Experimental studies towards the development of an ultra-compact electromagnetic calorimeter composed of oriented crystals

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on behalf of the STORM / OREO collaboration,

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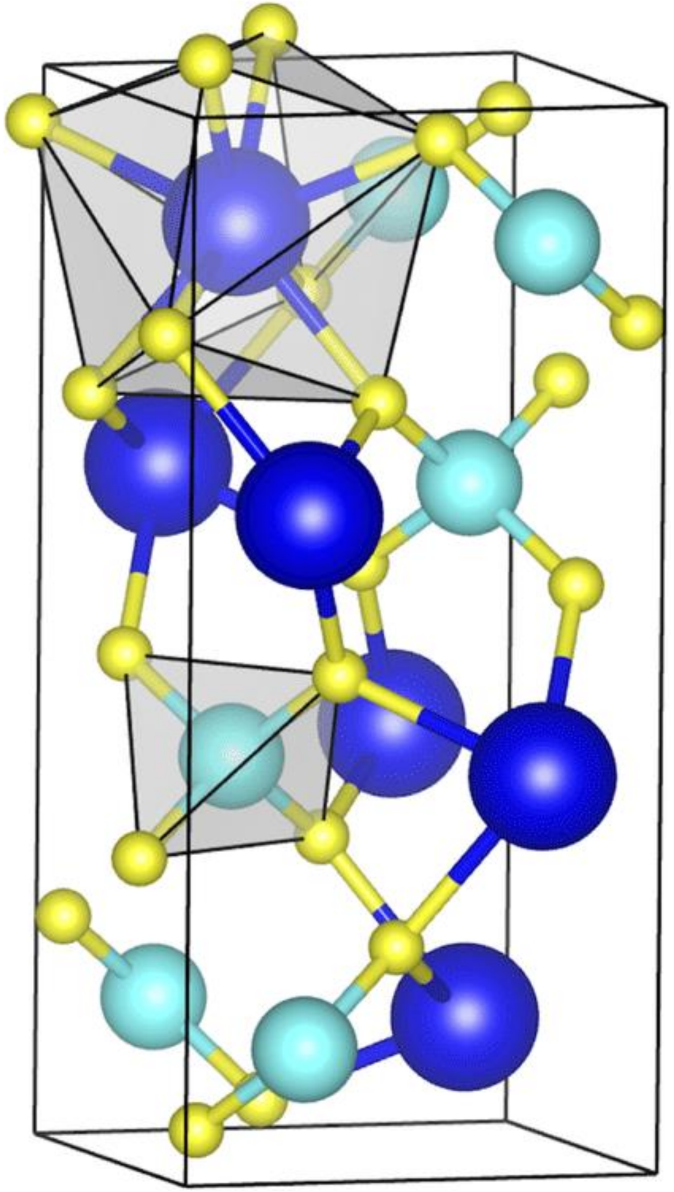
University of Ferrara & INFN Ferrara

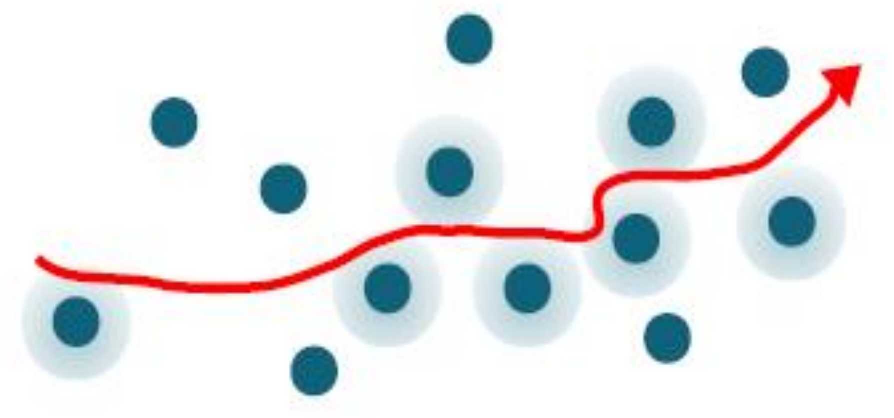
Channeling 2023, 05th June 2023

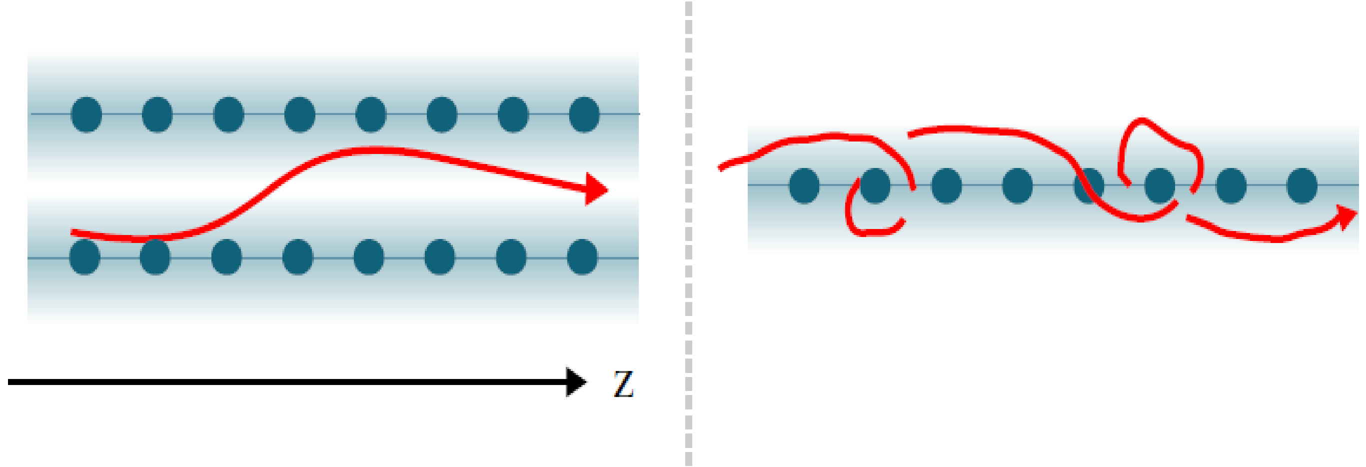
Overview

1. The **Strong Field** regime: from the physics to the applications to **calorimetry**
2. The STORM project:
   - Goals
   - Experimental methods
   - Main results
3. Conclusions & outlooks



The physics of oriented crystals





Electrons (positrons) incident on randomly oriented matter

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Bethe-Heitler bremsstrahlung due to the interactions with the single nuclei

Electrons (positrons) incident with a small enough angle (θ) with respect to the **plane** (left) or **axis** (right) of an oriented lattice

⇩

If θ is small enough, the electrons fall in a **bound state:** channeling motion + emission of **channeling radiation**

The Strong Field (SF) regime

Ultra-relativistic $e^{\pm}$ experience a **constant and enhanced electrical field** (ε) and emit hard photons with a high intensity (quantum synchrotron emission), if:

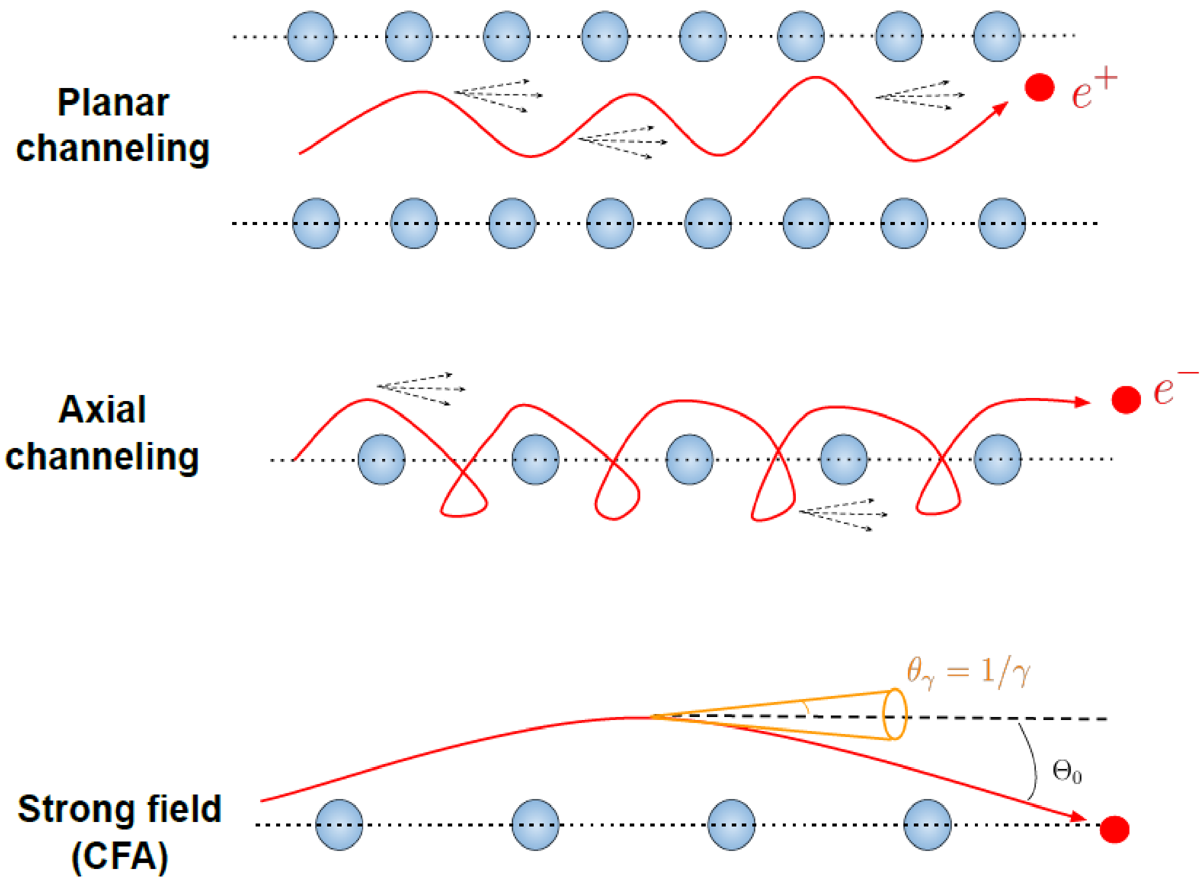
$$\chi = \frac{\gamma\varepsilon}{\varepsilon_0} > 1$$

$$\theta < \Theta_0 = \frac{U_0}{mc^2}$$

where $\varepsilon_0 \sim 1.32 \cdot 10^{18}\ \mathrm{V/m}$ is the Schwinger critical field and U_0 the potential well depth of the crystal axis.

- The effect is already visible at $\chi \sim 0.1$ ($\theta \sim 1°$, kinetic energy $E \sim 10$ GeV)
- The **angular acceptance** is **energy-independent** (and $\Theta_0 \gg \theta_{\mathrm{channeling}}$)

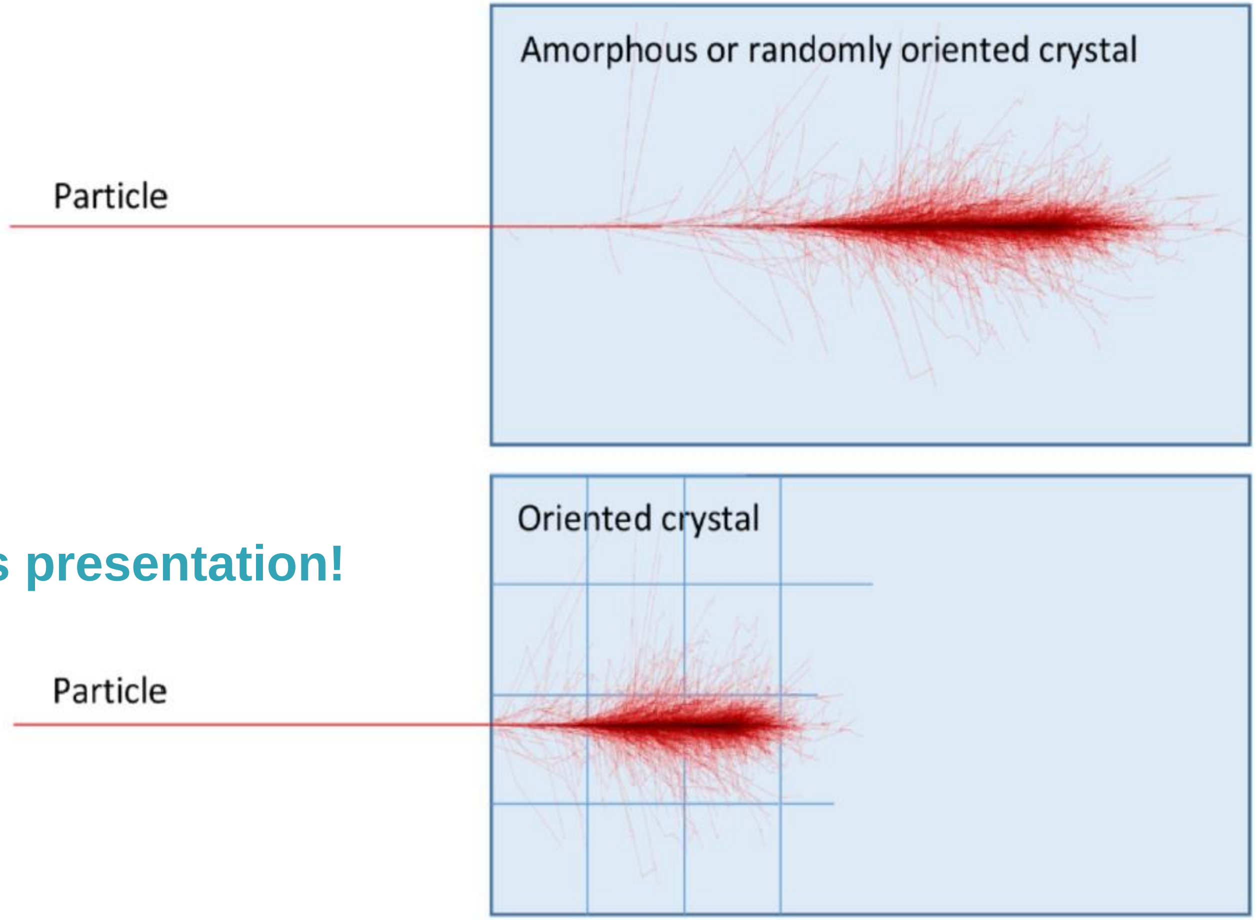
For the $\mathrm{PbWO_4}$ $\langle 100 \rangle$ axis, the full SF regime ($\chi = 1$) is attained at $\mathrm{E} \sim 32\ \mathrm{GeV}$, $\theta \sim 0.9\ \mathrm{mrad}$



The Strong Field (SF) regime

The strong crystalline field affects both bremsstrahlung (BS) and pair production (PP):

- e.m. showers become **more compact**
- The **"effective" radiation length** (X_0) decreases



Possible applications:

- **Innovative e.m. calorimeters** → **this presentation!**
- Intense positron sources for future colliders
- Absorbers for fixed target experiments
- Ultra-compact space-born telescopes for VHE gamma ray detection

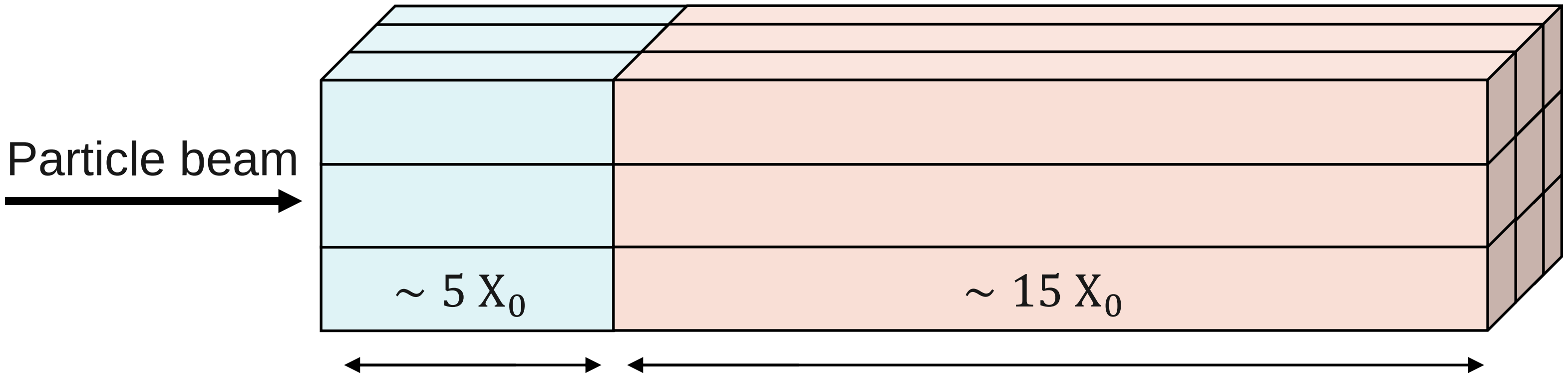
See L. Bandiera's talk on Wednesday!

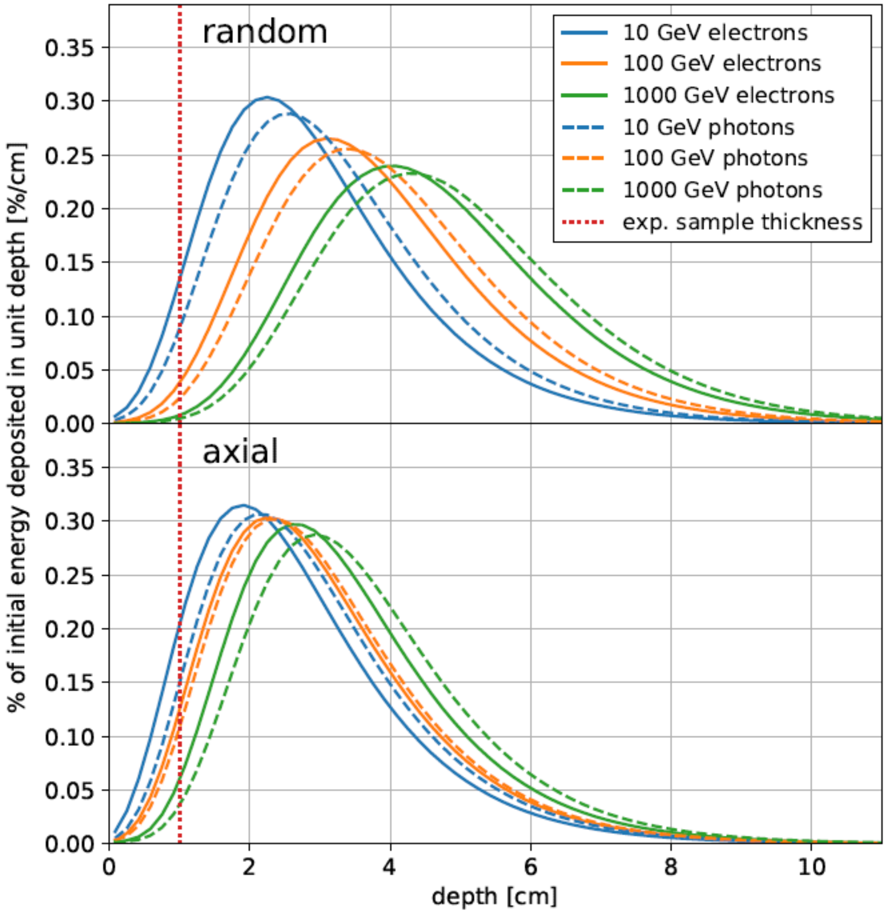
Applications to e.m. calorimetry

Proposal: **one oriented layer** ($\sim 5\,X_0$) + **one or more non oriented** layers ($\sim 15\,X_0$), each one coupled to photodetectors.

- **Better containment of the e.m. showers** up to several TeV
- **Reduced sensitivity to neutral hadrons**
- **Particle ID** (e.g., $n - \gamma$ discrimination)

Problem: the experimental data available today with <u>oriented scintillating crystals</u> are **insufficient** for any practical purpose…





The STORM project (INFN CSN/5): STrOng cRystalline electroMagnetic field

Main goal:

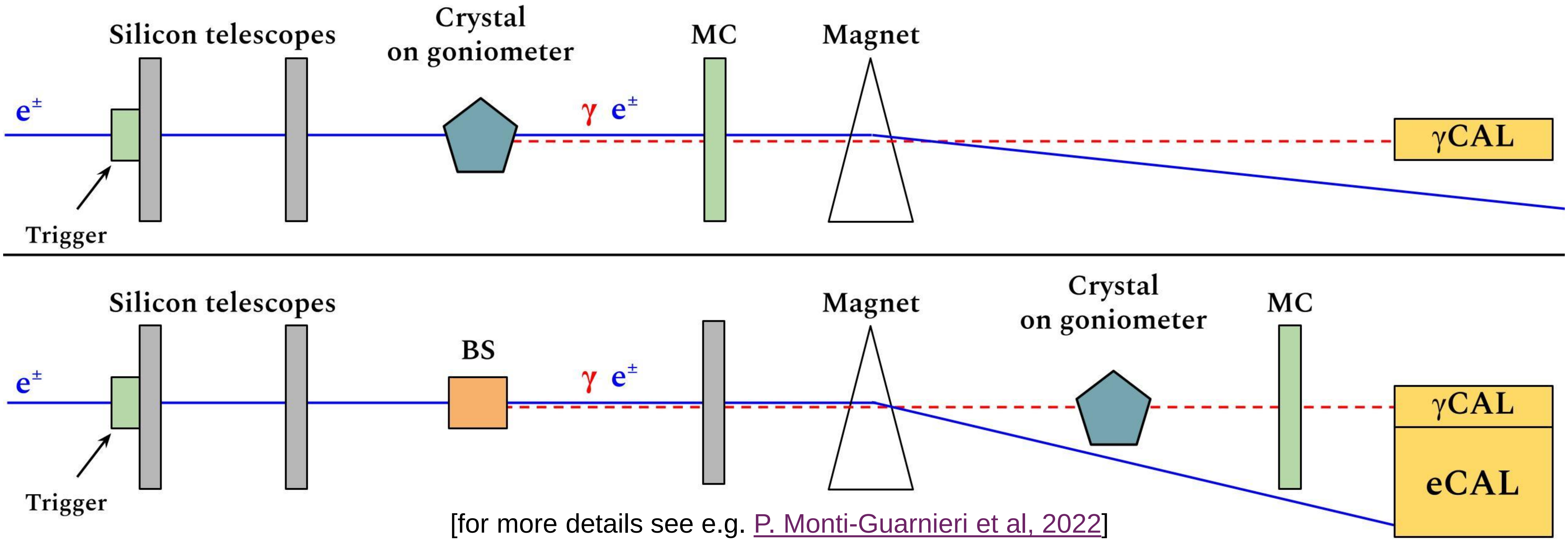
"*Investigation of the beam interactions with strong crystalline electromagnetic field […]* ***for applications in*** *accelerator and* ***detector physics***"

One of the main outcomes has been the **first-time** characterization of the SF regime by **direct light detection** in **oriented $\mathbf{PbWO_4}$ crystals**, with:

- Multiple crystal lengths $(0.45 - 4.6\ \mathrm{X_0})$
- $\mathrm{e}^{\pm}$ and photon beams
- A wide energy range $(20 - 120\ \mathrm{GeV})$

The STORM experimental setup

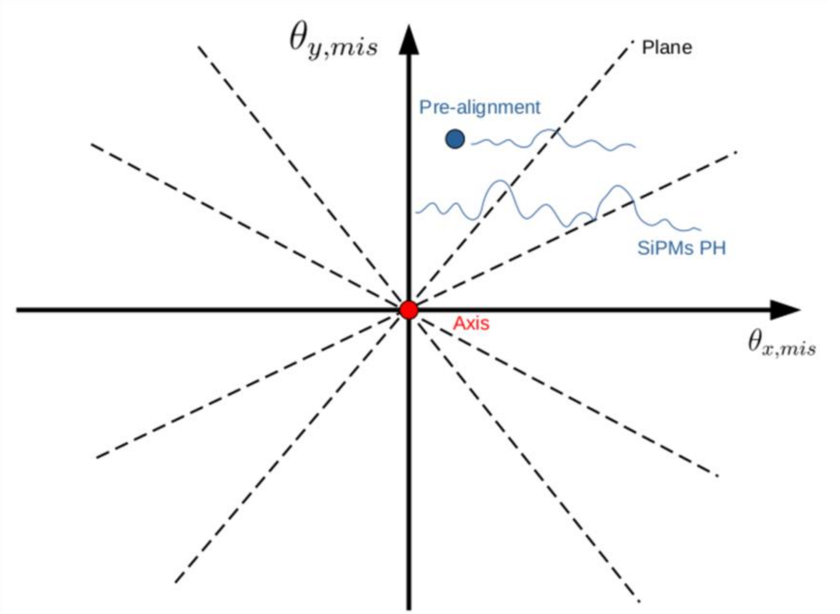
Setup used to characterize the Strong Field effects in crystal samples coupled to Silicon PhotoMultipliers (SiPMs) exposed to **high energy $e^{\pm}$** (top) or **photon** (bottom) beams, with a small divergence ($\sim 100\ \mu\text{rad}$)

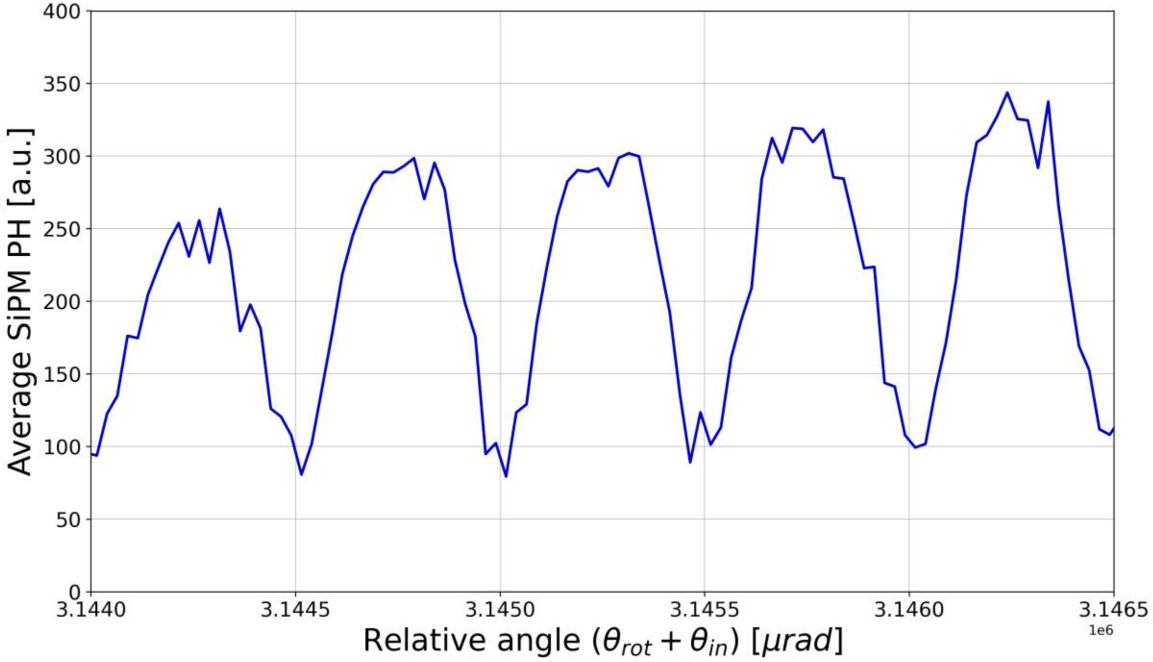


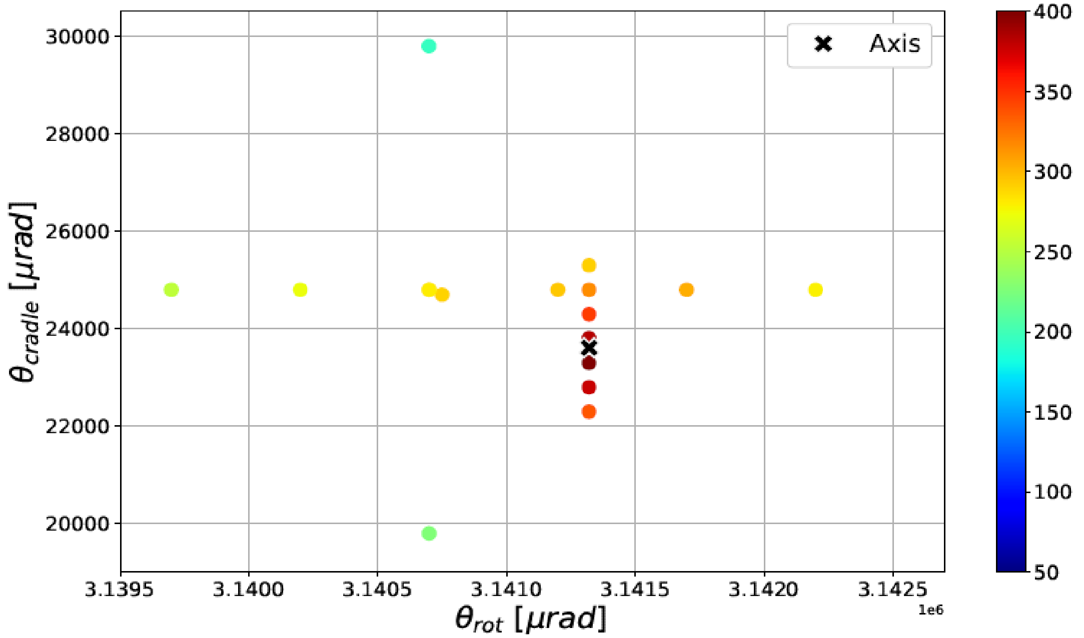
[for more details see e.g. P. Monti-Guarnieri et al, 2022]

The crystal-beam alignment

1. Laser-guided pre-alignment
2. **Stereogram** reconstruction, carried out by performing several **angular scans,** in search for the position of **maximum particle multiplicity and maximum energy deposit.**







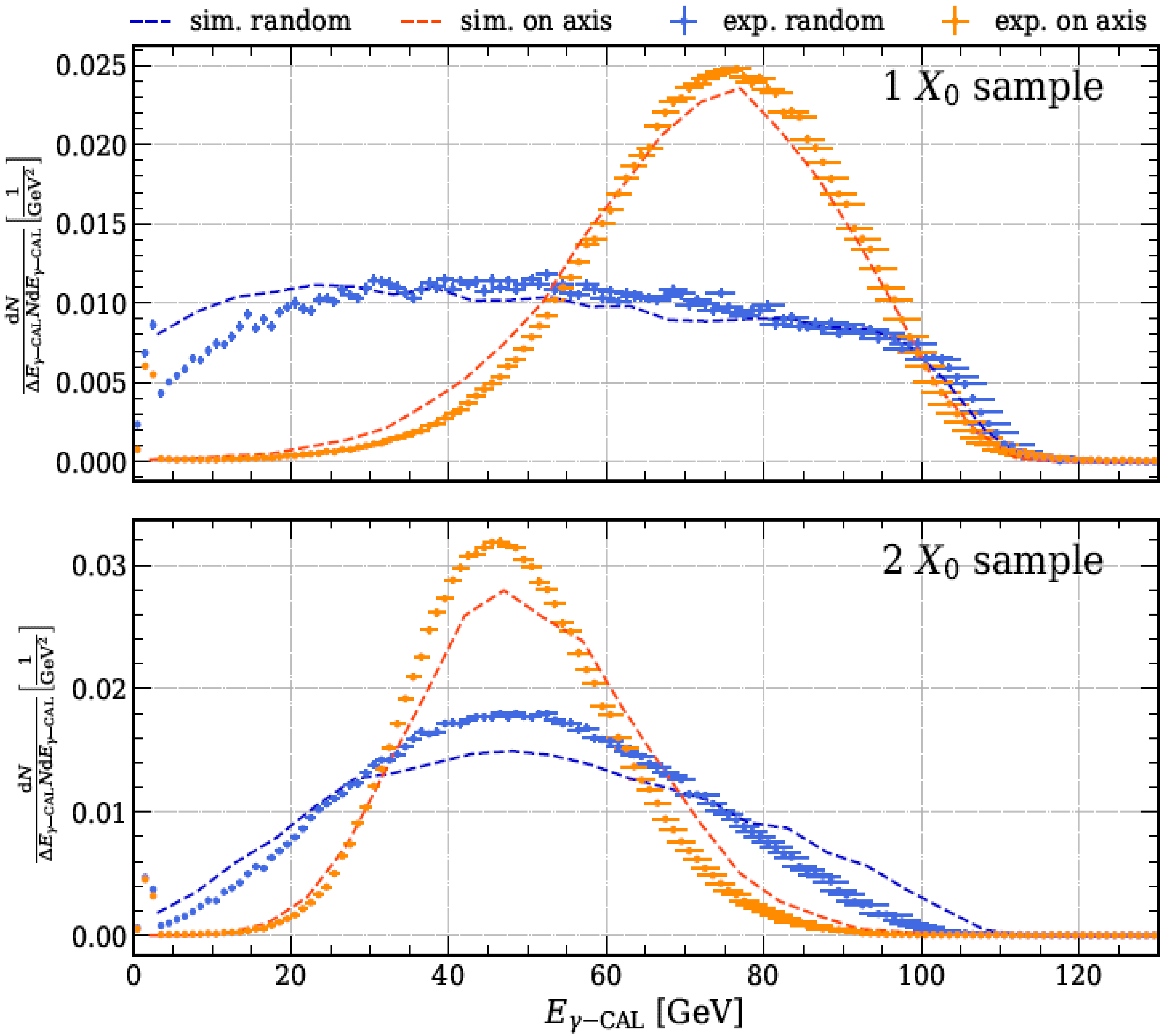
Strong Field effects in $PbWO_4$ crystals

Radiation spectra measured by γCAL, for a 120 GeV/c electron beam impinging on a $\mathbf{PbWO_4}$ crystal:

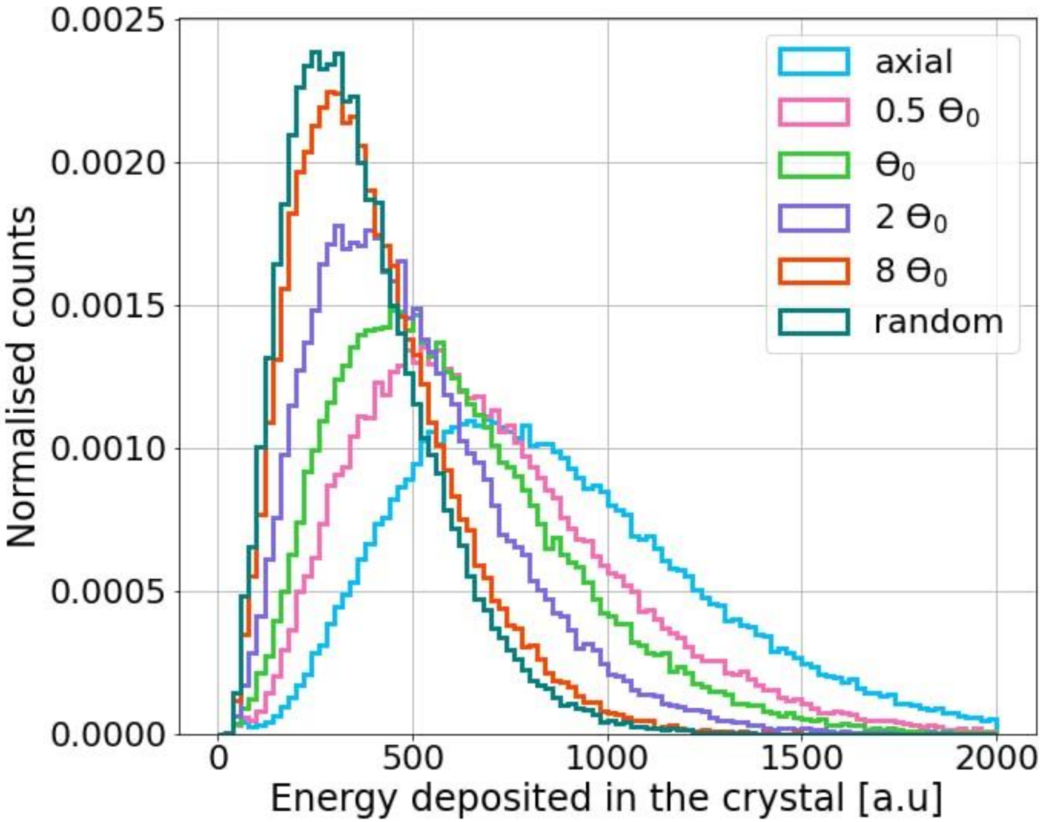
- In “axial” alignment (0 mrad)
- In “random” orientation (50 mrad)

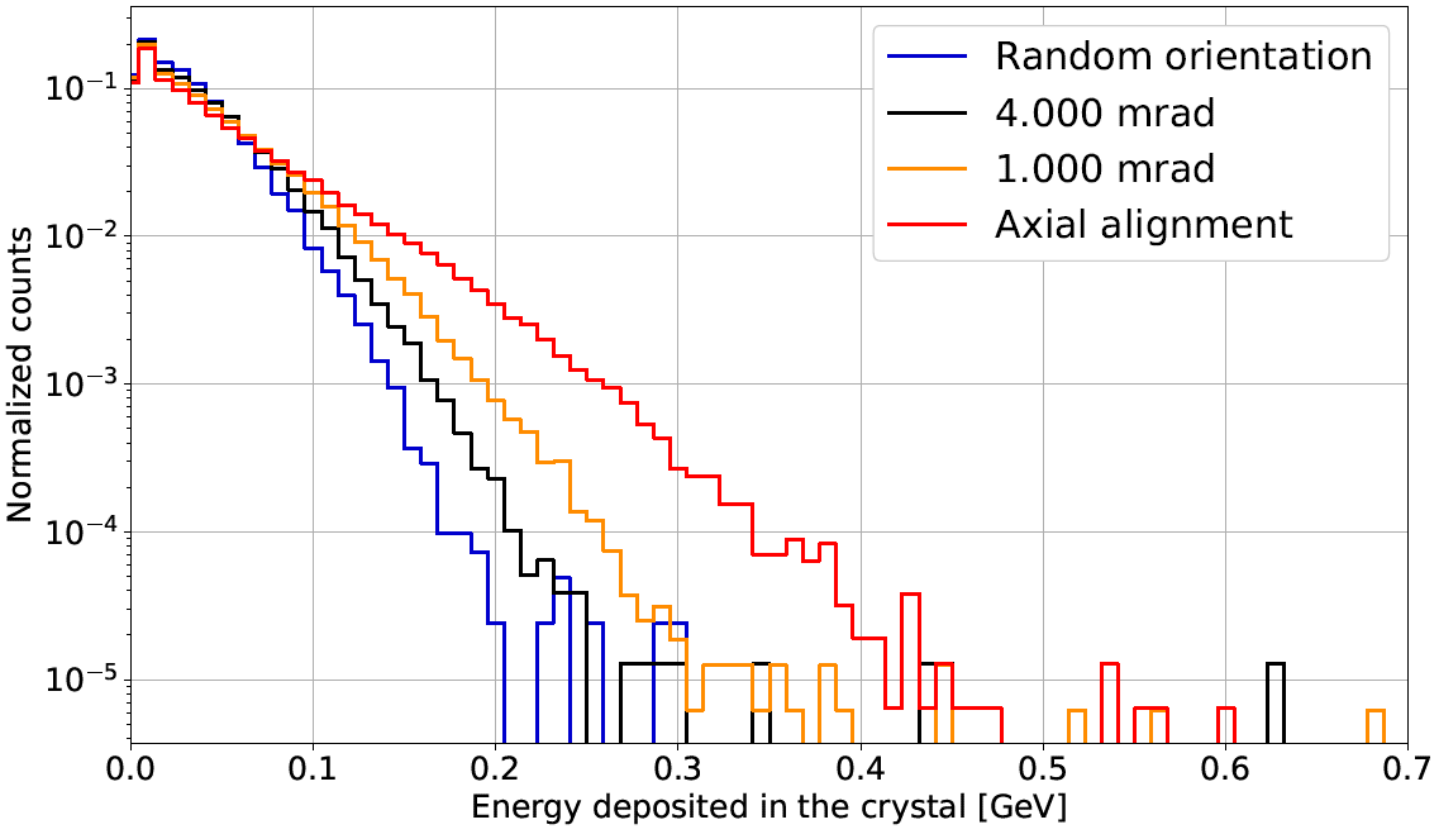
Good agreement with the numerical simulations!

[figures from M. Soldani PhD thesis, 2023]



Strong Field effects in $PbWO_4$ crystals

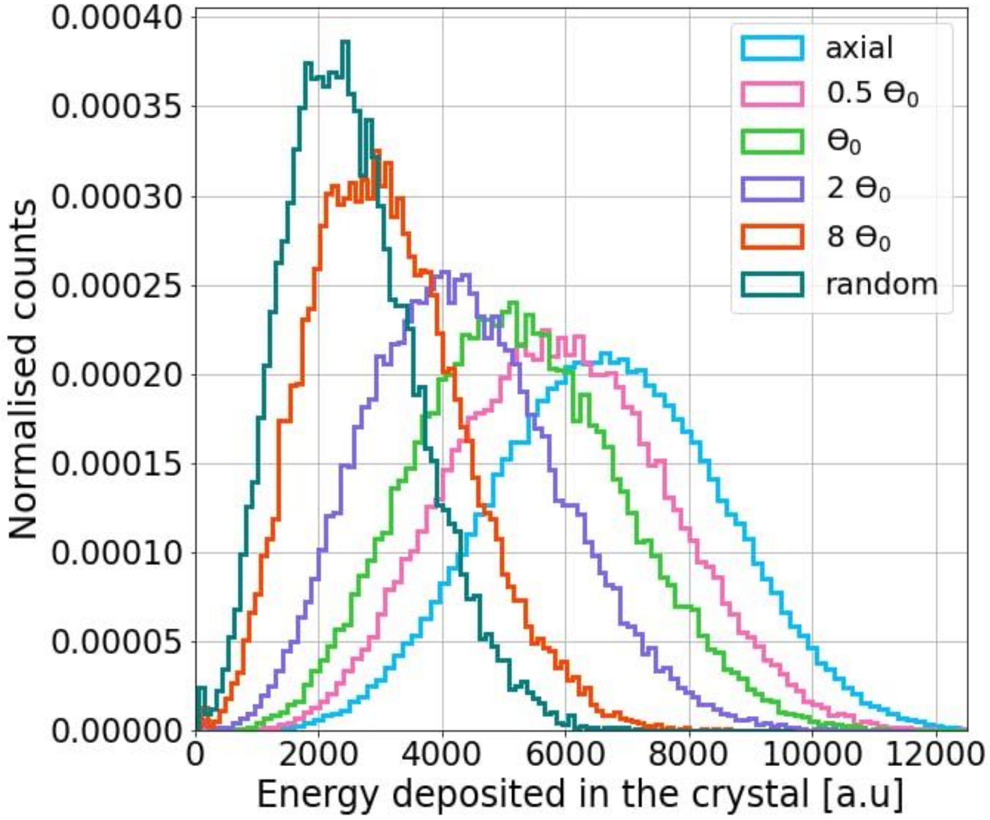


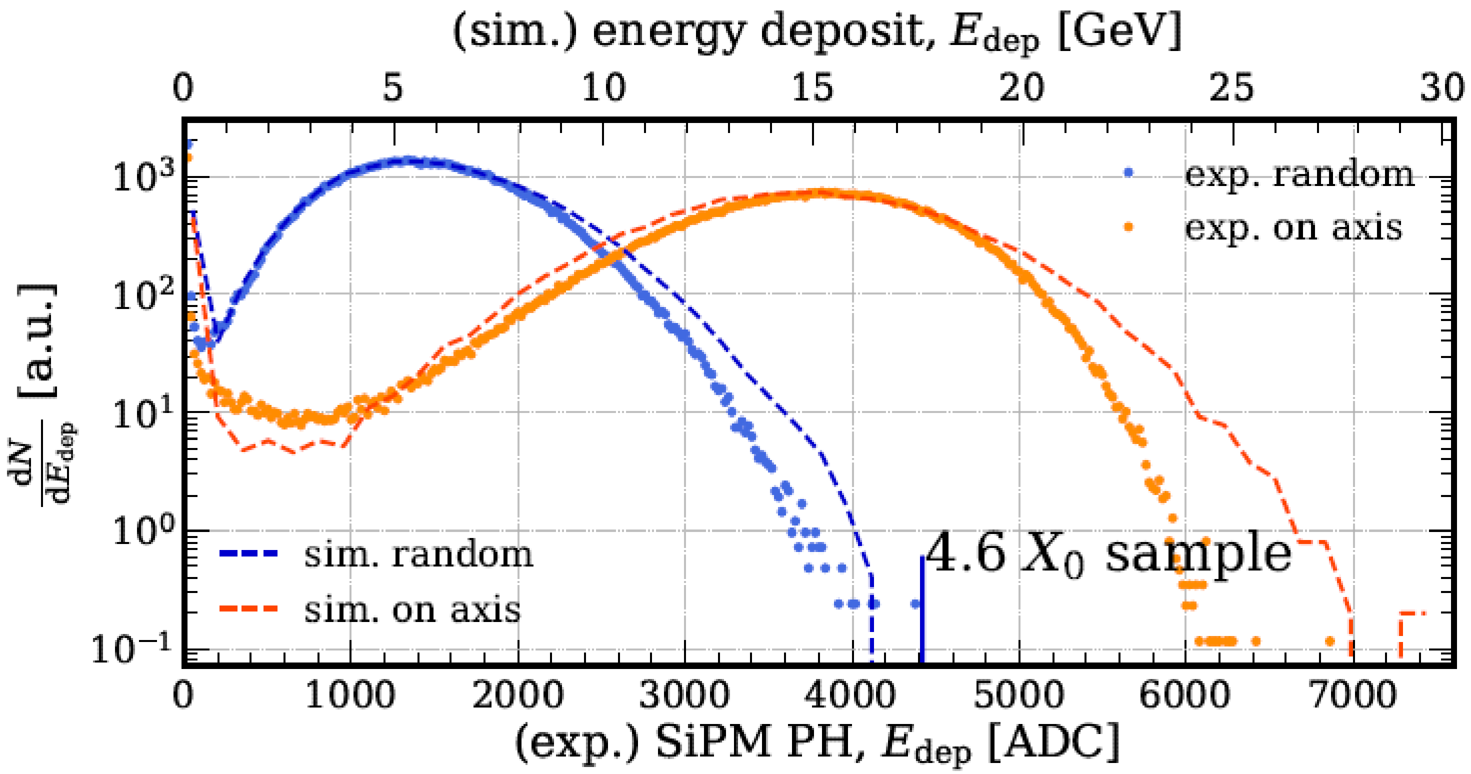


Energy deposited in a $1\,X_0$ $PbWO_4$ crystal by a $120\,\mathrm{GeV}/c$ electron beam (left) and a tagged photon beam (right).

[Figures from A. Selmi MS Thesis, 2022 and P. Monti-Guarnieri MS Thesis, 2023]

Strong Field effects in $\mathbf{PbWO_4}$ crystals

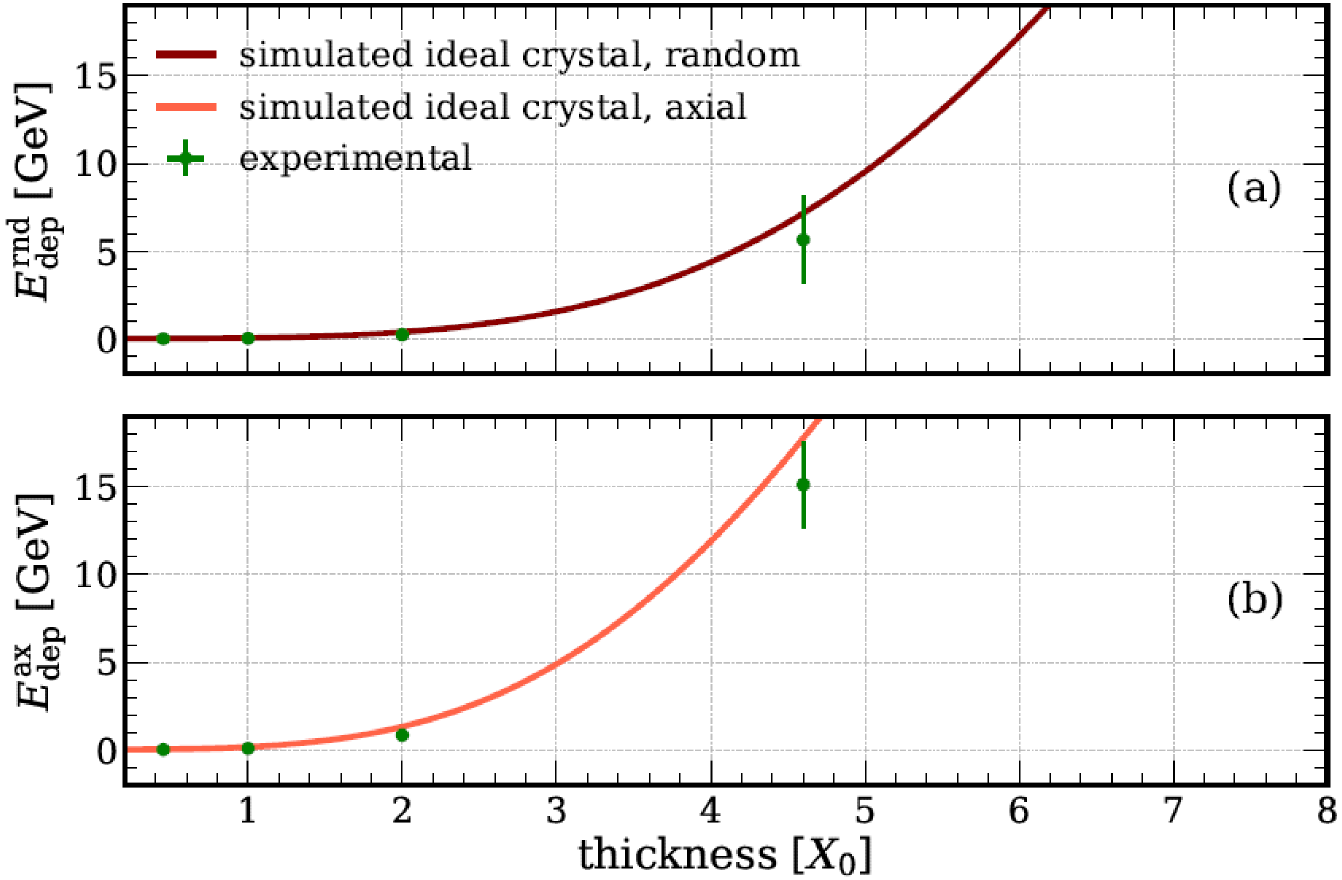




Energy deposited in a $\mathbf{2\,X_0}$ $\mathbf{PbWO_4}$ crystal (left) and a $\mathbf{4.6\,X_0}$ crystal (right) by a $120\ \mathrm{GeV}/c$ electron beam

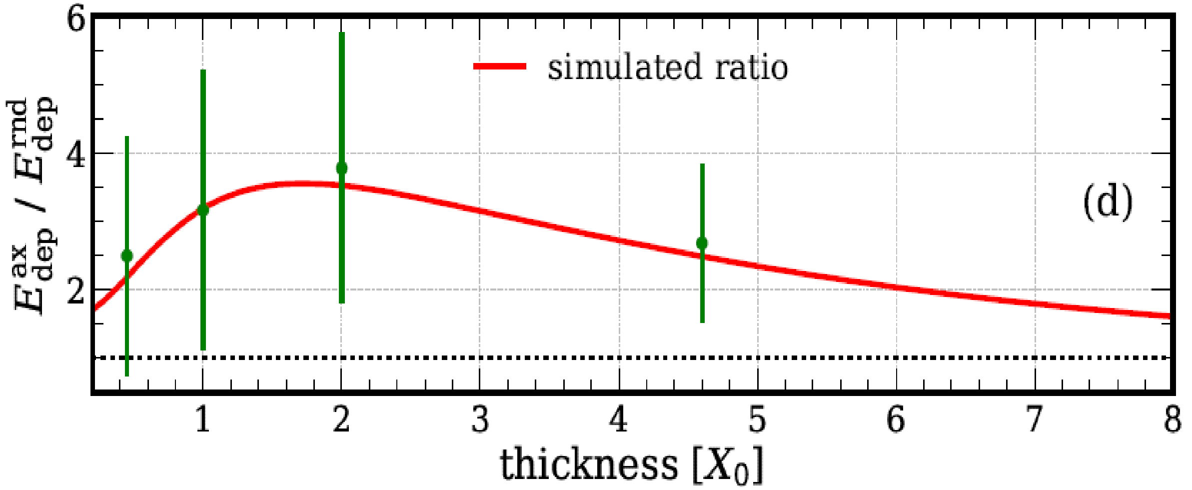
[Figures from A. Selmi MS Thesis, 2022 and P. Monti-Guarnieri MS Thesis, 2023]

Energy absorption curves for $\mathbf{PbWO_4}$



The axial-to-random enhancement of the energy loss **peaks at $\sim \mathbf{3.5}$** and then decreases, due to the angular spread of the e.m. shower.

[figures from M. Soldani PhD Thesis, 2023]



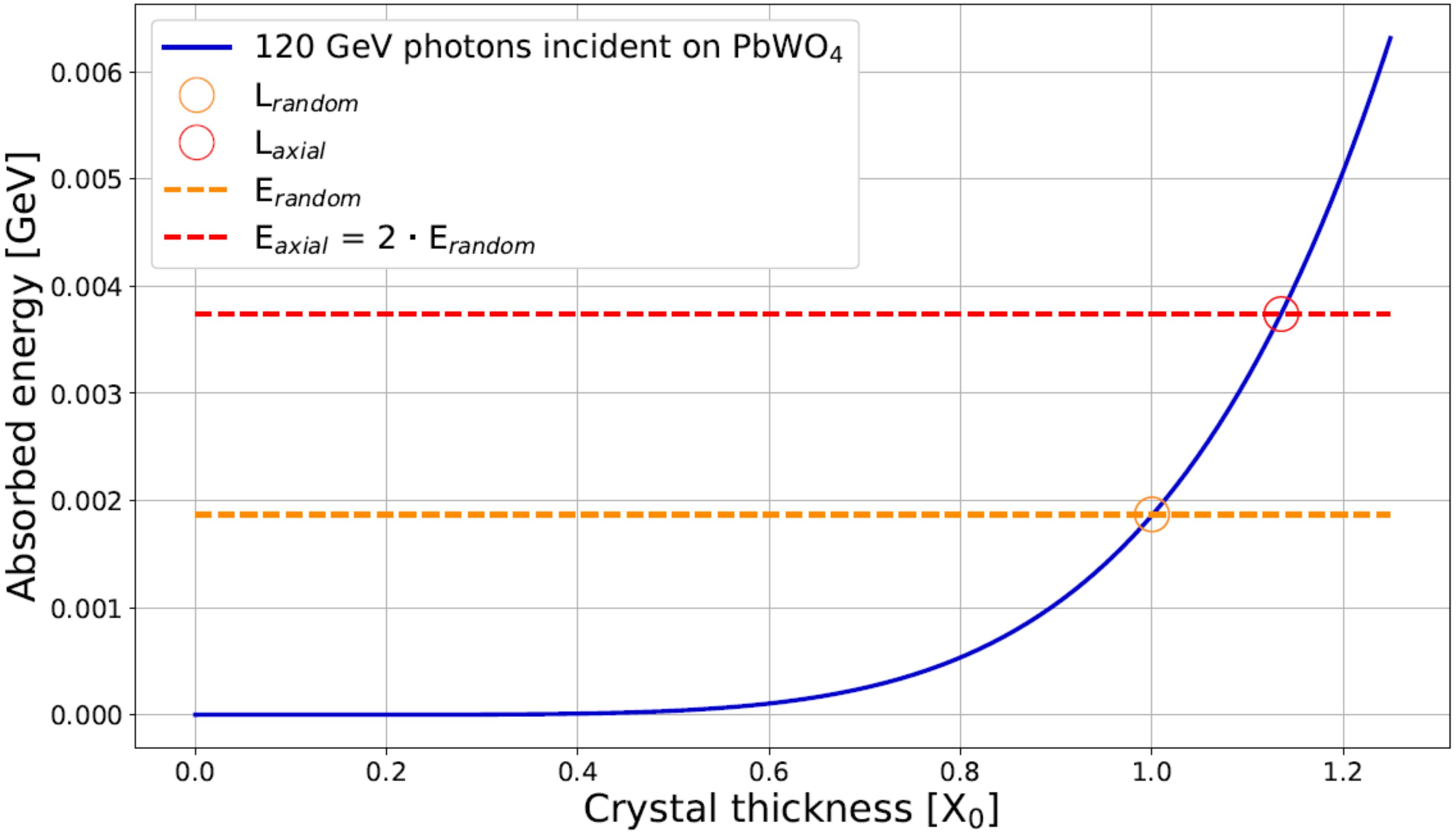
Reduction of the $PbWO_4$ radiation length

Given an energy enhancement factor, the **equivalent length** of the crystal in the axial alignment (L_{eq}) can be estimated, if the energy loss curve in the non-oriented material is known (e.g., with Geant4).

This allows to estimate the **"relative reduction of the radiation length"**:

$$\Delta X_0^{eff} = \left(1 - \frac{L_{true}}{L_{eq}}\right)\%$$

where L_{true} is the physical length of the sample.

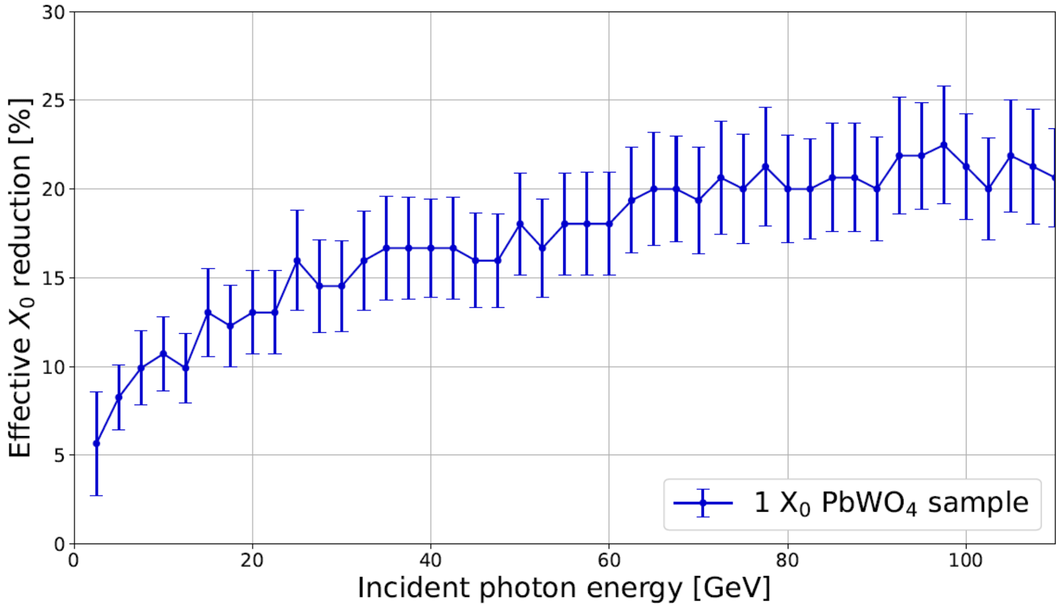


Reduction of the $PbWO_4$ radiation length

Relative reductions of the radiation length of $\mathbf{20-40\%}$ have been observed (w.r.t. the «ordinary» value: $X_0 \sim 8.9$ mm).

[figure from P. Monti-Guarnieri MS Thesis, 2023]

[tabulated values from M. Soldani PhD Thesis, 2023]

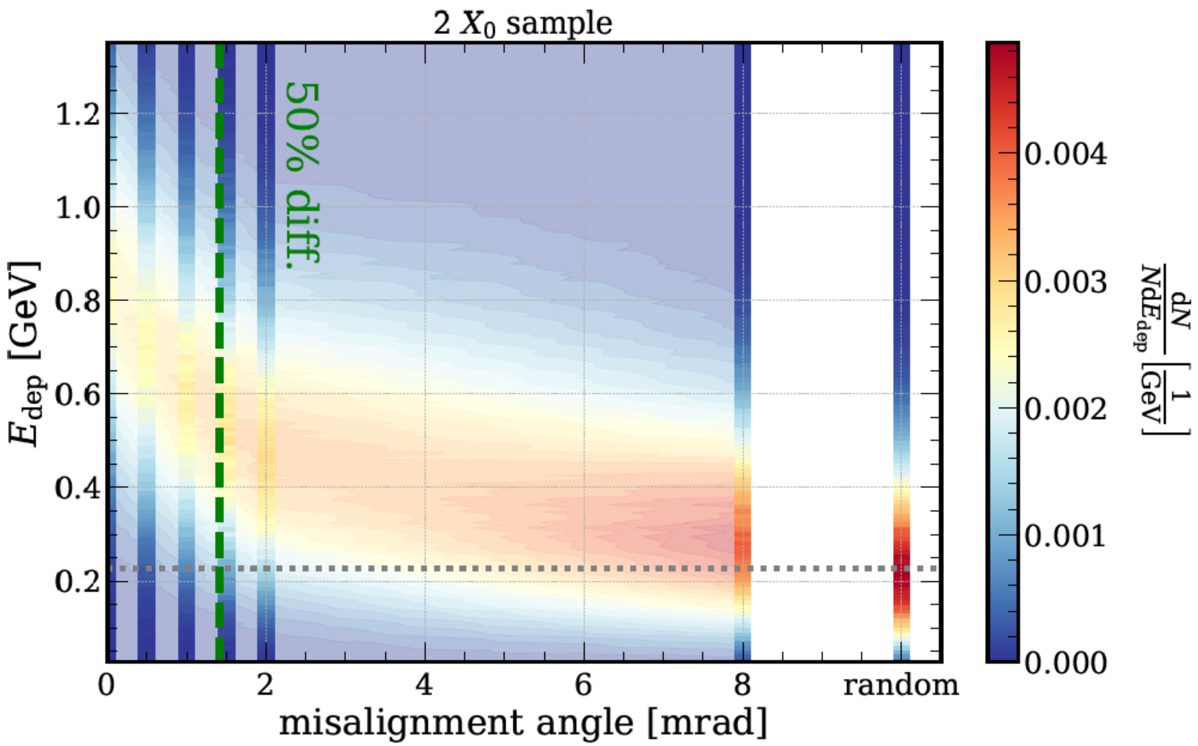


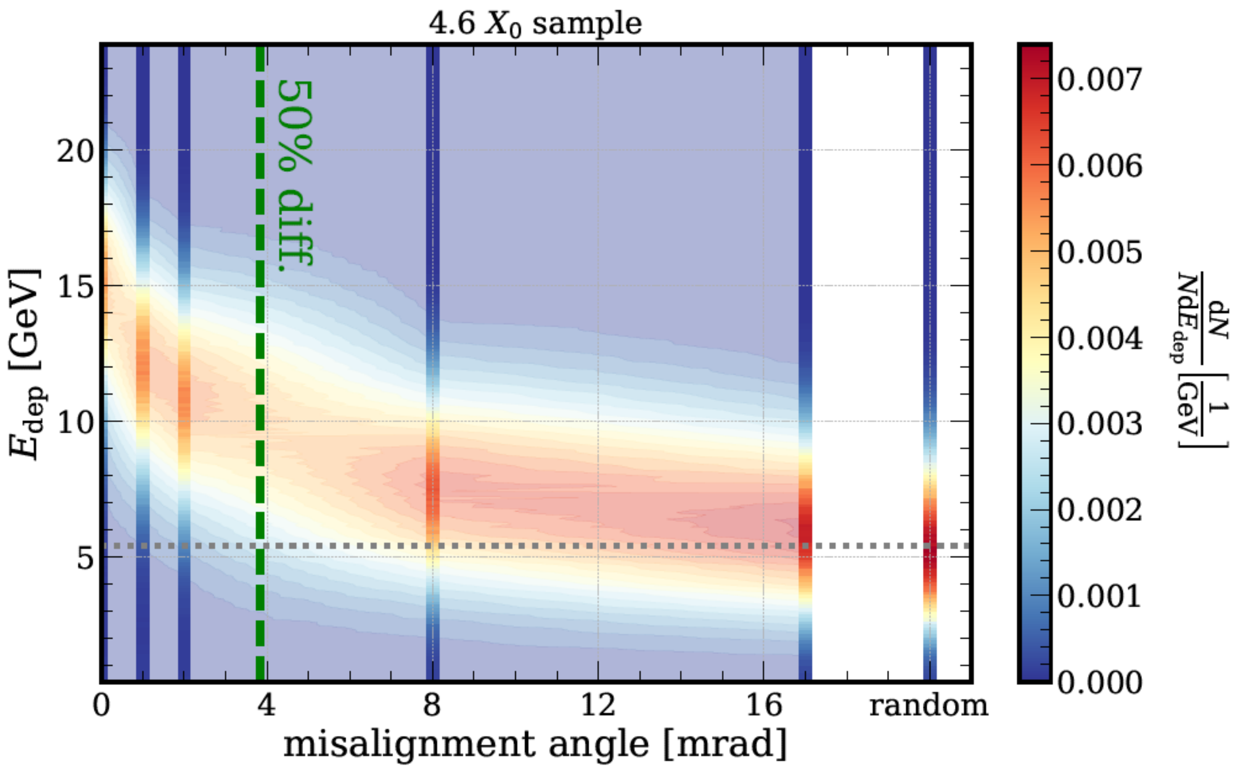
Thickness $[X_0]$	Effective thickness $[X_0]$	Thickness increase $[\%]$	Effective radiation length [mm]	Radiation length reduction $[\%]$
0.45	0.745	65.48	5.38	39.6
1	1.520	51.98	5.86	34.2
2	2.923	46.17	6.09	31.6
4.6	6.208	34.96	6.60	25.9

Angular acceptance of the Strong Field regime

The Strong Field is fully attained only with $\theta \leq \Theta_0 \sim 0.9\,\mathrm{mrad}$, but there is a **non negligible enhancement** up to $8 \cdot \Theta_0$

[figures from M. Soldani PhD Thesis, 2023]





Conclusions & outlooks

Achievements of the **STORM** project:

- ✓ Observation of the acceleration of the e.m. shower in oriented **$PbWO_4$ crystals** ($0.45 - 4.6\ X_0$), with $e^{\pm}$ and γ beams in the $20 - 120$ GeV energy range
- ✓ Measurement of a **$20 - 40\%$ reduction** of the effective radiation length of the material
- ✓ Characterization of the SF regime **for the first time** by means of **direct light detection**
- ✓ Development of novel **tools** for the Geant4 simulation of the interactions in oriented crystals

What remains to be done:

Realize the first **calorimeter** composed of **oriented crystals** (**OREO project**, INFN CSN/5).

Thank you for your attention!

For questions or comments please contact: pietro.monti-guarnieri@cern.ch

$e^{\pm}$ radiative phenomena in an oriented crystal

SB: Standard Bremsstrahlung

CB: Coherent Bremsstrahlung

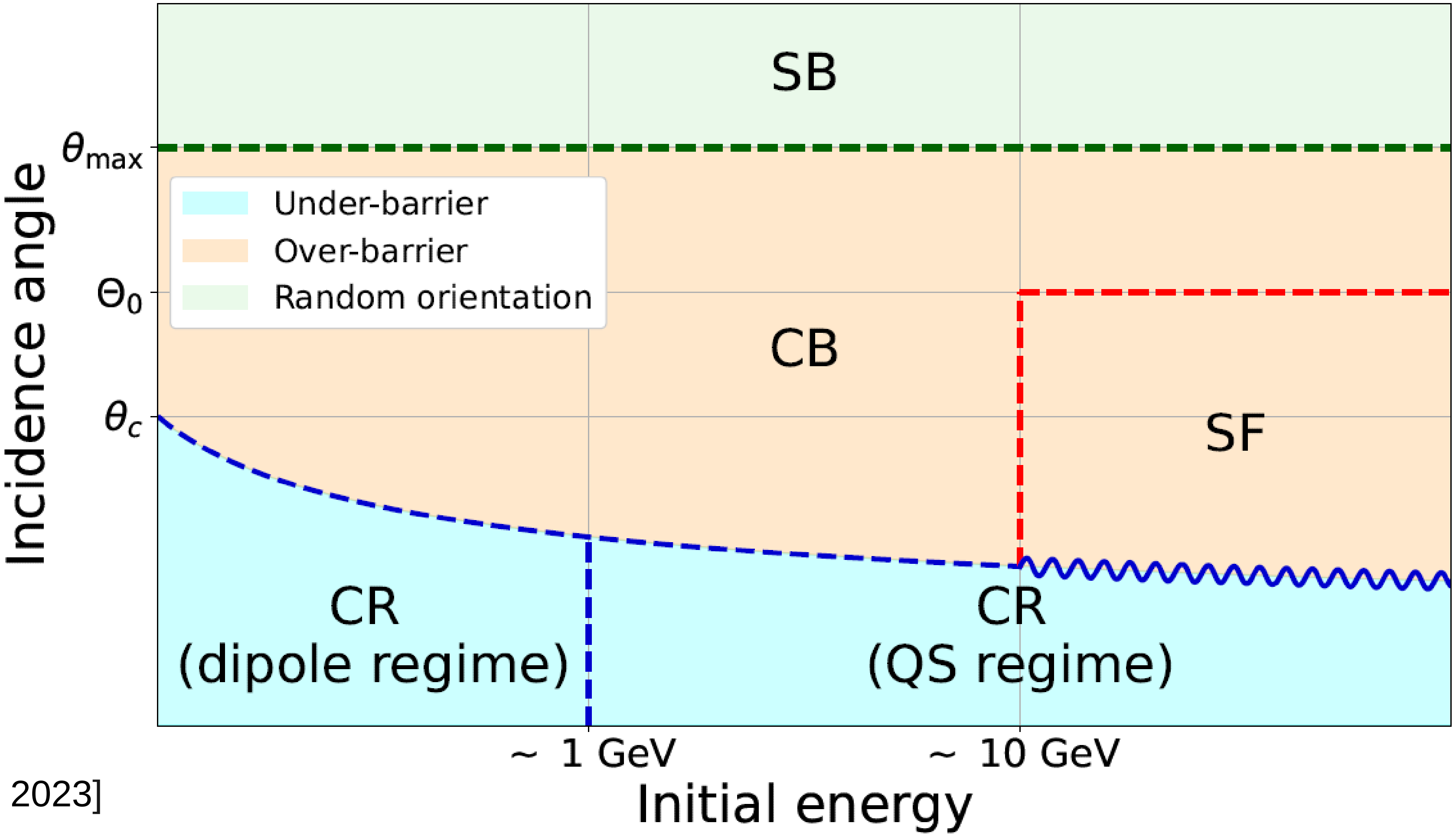
CR: Channeling Radiation

SF: Strong Field

$$\theta_{\max} \sim 50\ \Theta_0$$

$$\Theta_0 = \frac{U_0}{mc^2}$$

$$\theta_c = \sqrt{\frac{2U_0}{pv}}$$

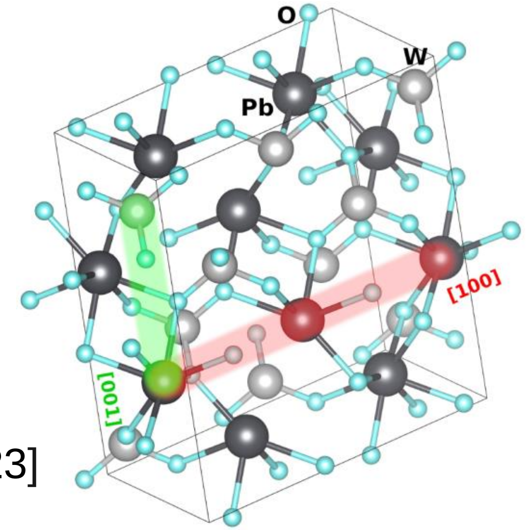


[picture from P. Monti-Guarnieri MS Thesis, 2023]

Why lead tungstate ($PbWO_4$)?

Wide-spread used crystal in particle physics applications (e.g., CMS eCAL), due to:

- Easiness of large-scale production
- Optimal timing properties (PWO-UF)
- Good radiation hardness
- Short radiation length
- High light yield



[picture and tables from P. Monti-Guarnieri MS Thesis, 2023]

Physical parameters [35]		
Parameter	**PbF_2**	**$PbWO_4$**
Density (ρ)	7.78 g/cm^3	8.30 g/cm^3
Relative mass fractions	Pb: 84.6 %	Pb: 45.6 %
	F: 15.5 %	W: 40.4 %
		O: 14.0 %
Minimum ionization (ε_{MIP})	9.34 MeV/cm	10.20 MeV/cm
Radiation length (X_0)	0.94 cm	0.89 cm
Nuclear interaction length (λ_{int})	22.10 cm	20.27 cm
Critical energy for electrons (E_c)	9.35 MeV	9.64 MeV
Molière radius (R_M)	2.12 cm	1.96 cm

Crystallographic parameters		
Parameter	**PbF_2**	**$PbWO_4$**
Lattice structure	Body Centered Cubic [108]	Tetragonal [50]
Reference axis	$\langle 110 \rangle$	$\langle 100 \rangle$
Interatomic pitch (d)	4.19 Å[109]	5.45 Å[110]
Effective screening length (a_{eff})	0.205 Å	0.218 Å
Axial potential well depth (U_0)	332 eV	464 eV [74]
θ_c for 10 GeV/c electrons	0.257 mrad	0.305 mrad
θ_c for 100 GeV/c electrons	0.081 mrad	0.096 mrad
Θ_0	0.650 mrad	0.908 mrad
χ for 10 GeV/c electrons	0.240	0.314
χ for 100 GeV/c electrons	2.400	3.140
Electron energy such that $\chi = 0.1$	4.166 GeV	3.184 GeV
Electron energy such that $\chi = 1.0$	41.659 GeV	31.844 GeV

What about positrons?

[figure from M. Soldani PhD Thesis, 2023]

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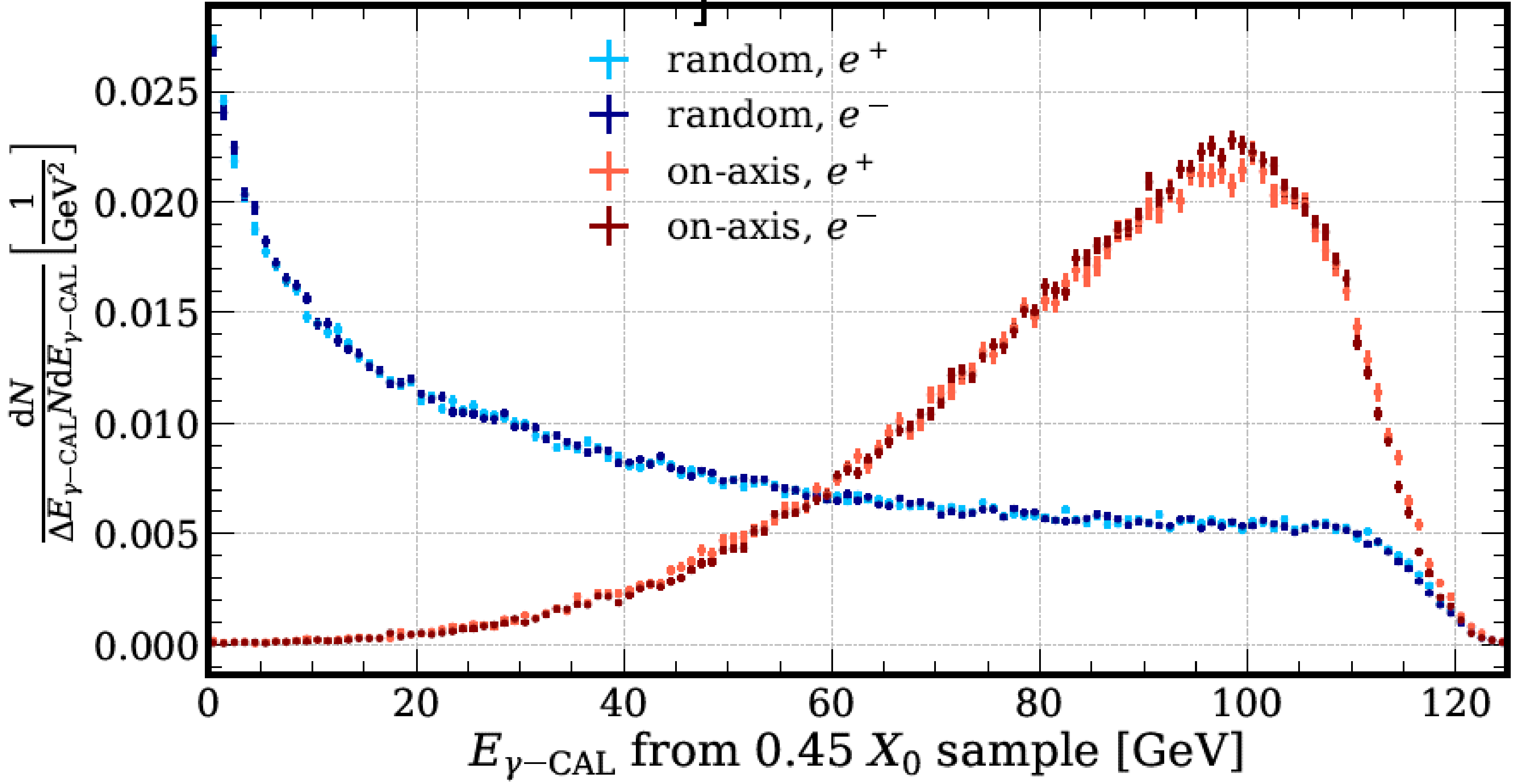
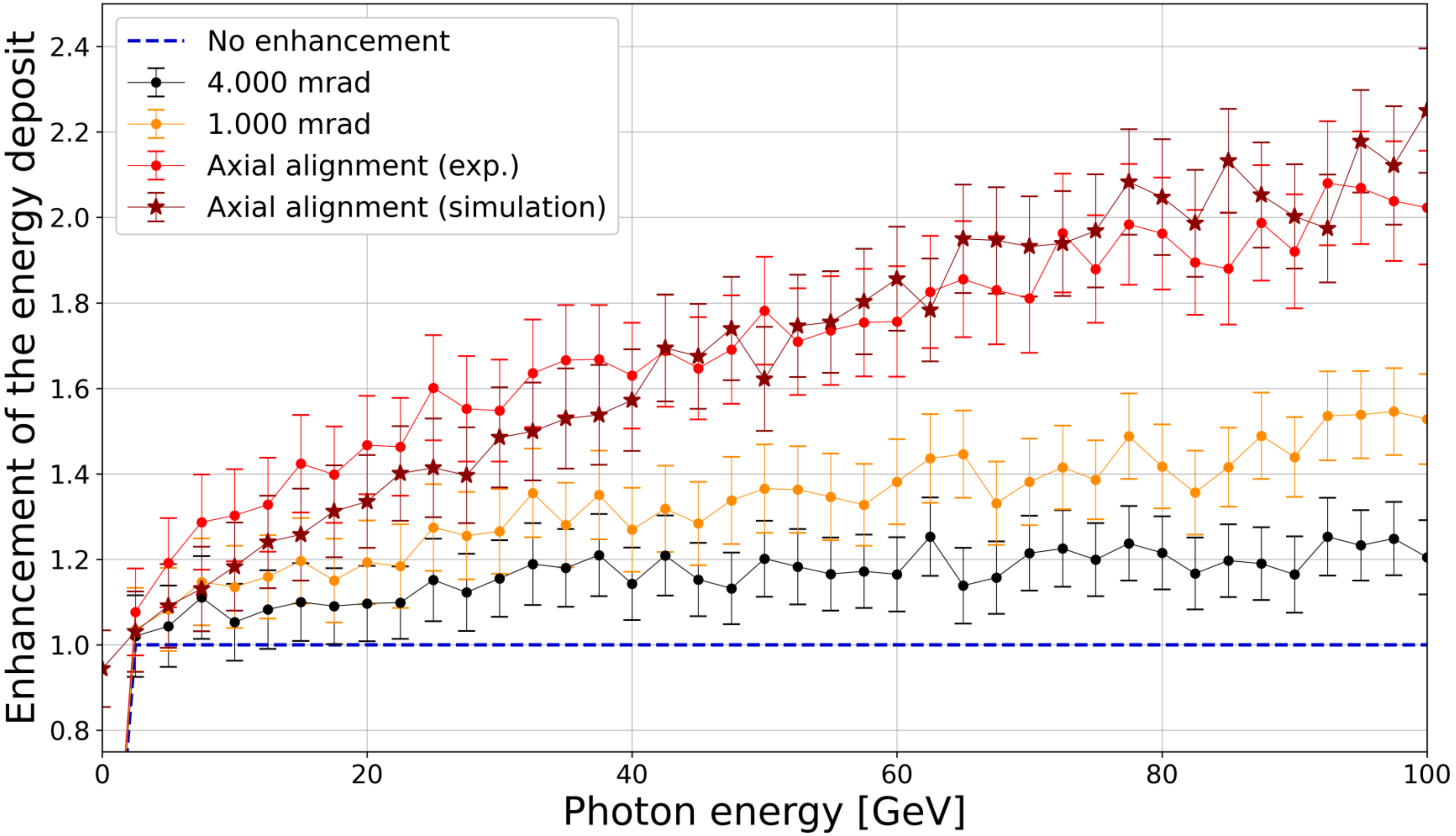


Angular acceptance of the Strong Field regime

Tagged photon beam incident on a $1\,X_0$ $PbWO_4$ sample ($\langle 100 \rangle$ axis)

[figure from P. Monti-Guarnieri MS Thesis, 2023]



Strong Field effects in a Cherenkov radiator ($\mathbf{PbF_2}$)

[figure from P. Monti-Guarnieri MS Thesis, 2023]