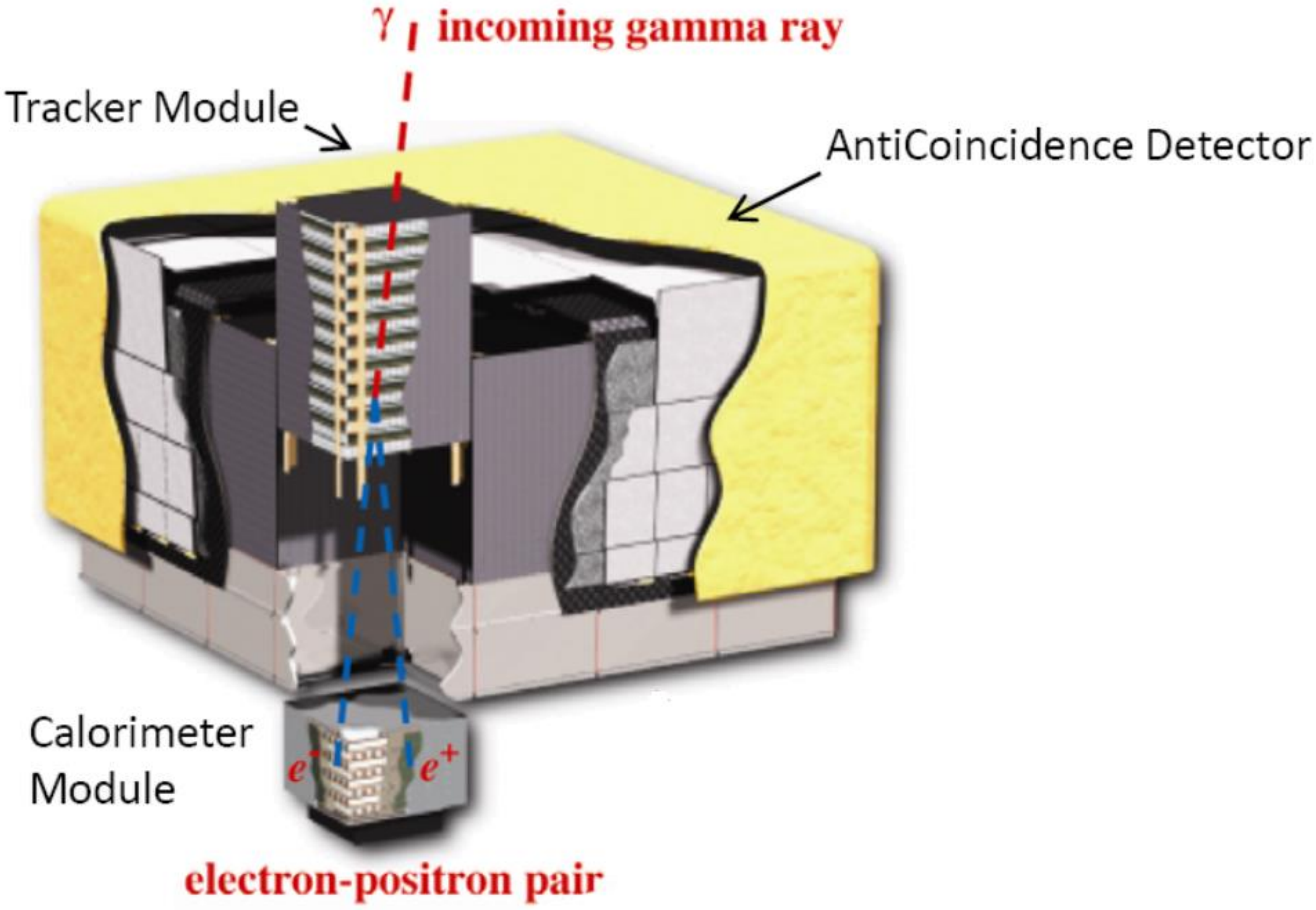
Overview

1. What are **oriented crystals**?

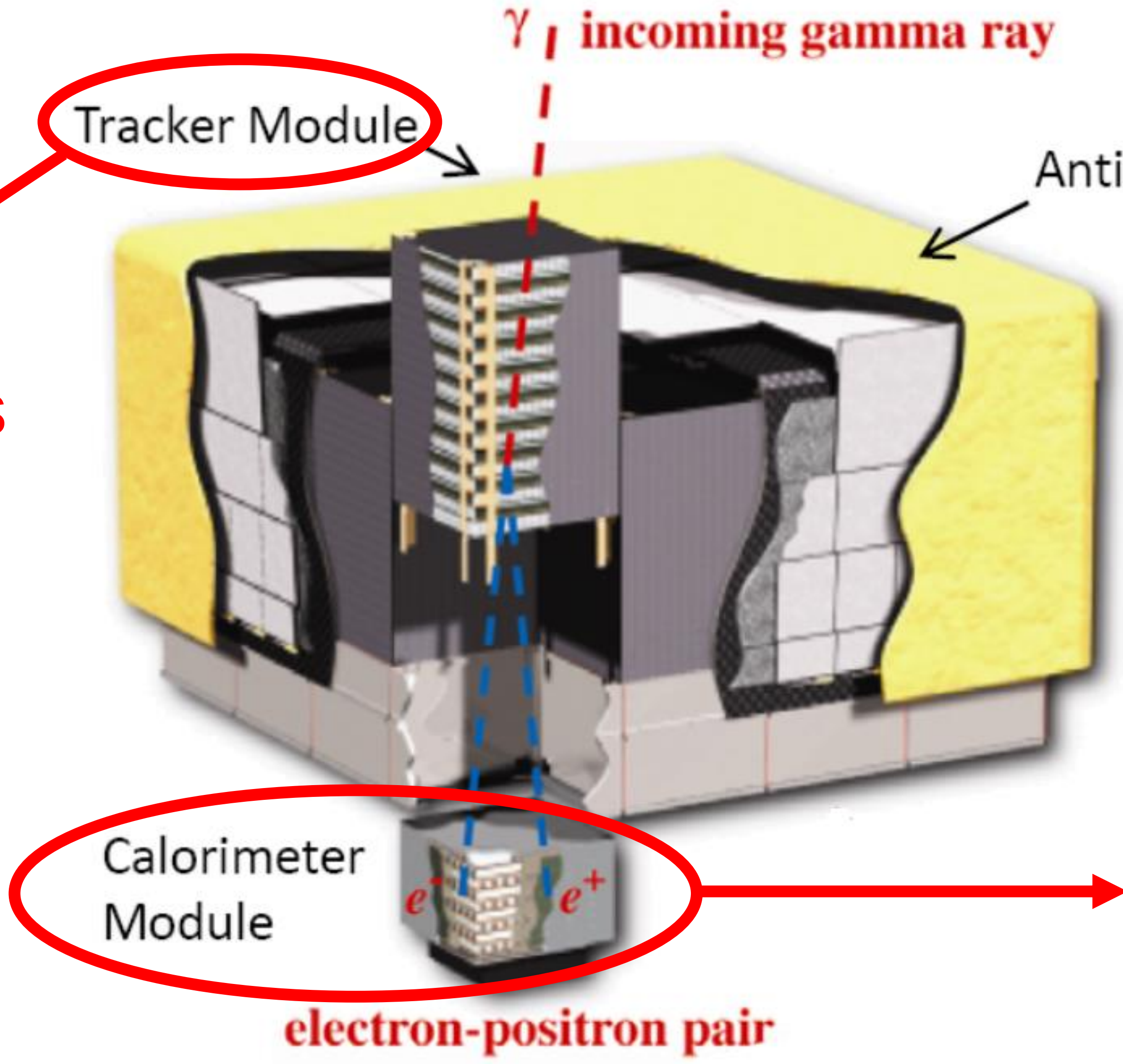
2. How (& why) would they be used in satellite-based γ-ray astronomy?



Key point: this is not a presentation about a specific mission concept!



Can you find the crystals in this picture?



Silicon detectors
Tungsten foils

CsI(Tl) bars

(+ NaI crystals in the GBM…)

Can you find the crystals in this picture?

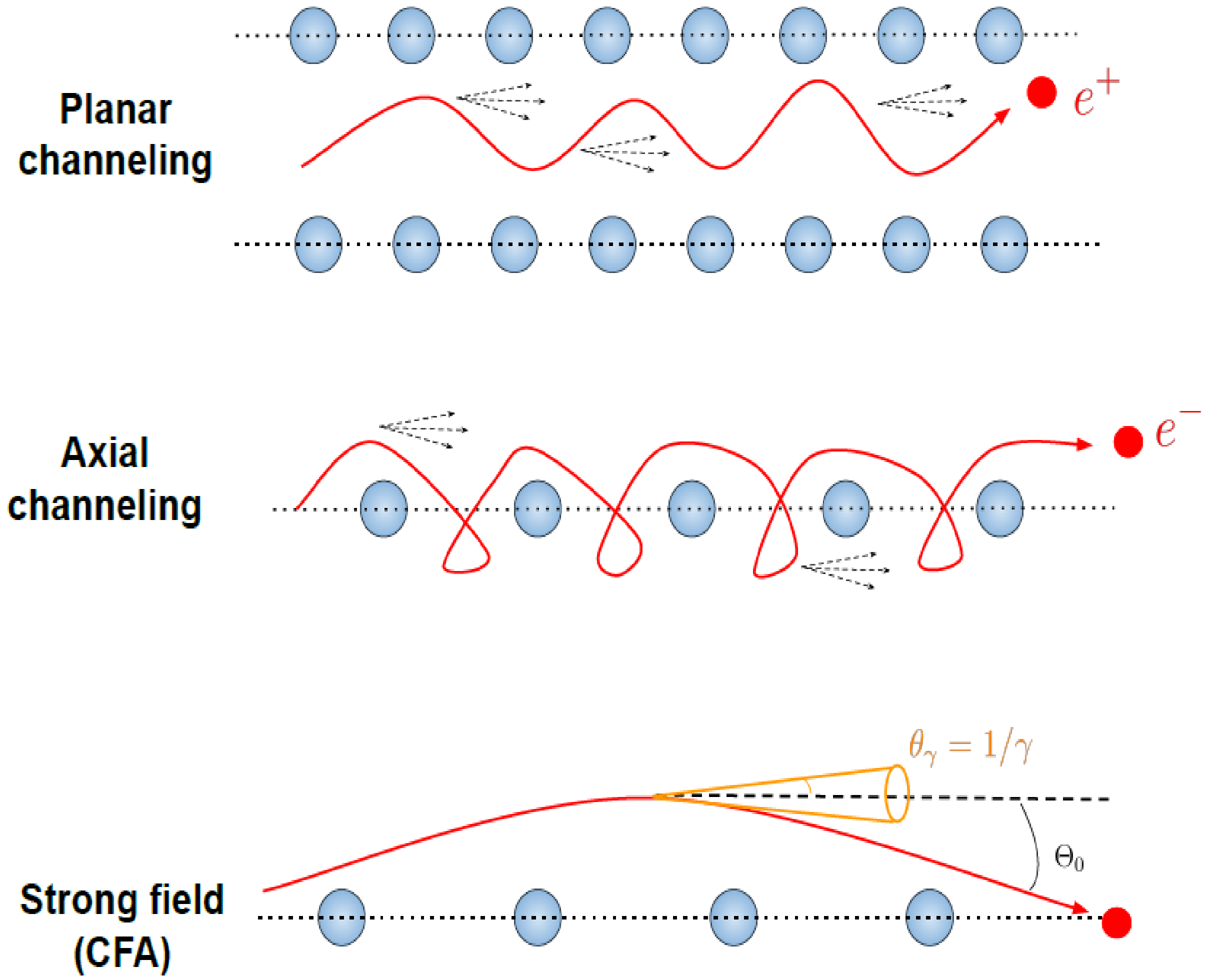
A VHE (> 10 GeV) $e^{\pm}$ moving along a crystal axis experiences a Lorentz-boosted **intense electric field**:

- The **bremsstrahlung** cross-section increases
- **Angular acceptance** (energy independent):

$$\Theta_0 \sim \mathcal{O}(0.1°)$$

but weaker effects are visible even at **smaller energies and larger angles**, even up to $\sim 1°$

A similar enhancement is observed for the photon pair production!



Consequence:

Strong acceleration of the e.m. shower development

= reduction of the "effective" thickness of the material

For more details, see:

- Phys. Rev. Lett. 121, 021603 (2018)
- arXiv:2404.12016

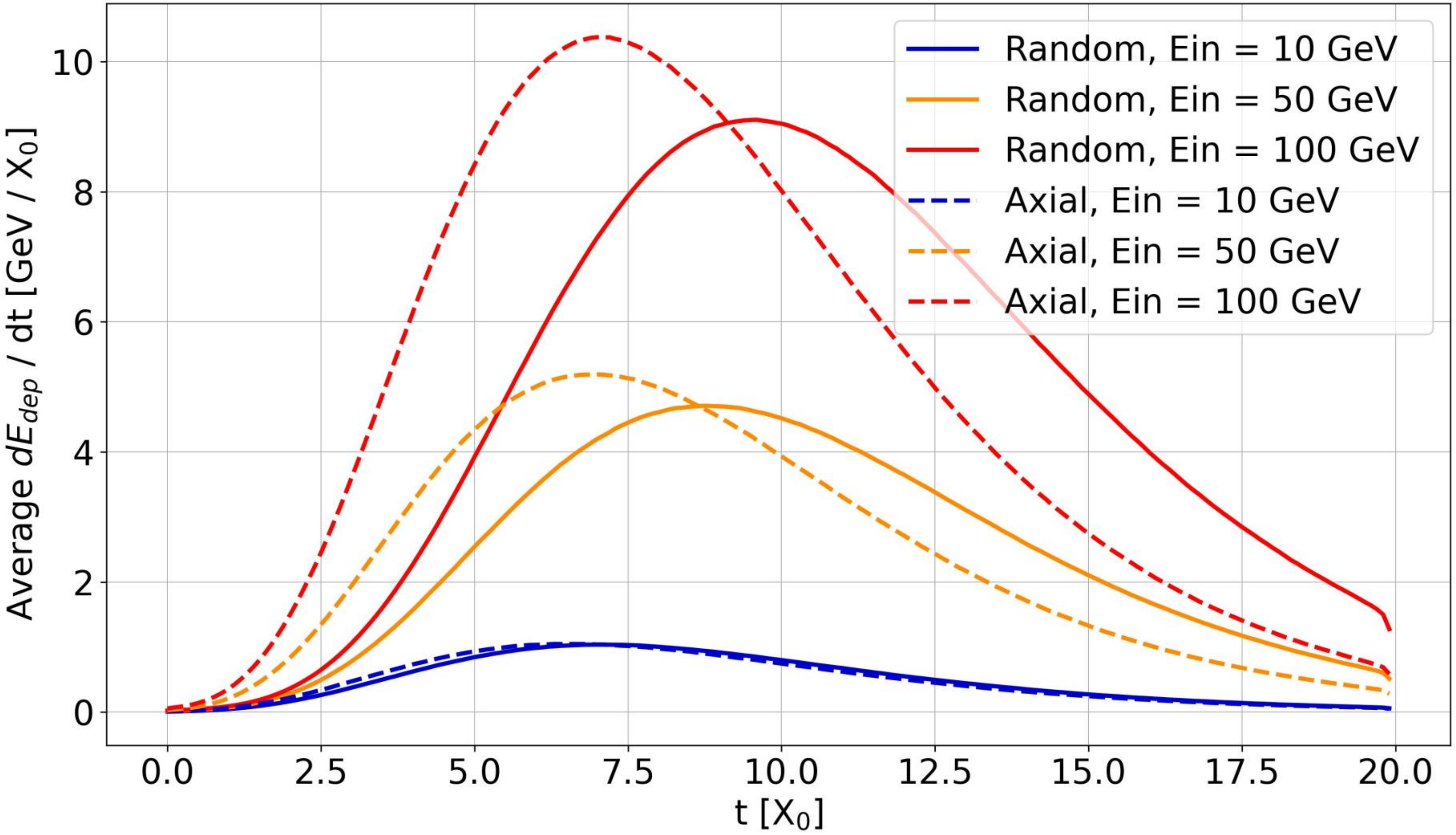


Figure: photons incident on a $PbWO_4$ oriented crystal (Geant4)

Concept: build an oriented satellite detector (e.g. Fermi):

✓ Extended energy range

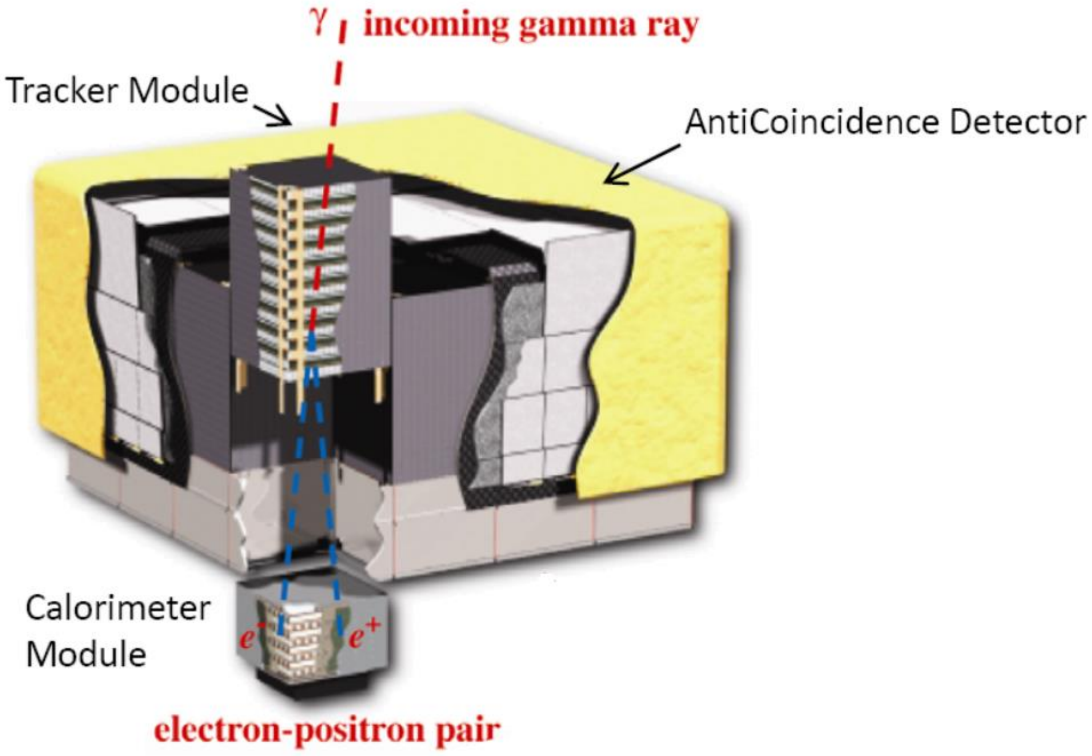
- ➢ Useful for AGN population studies, Dark Matter searches, investigation of unresolved sources, measurement of the spectra of cosmic $e^{\pm}$, …

✓ Improved energy resolution

- ➢ Necessary for resolving Dark Matter lines!

✓ Improved background rejection

- ➢ Because **hadronic showers are not accelerated!**

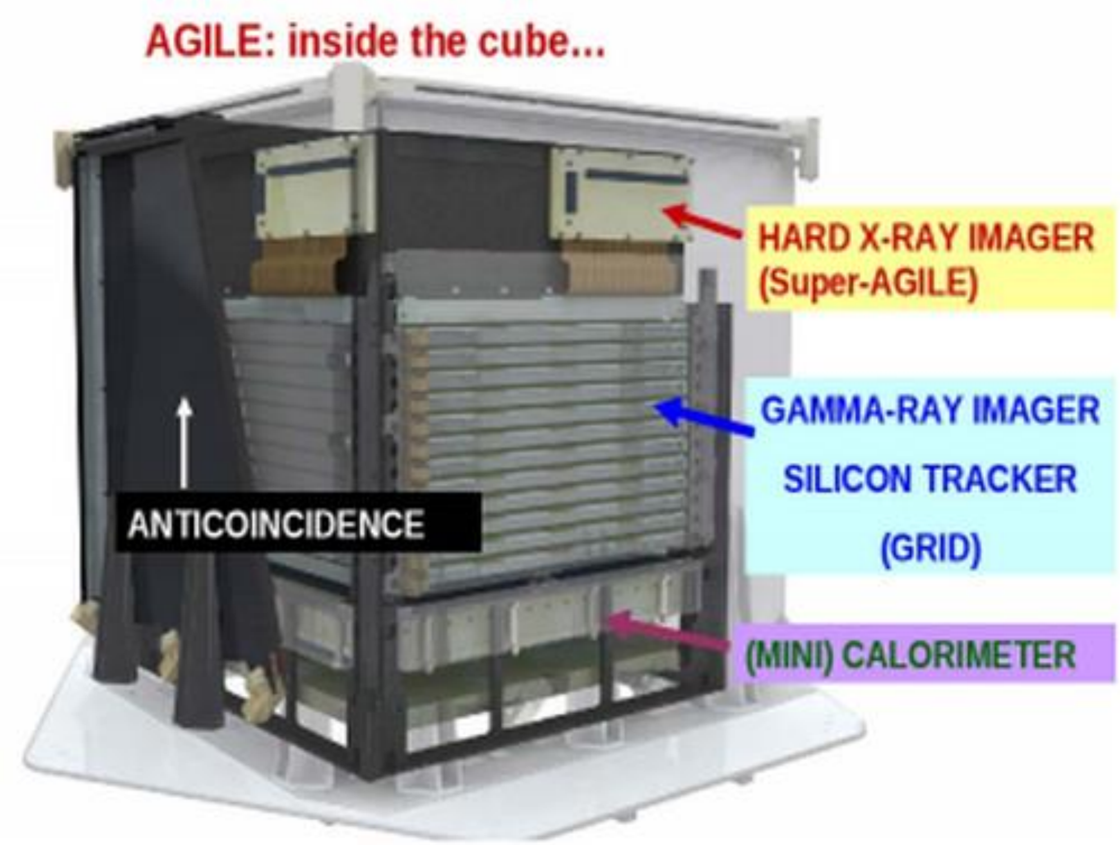


And the system would work "normally" when not pointing!

Alternative:

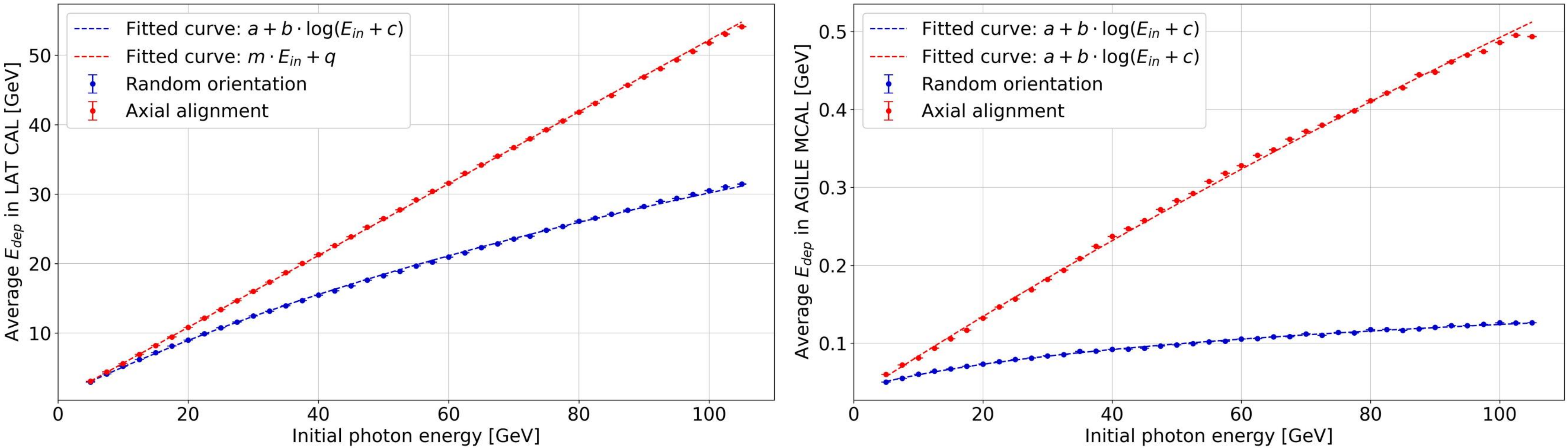
✓ **Reduce the detector thickness and increase the effective area**

- Larger area and higher sensitivity to VHE photons
- **No additional cost in terms of budget material**
- Application: **monitor of transient sources** (GRBs) with **high localization precision**!

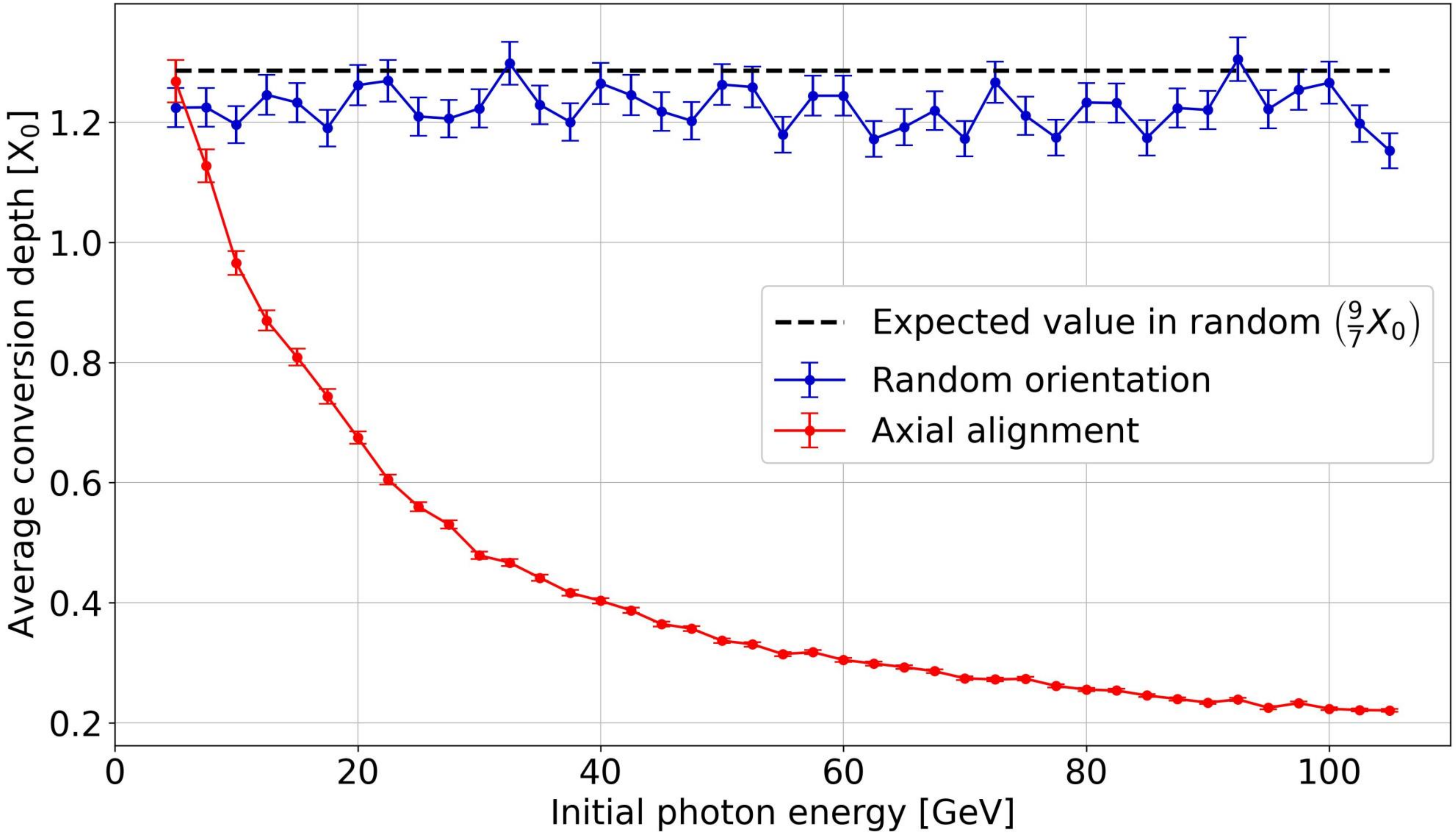


Oriented crystals can be used everywhere, with a bit of creativity!

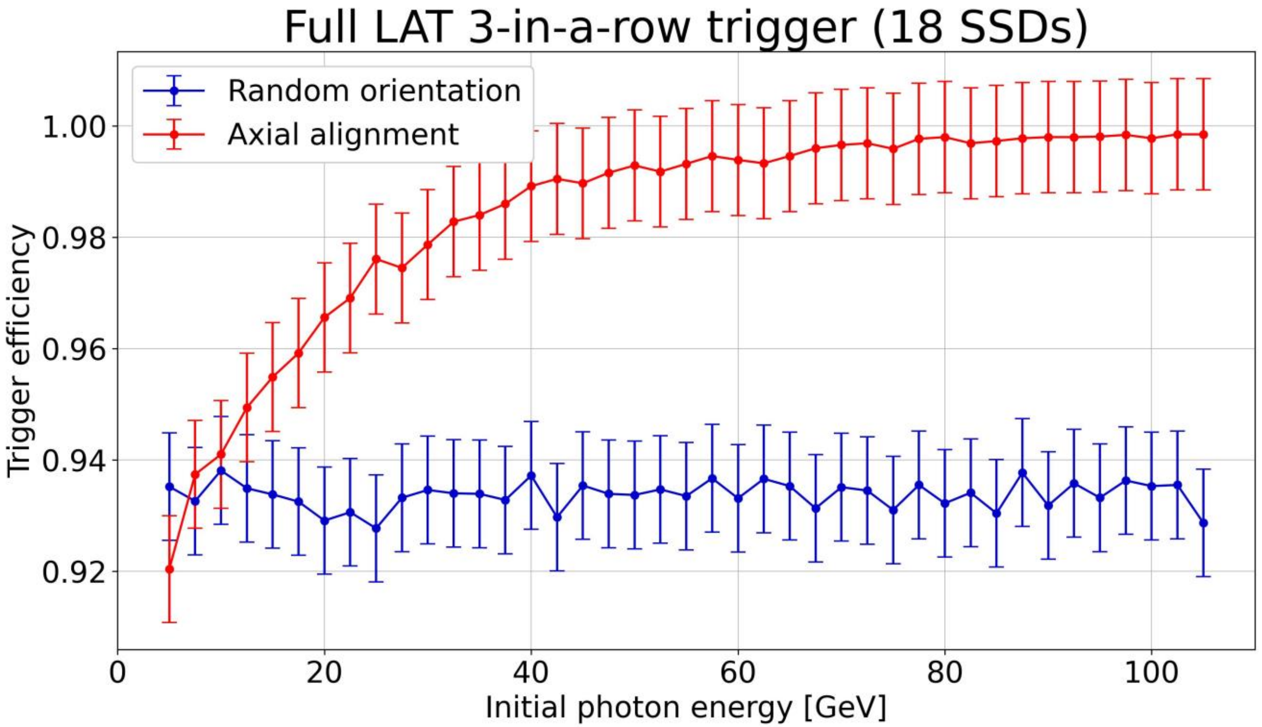
More on the shower acceleration

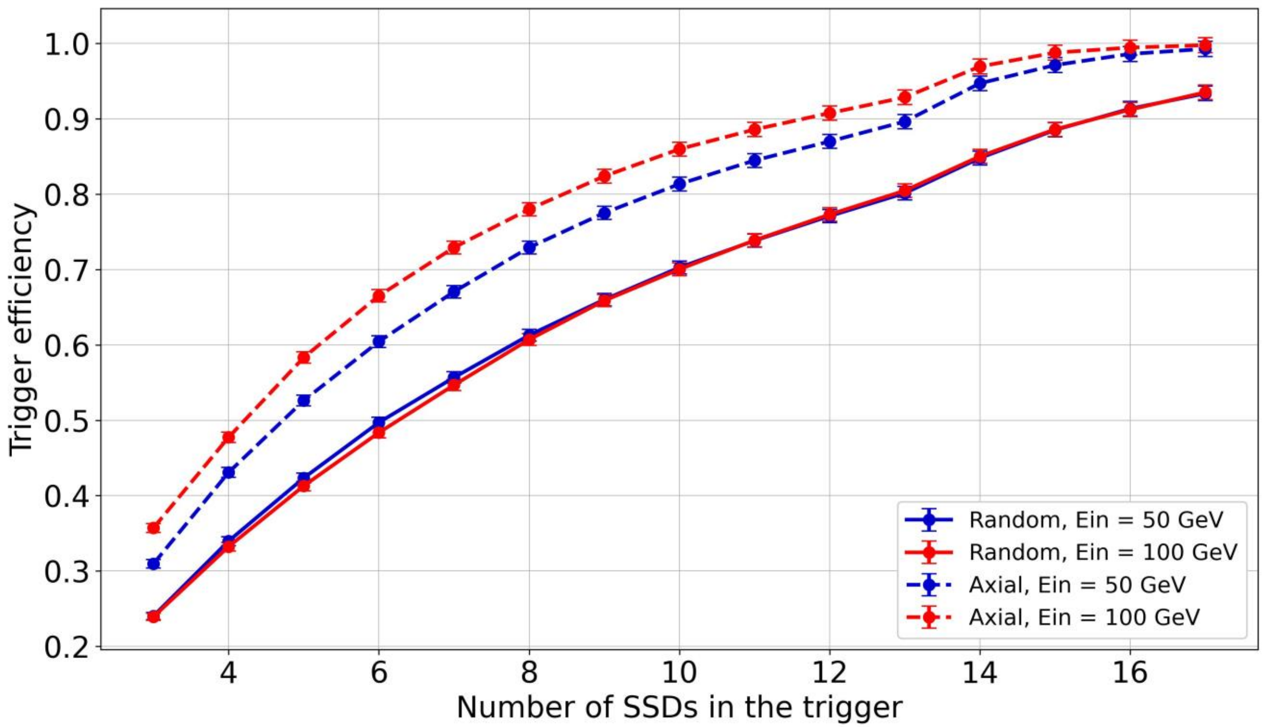


Shower acceleration observed in a LAT-like (left) and an AGILE-like (right) oriented $PbWO_4$ calorimeter



Depth of first photon interaction (pair conversion), inside an oriented W crystal





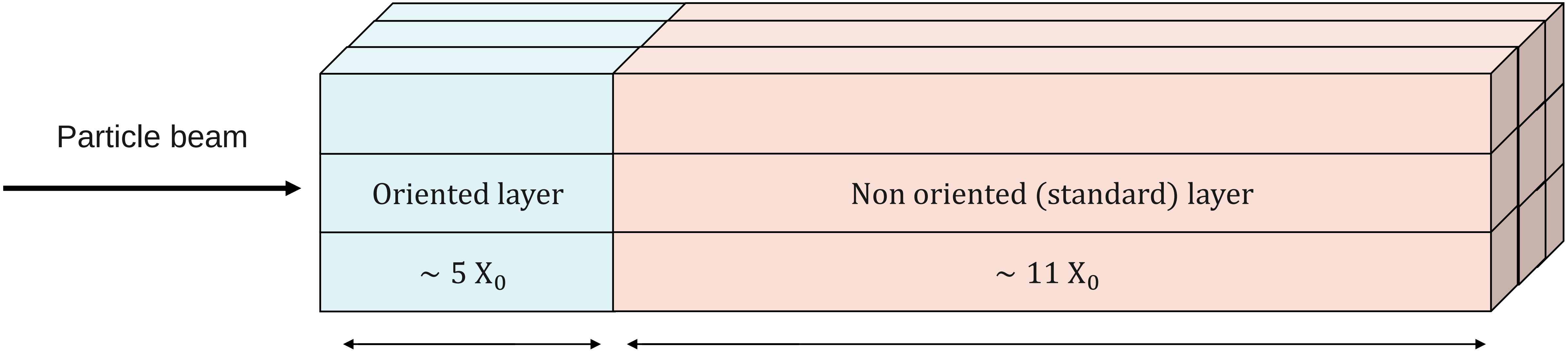
Improved efficiency with a LAT-like trigger system

The OREO project (INFN CSN/5)

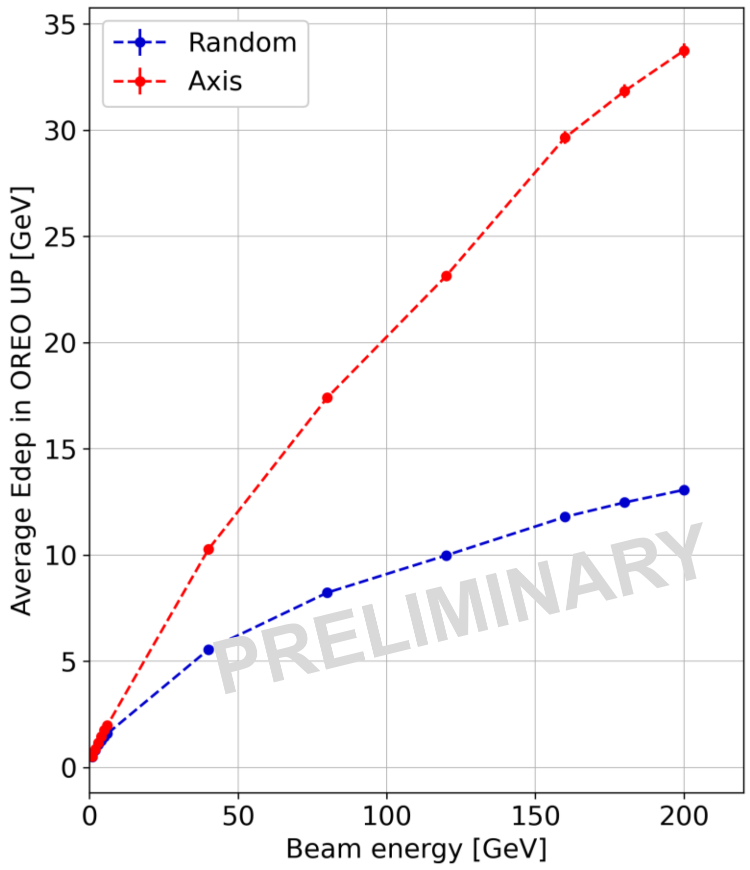
Aim:

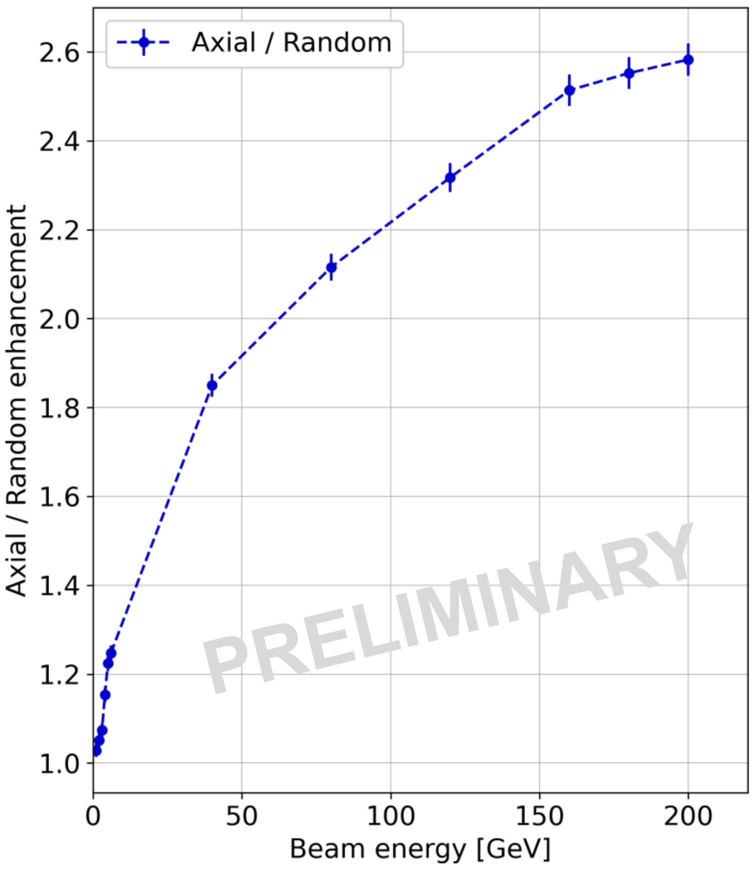
Developing the first prototype electromagnetic calorimeter composed of ***oriented $PbWO_4$ crystals*** *readout by Silicon PhotoMultipliers (SiPMs)*

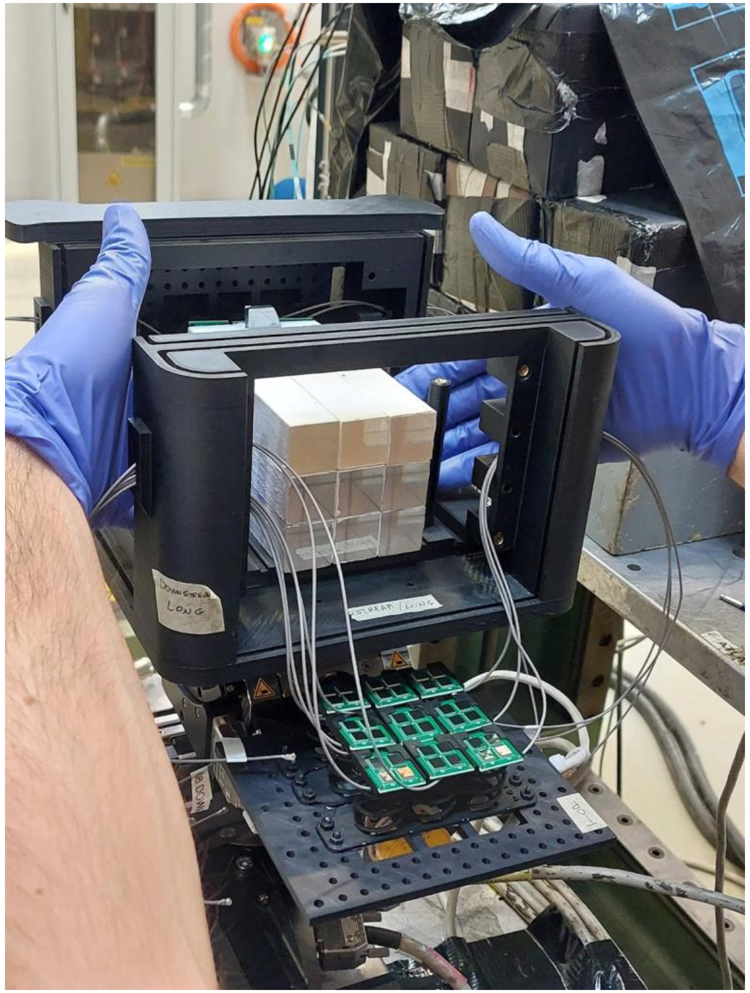
Principal Investigator: dr. **L. Bandiera** (INFN Ferrara)



- ✓ Demonstrated the feasibility of **assembling an oriented calorimeter** with well inter-aligned crystals
- ✓ Developed a custom library for the **Geant4 simulation** of the interactions in oriented crystals





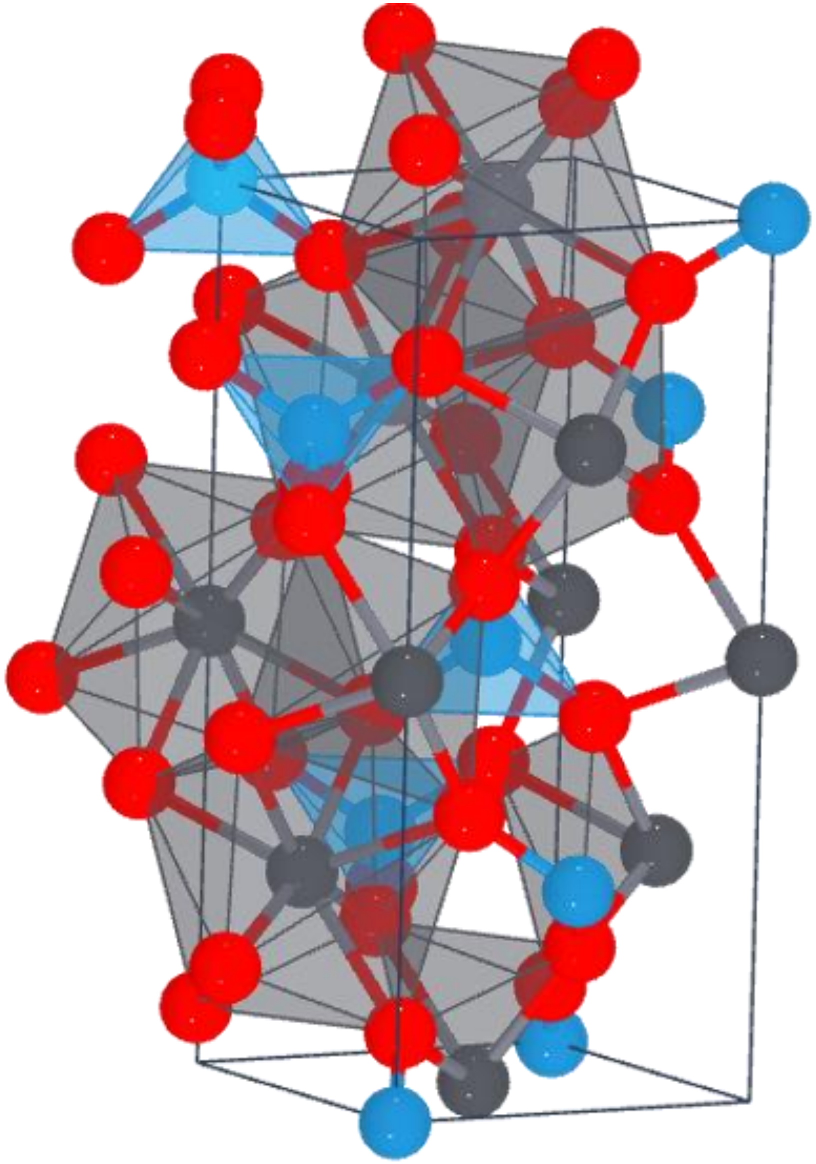


Conclusions

Oriented crystals have been proven to be a **viable option for future pointing γ-ray telescopes**:

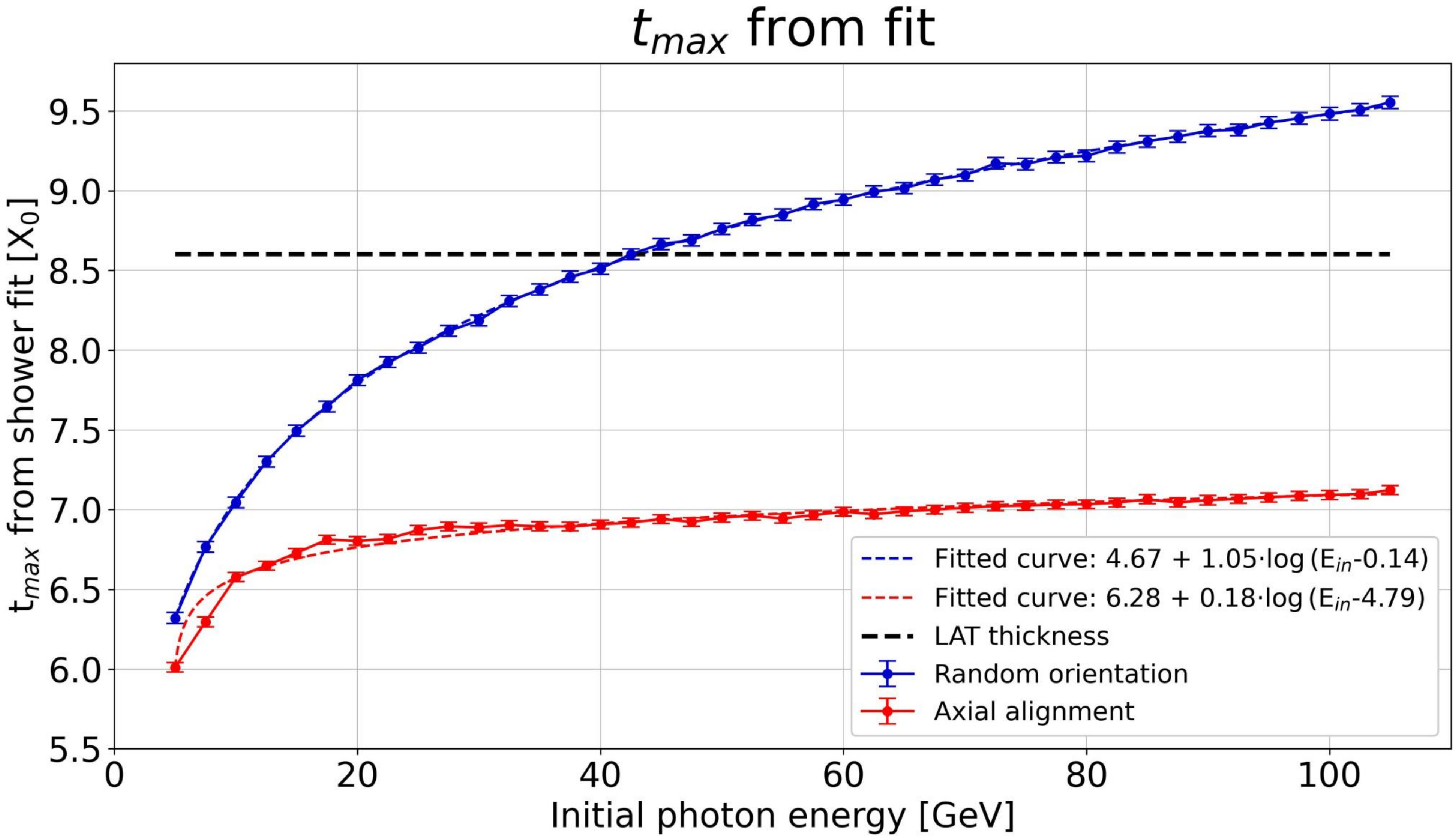
- ✓ Increase the sensitivity and energy resolution above few GeV
- ✓ Either improve the detector performance or reduce its thickness to increase its area (**cost reduction**!)
- ✓ Several possible layouts, depending on your favourite physics case: Fermi-like, Agile-like, whatever!

And the world of crystals is still full of other possibilities to be explored (e.g. Coherent Pair Production at sub-GeV scale)!



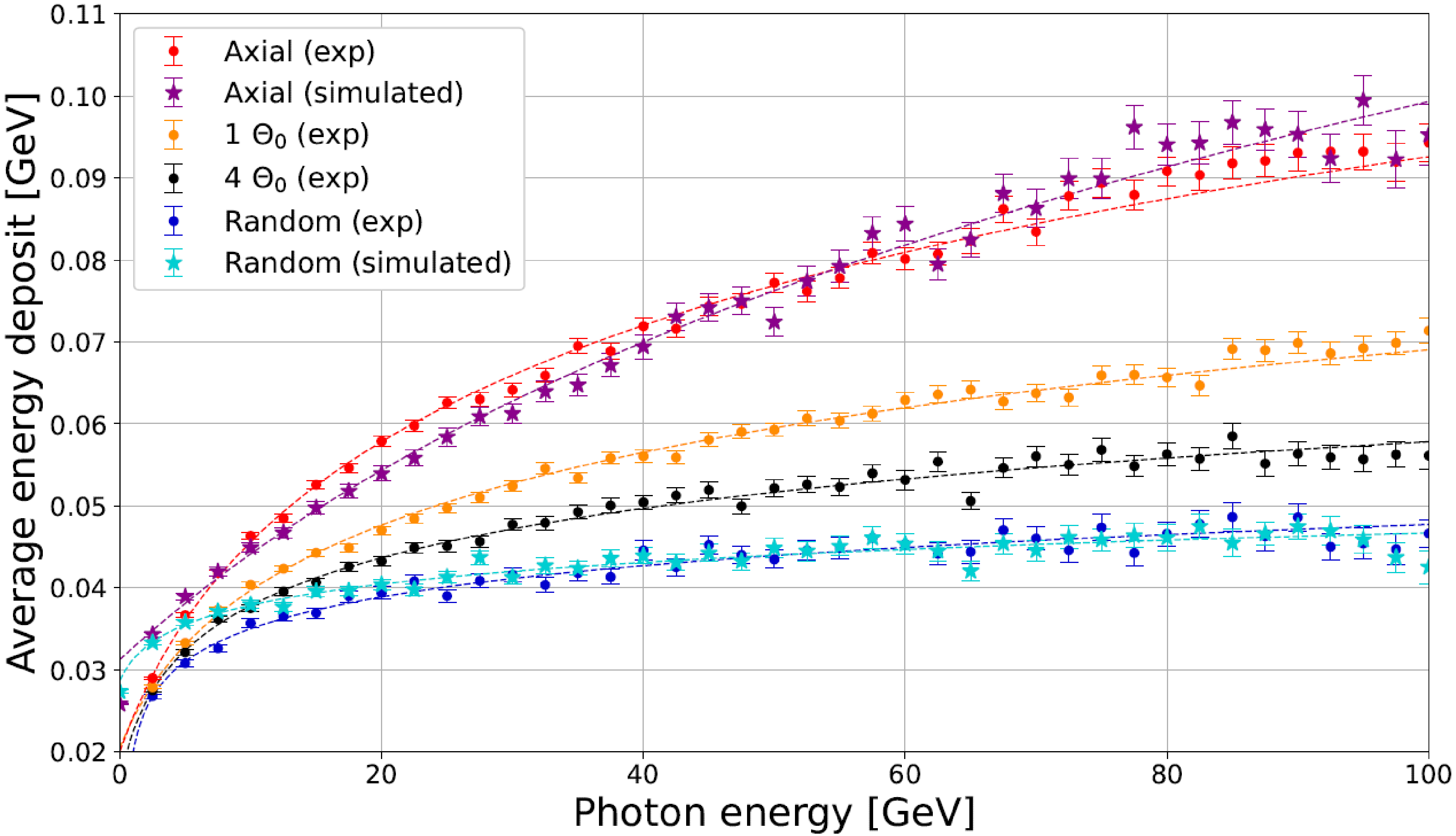
Thank you for your attention!

For questions or comments please contact: pietro.monti-guarnieri@phd.units.it



Peak of the energy deposit curve inside an oriented $PbWO_4$ crystal

Experimental study of a 1 X_0 $PbWO_4$ crystal

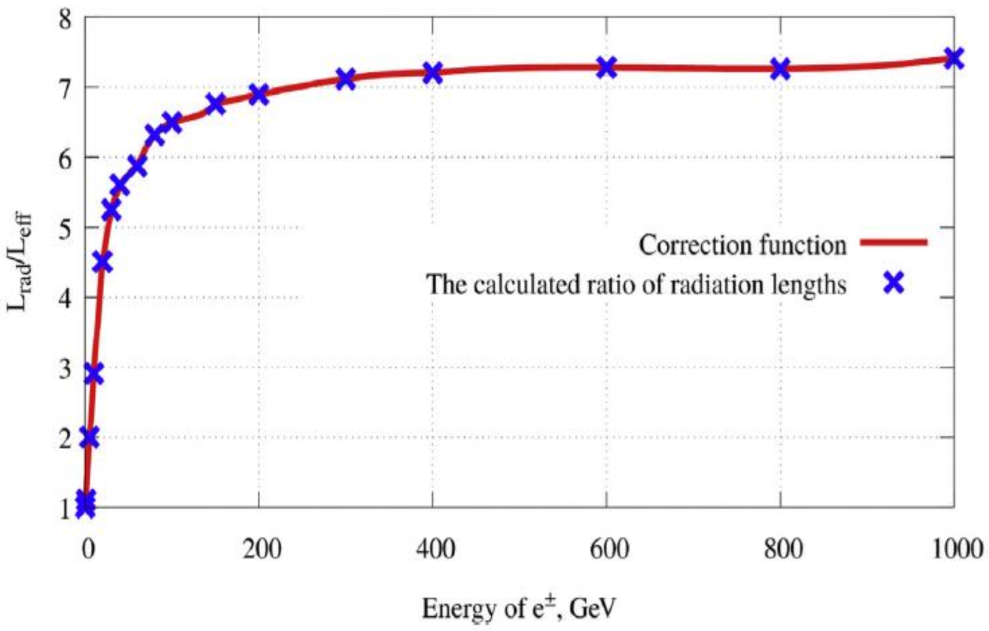


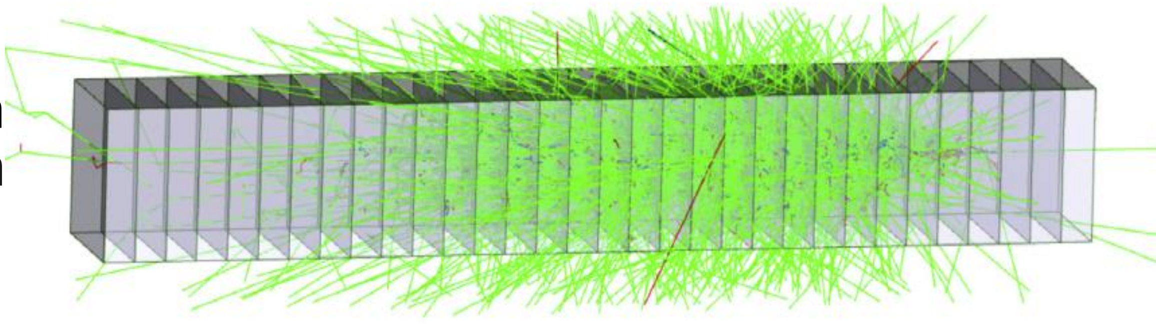
Simulating the oriented crystals physics

Crystal physics is **not implemented** in the default Geant4 libraries. What to do, then?

- Perform a full numerical simulation of the e.m. shower development in an oriented crystal (for a **given material, axis, particle energy and incidence angle**)
- Compute the enhancement of the **Bremsstrahlung** (BS) and **Pair Production** (PP) cross-sections
- Use the coefficients to manually correct in Geant4 the BS/PP cross-sections in the target

The code has been extensively validated with experimental tests performed at CERN and DESY, from 10 to 200 GeV!





For more details see e.g.: Nucl. Instrum. Methods Phys. Res. B 402 (2017) 35.