next-generation ultra-compact **calorimeters** based on **oriented crystals**

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why *oriented* crystals?

which crystals?

how to probe this?

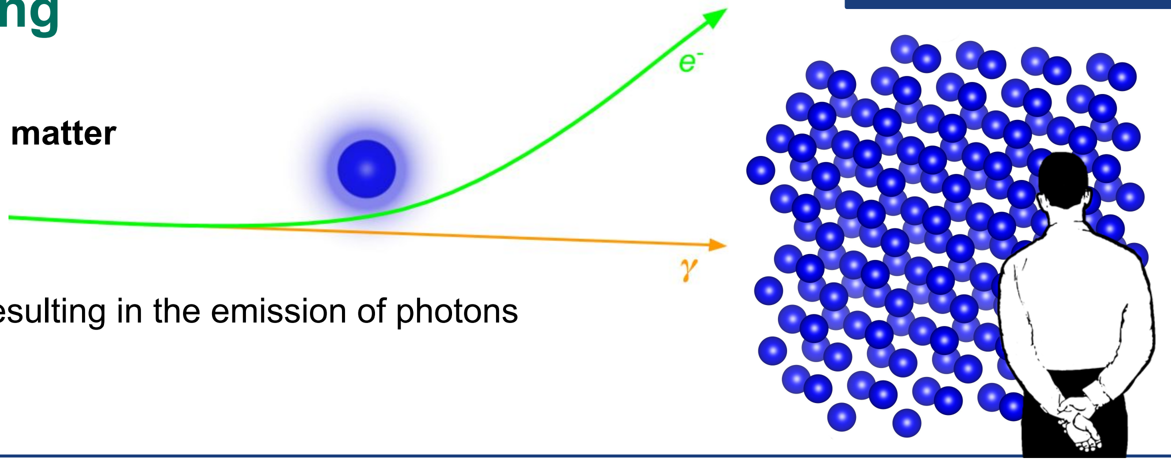
where to exploit this?

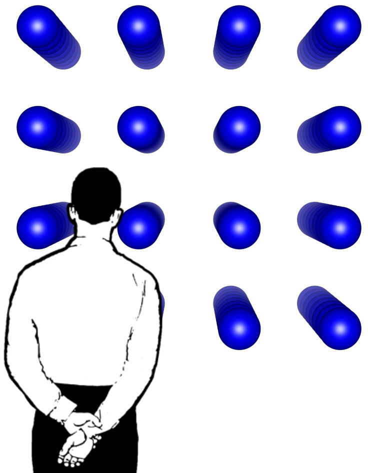
lattice effects **axial channeling**

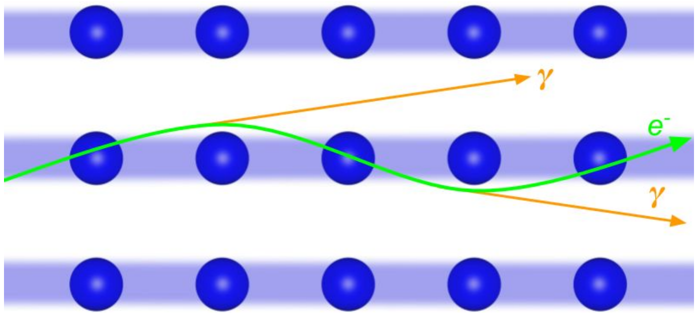
passage of **electrons through amorphous matter**

random interactions with single-nucleus Coulomb fields, independent to each other

→ Bremsstrahlung radiation emission, resulting in the emission of photons with a Bethe-Heitler spectrum







at *small* angle between the particle trajectory and the nuclear strings, **axial condition**:

- continuous potential along the axes (Lindhard) → <u>oscillatory dynamics</u>
- electromagnetic radiation builds up coherently → for ≳GeV particles, <u>high-intensity radiation emission, peaked at high photon energy fraction</u>

the strong crystalline field

small **particle-to-axis angle** (within few mrad)

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

less pronounced effects attained within 1°

+

high energy (≳10 GeV) → **Lorentz contraction**

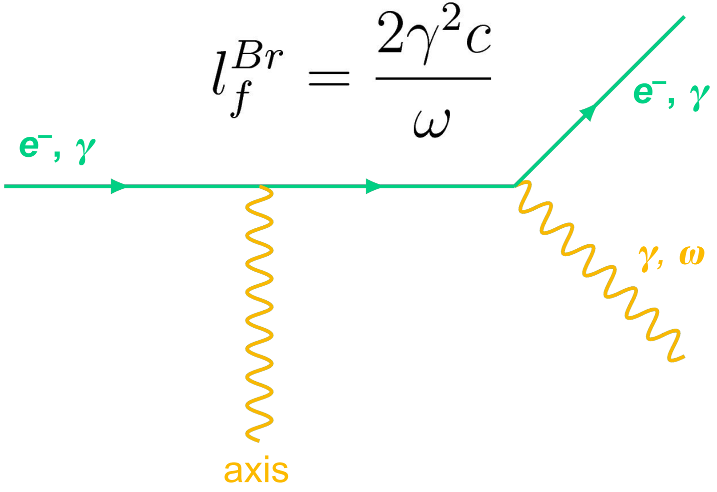
$$\chi = \frac{\gamma E}{E_0} > 1 \qquad E_0 = \frac{m^2 c^3}{e\hbar} = 1.32 \cdot 10^{18}\,\frac{\mathrm{V}}{\mathrm{m}}$$

= Strong Field

(U_0 and E being the axis potential and the corresponding field in the lab frame → crystal-dependent)

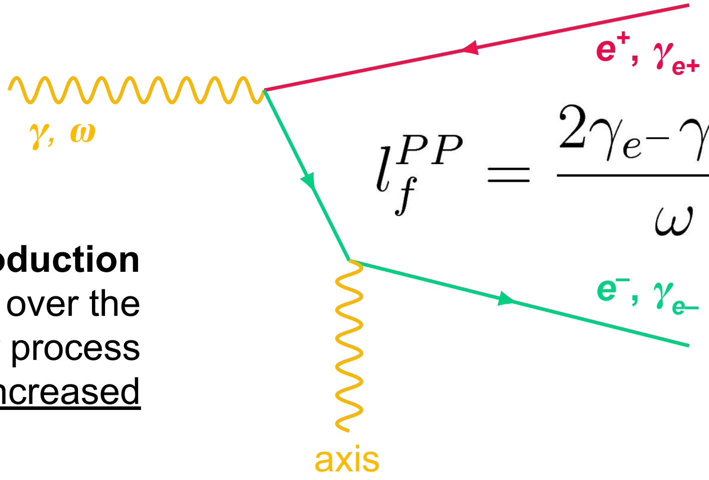
lattice effects **the strong crystalline field**

$$l_f^{Br} = \frac{2\gamma^2 c}{\omega}$$



enhanced Bremsstrahlung
quantum synchrotron radiation (in which electron fractional energy loss is non-negligible)
→ more intense hard photon emission

$$l_f^{PP} = \frac{2\gamma_{e^-}\gamma_{e^+}c}{\omega}$$



enhanced Pair Production
coherent interaction dominates over the Bethe-Heitler process
→ overall PP cross section strongly increased

light-emitting crystals

electromagnetic shower is way more compact

or equivalently

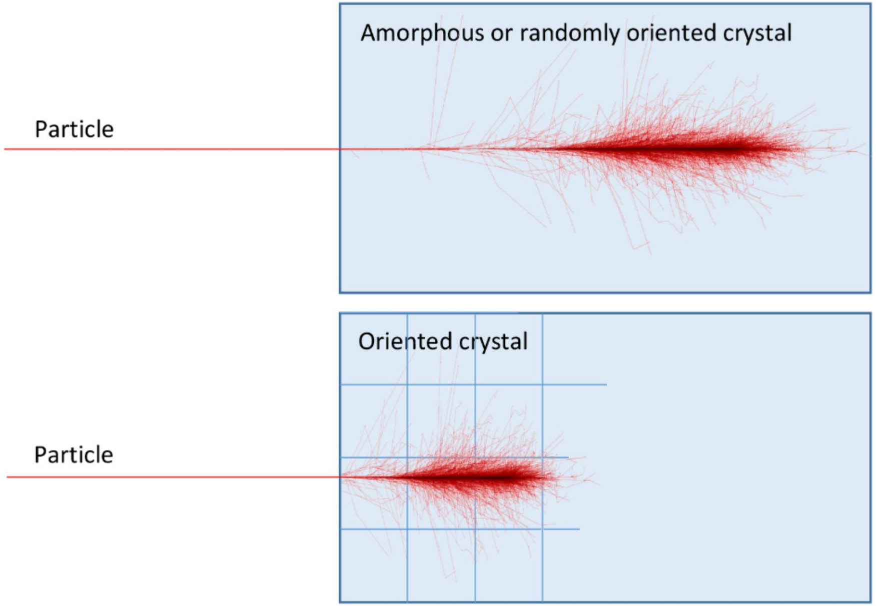
effective radiation length X_0 is much shorter

scintillators and Cherenkov emitters commonly employed in HEP electromagnetic calorimetry: lattice effects are neglected

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, with the same light yield</u>

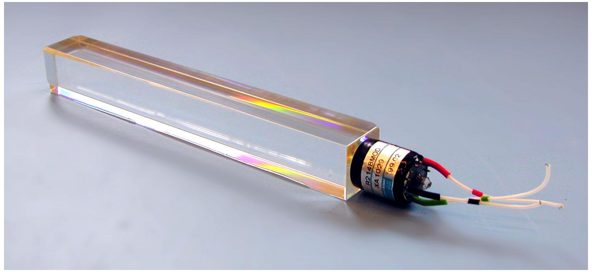
→ enhanced compactness

→ budget-saver



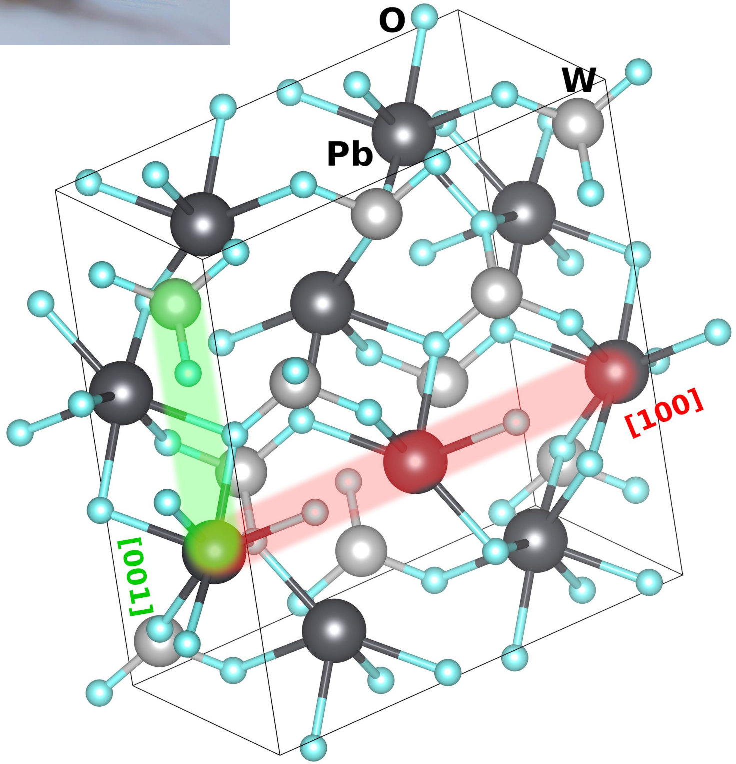
status of the investigation

$PbWO_4$



- scintillator, with well-peaked light emission in the blue
- optically transparent
- exploited by the CMS ECal → well known
- high density, high *Z*
- short X_0 (8.903 mm) and Molière radius
- cheap fabrication into big samples and with good crystalline quality
- axes properties

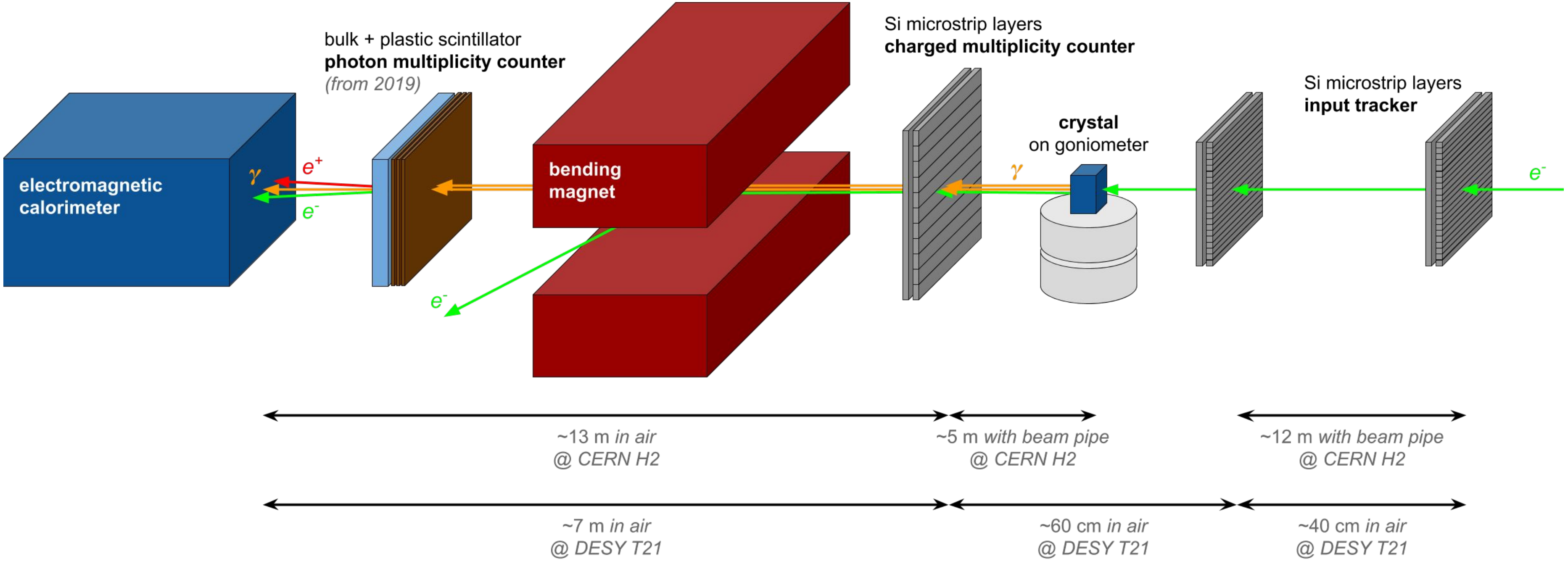
	[001]	[100]
interatomic pitch	12.020 Å	5.456 Å
U_0	~600 eV	~700 eV
Θ_0	~1 mrad	
SF threshold (χ=1)	~30 GeV	



status of the investigation

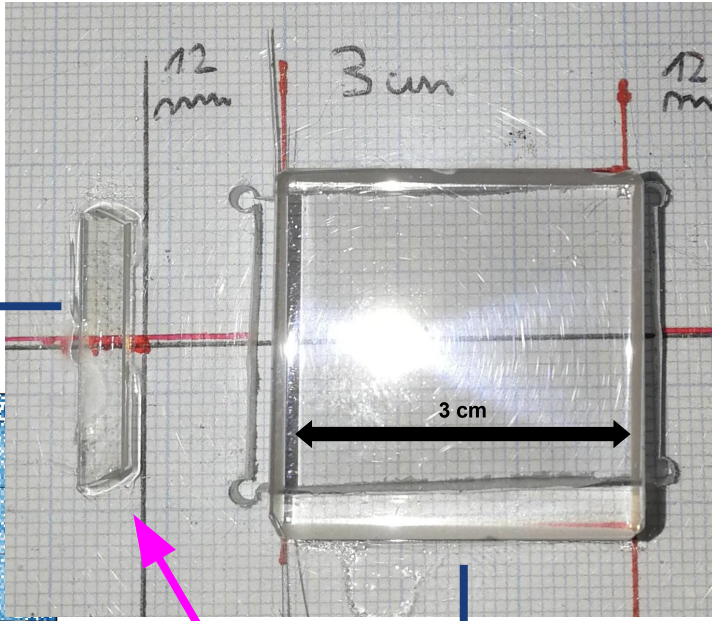
since 2017, tests with **electron beams** at

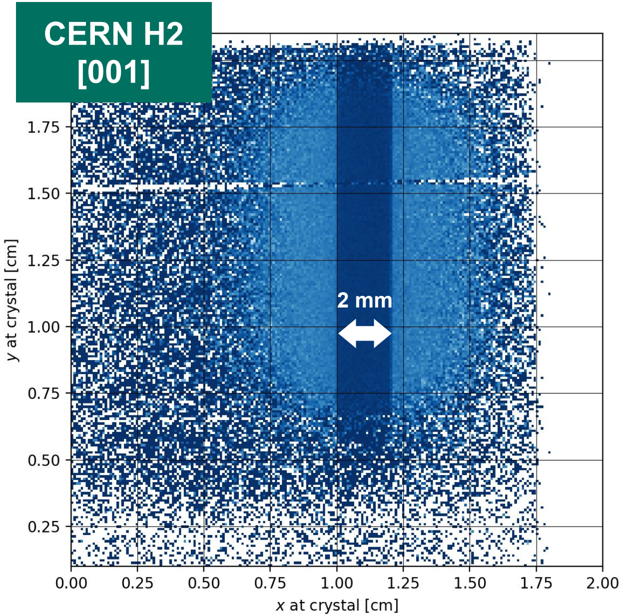
- CERN H2, H4 at **120 GeV/*c*** ***χ*~4** → full SF regime
- DESY T21 at **5.6 GeV/*c*** ***χ*~0.2** → below SF threshold, but still within its regime

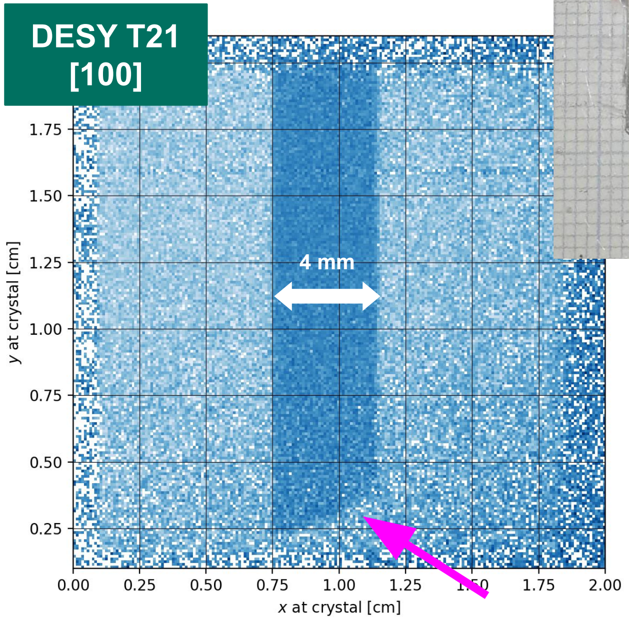


the test samples

strip
~0.22 X_0 thick when in [100] configuration
~0.36 X_0 thick when in [001] configuration







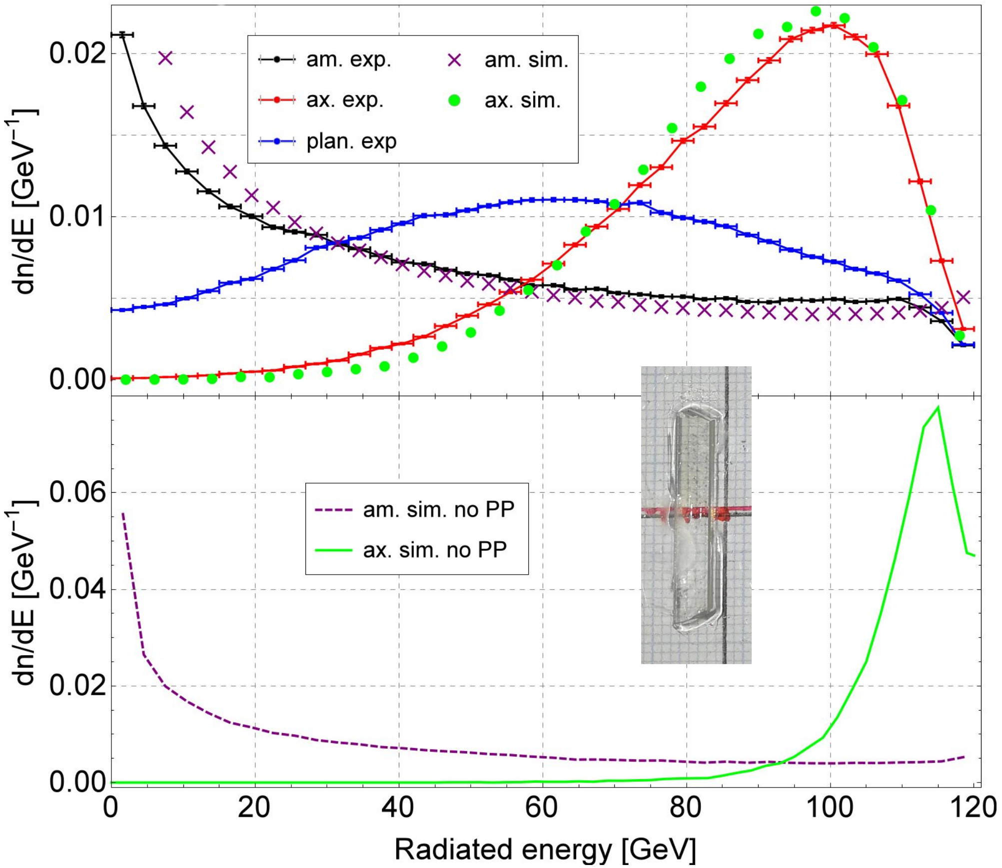
square
huge and thick (~X_0) PWO [100] block machined from a CMS ECal endcap spare element

2017 @ CERN **output radiation**

study of the **energy loss** (emerging as electromagnetic radiation) inside the sample:

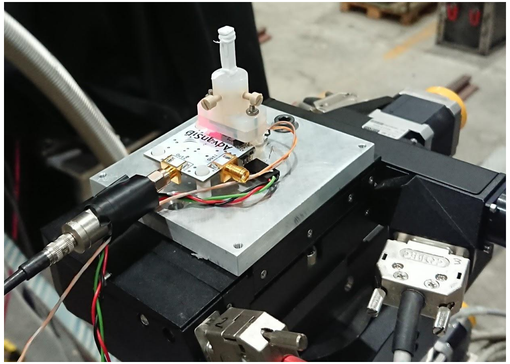
- full agreement between measured spectra and simulations

- <u>on-axis</u> net energy loss indicates a <u>5-fold reduction of the crystal X_0 with respect to the off-axis amorphous-like case</u>

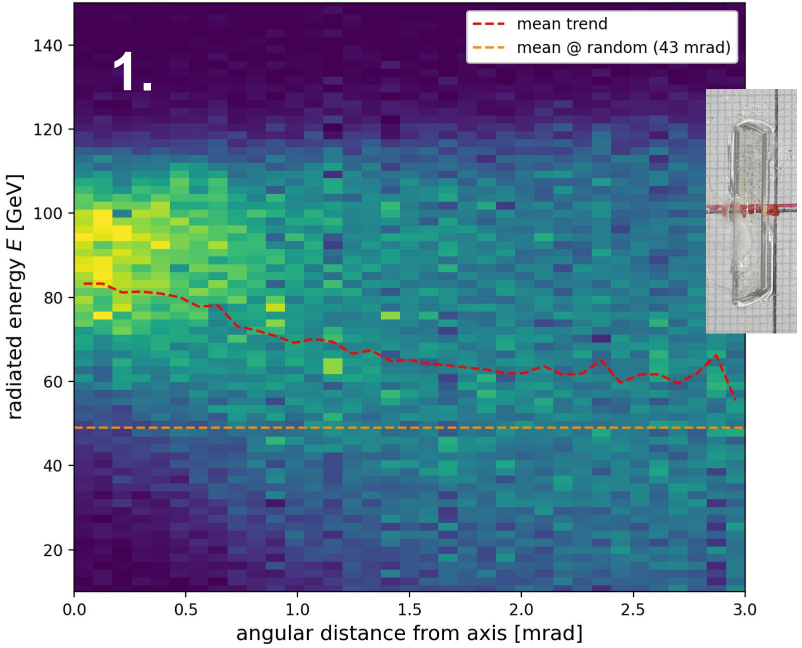


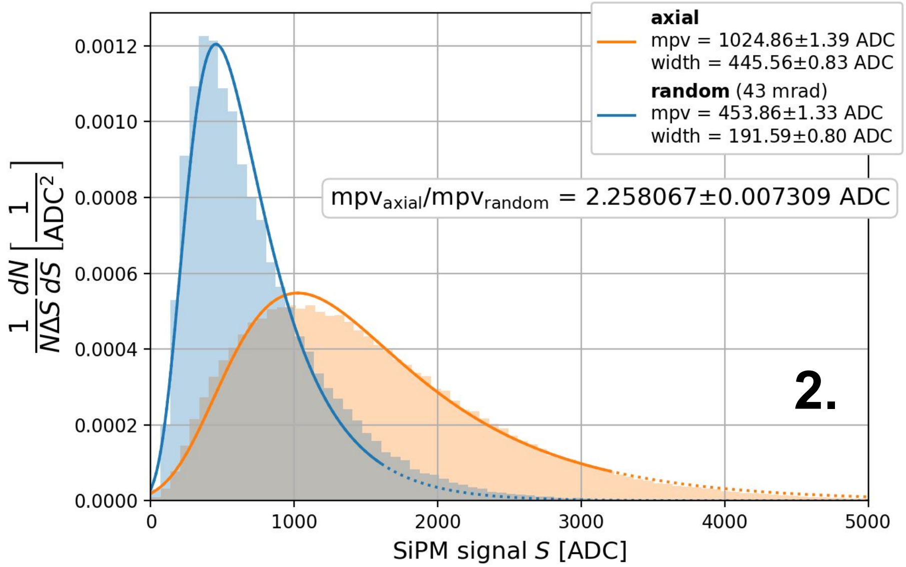
L. Bandiera et al. **Strong reduction of the effective radiation length in an axially oriented scintillator crystal** *Phys. Rev. Lett.*, 121(2):021603, 2018

2018 @ CERN light yield enhancement

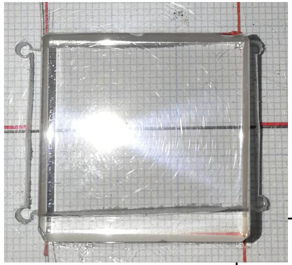


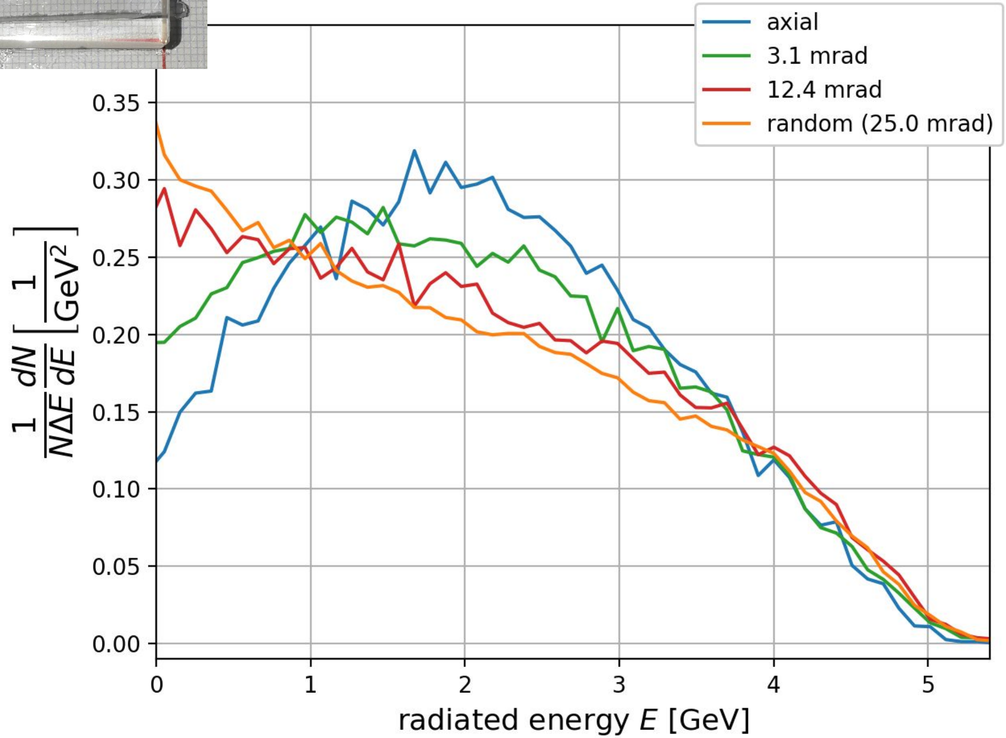
1. SF **angular range**: enhancement peak within ~2 mrad around the axis, while the effect extends up to several mrad (→ ~1°)
2. SiPM-based sample **scintillation light readout**: axial-to-random (i.e. amorphous-like) signal peak ratio is fully compatible with the simulations





2019 @ DESY **radiation at the GeV scale**

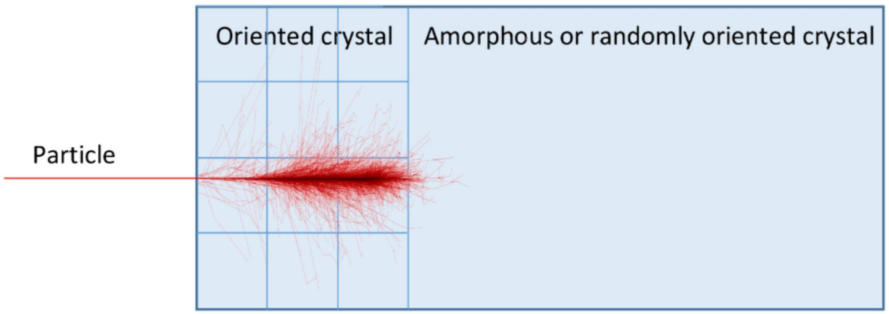




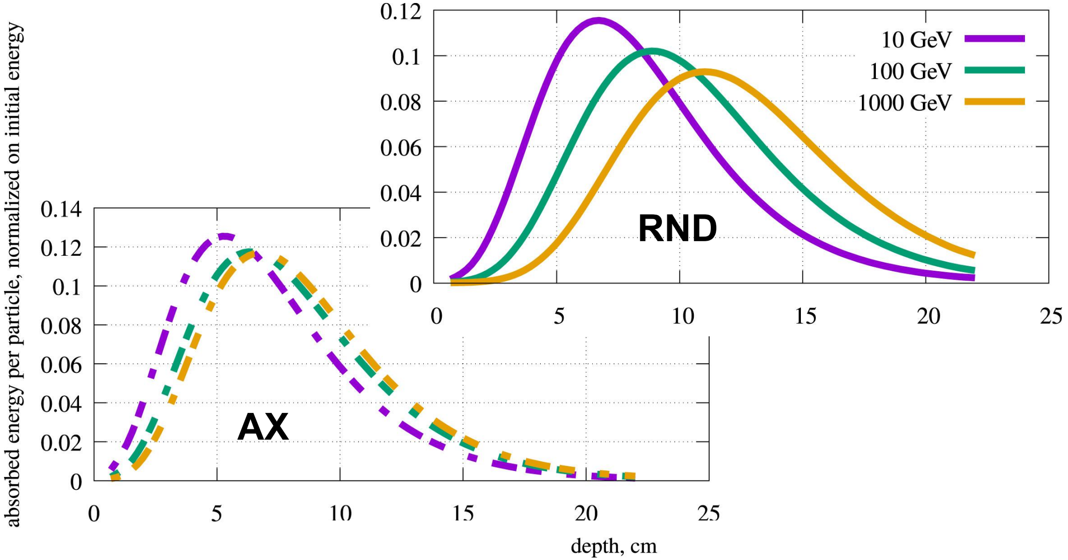
energy loss studies in the **sub-SF** energy regime and **in a wide angular window**: axis still affect the radiation spectra macroscopically; effect angular range is very large and transition to amorphous-like configuration is smooth

applications HEP fixed-target experiments

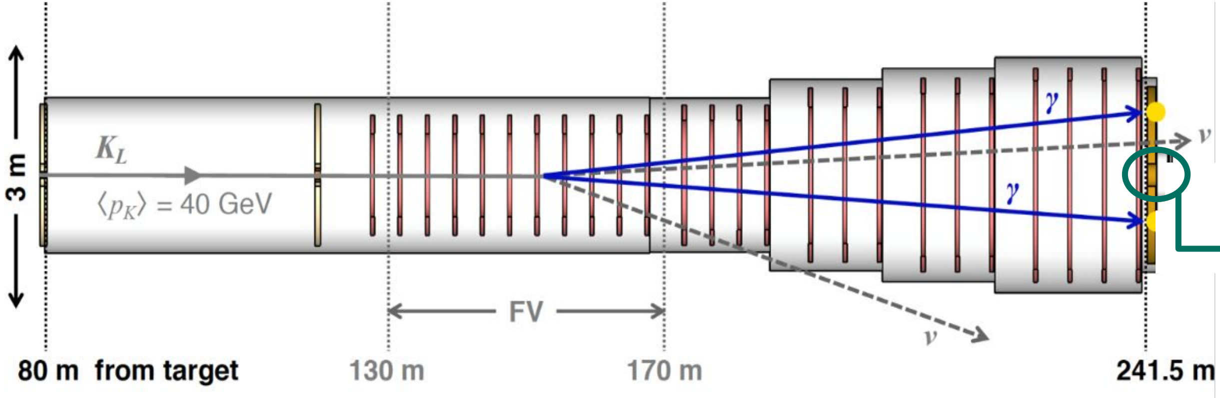
- forward geometry → particles enter the detector with <u>small angle, small transverse area</u>
- in case of large-angle events, performance will equal that of the current state of the art
- a structural compromise between oriented (front side) and random layers (rear side): <u>optimal trade-off between compactness, cost and mechanical alignment precision</u>



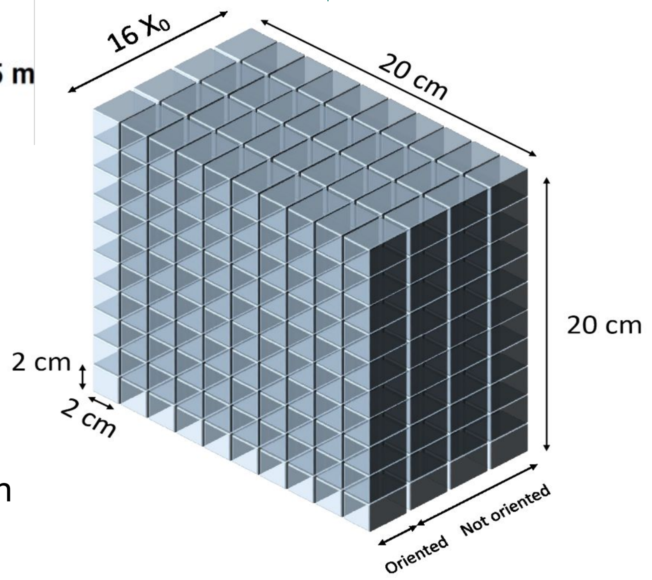
note: the higher the particles energy, the stronger the shower enhancement, → in the end, <u>the shower peak longitudinal position is independent on the initial energy</u>



applications KLEVER Small Angle Calorimeter



K_L Experiment for VEry Rare events
it will study $K_L \to \pi^0 \nu \underline{\nu}$ at the CERN SPS



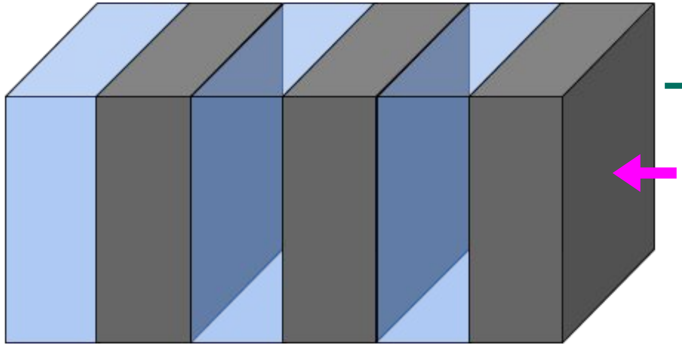
main requirement: high sensitivity to photons (with moderate energy resolution) and blindness to neutral hadrons (≲500 MHz background vs ~140 MHz input K_L), i.e. small X_0 and large λ_{int}

→ **this is a job for an oriented crystal!**

candidates
- **PWO** scintillator, well-known
- **PbF_2** (lead fluoride) Cherenkov emitter → good time resolution

M. Moulson **KLEVER: An experiment to measure BR($K_L \to \pi_0 \nu \underline{\nu}$) at the CERN SPS** *J. Phys. Conf. Ser.*, 1526(1):012028, 2020

applications sampling calorimeters



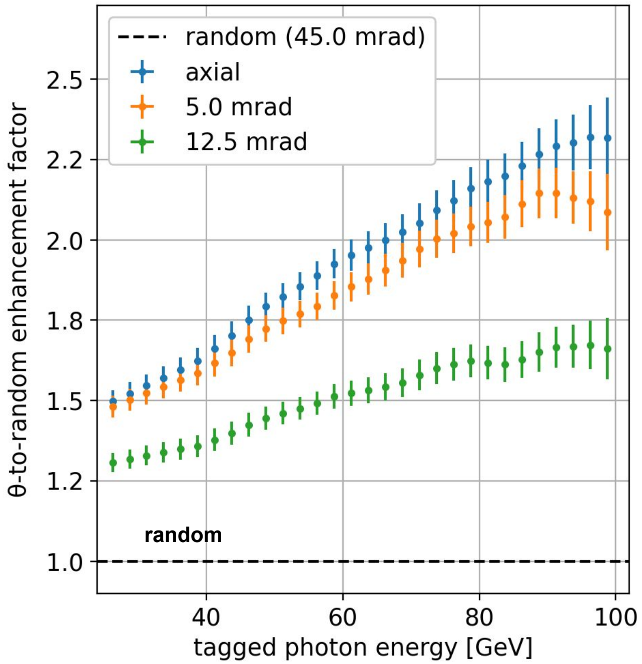
passive layers
<u>oriented crystalline</u> metals, e.g. <u>tungsten</u>

- compact and lighter
- budget-friendly
- possibility of improving the energy resolution

active layers
standard plastic scintillator and readout system
→ well-known technology

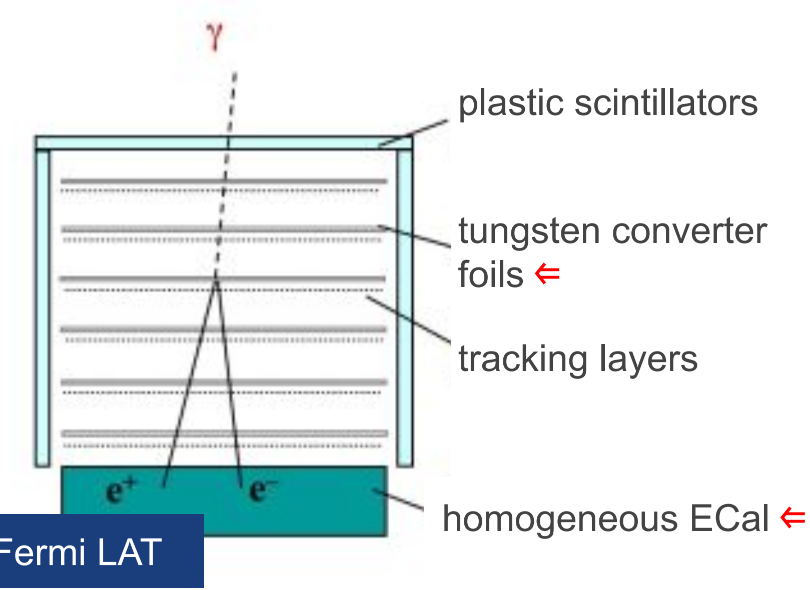
test at CERN H2 in 2018 with a Bremsstrahlung photon beam (endpoint 120 GeV) and a [111] tungsten oriented sample,
KLEVER beamline photon converter candidate

(results to be published soon…)



applications satellite-borne γ observatories

- typical event: high-energy (≳100 GeV) photons from well-localised, point-like sources
- lightweight detector with no energy resolution limitation → excellent for the rocket payload and for the operation budget
- currently available satellite pointing systems can aim at the γ sources with less than 1° angular resolution
- in absence of a pointing system or in case of unexpected large-angle events, the crystals retain the current state-of-the-art resolution



e.g. Fermi LAT

oriented crystals might represent an important milestone in the progress of electromagnetic calorimetry

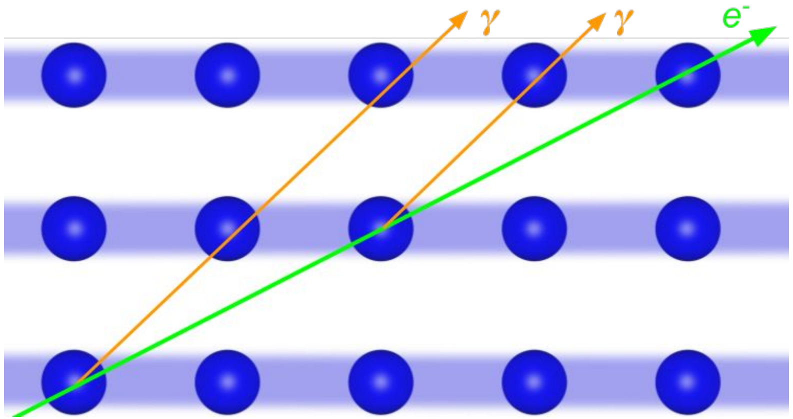
outlook

- further beamtests with new crystalline samples, both optically transparent (e.g. PbF_2) and metallic (e.g. Ir)
- experimental setup optimisation for the measurement of the output radiation in terms of single photons
- further tests with photon beams to probe he Strong Field PP features
- development of a custom readout system for the scintillation and Cherenkov light emitted inside the samples → larger-scale detector prototype…

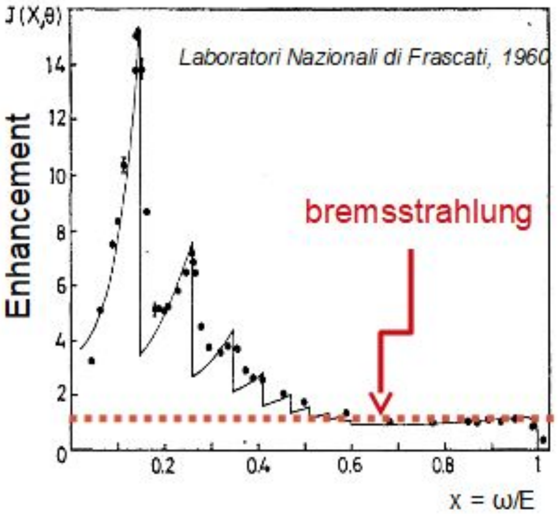
thank you!

any comments or questions? contact me at *mattia.soldani@fe.infn.it*!

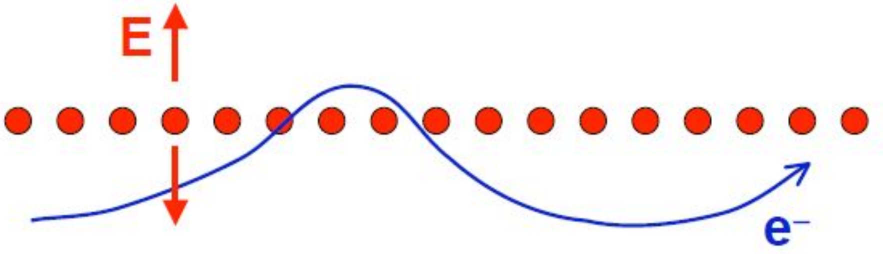
Coherent Bremsstrahlung/Pair Production



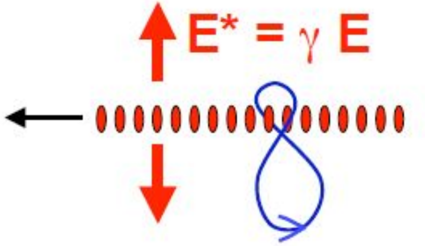
incidence angle >>Θ_0 wrt. the axis and match between the charge-lattice momentum transfer and a reciprocal lattice vector, i.e. trajectory along an off-axis periodic string → overbarrier coherent effect, contributing to the Bremsstrahlung/PP enhancement at large angle (up to 1°) + monochromatic components



crystalline field Lorentz boost



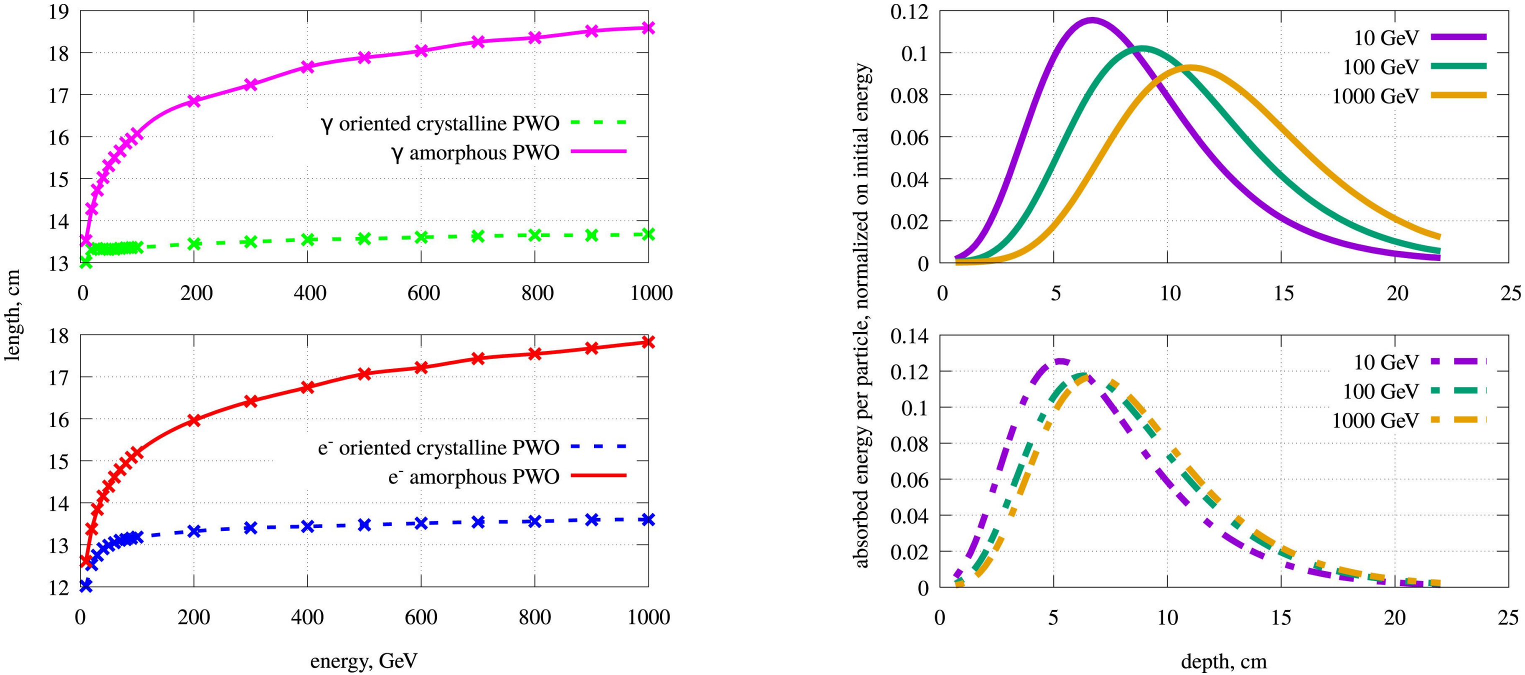
lab. frame



e⁻ - comoving frame

Geant4-based simulations

important inputs are given by simulations performed with a **modified Geant4** version — Bremsstrahlung and PP cross sections are rescaled in agreement with full Monte Carlo based on the Baier-Katkov quasi-classical operator method to simulate the radiation/PP enhancement in oriented crystals.



V. Guidi, L. Bandiera, V. Tikhomirov **Radiation generated by single and multiple volume reflection of ultrarelativistic e⁺ and e⁻ in bent crystals** *Phys. Rev. A*, 86:042903, 2012

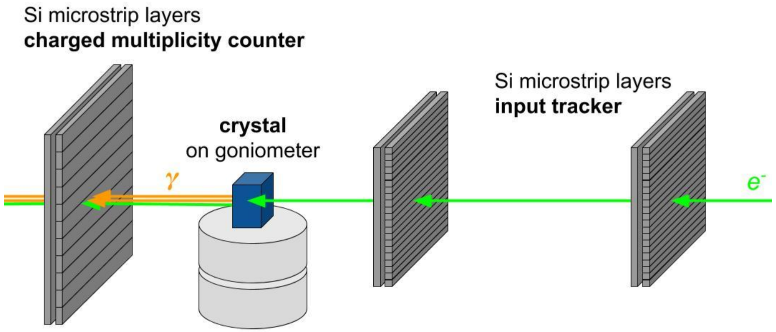
L. Bandiera, V.V. Haurylavets, V. Tikhomirov **Compact electromagnetic calorimeters based on oriented scintillator crystals** *Nucl. Instr. Meth. A*, 936:124, 2019

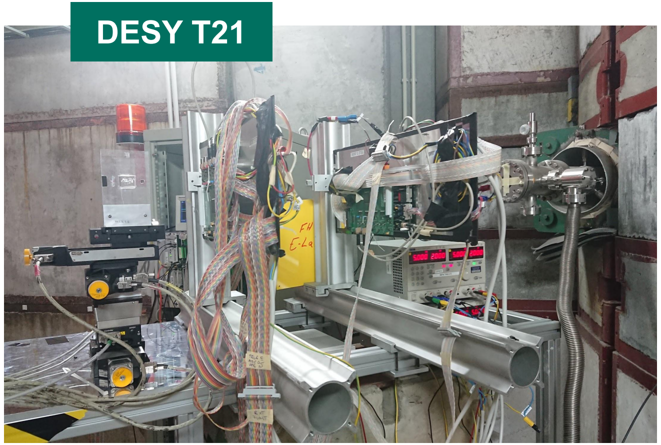
the setup input stage

input tracker
~2×2 cm² *xy* double-sided Si microstrip sensors, with 50 µm readout pitch, analog readout and an overall ~10 µm single-hit resolution

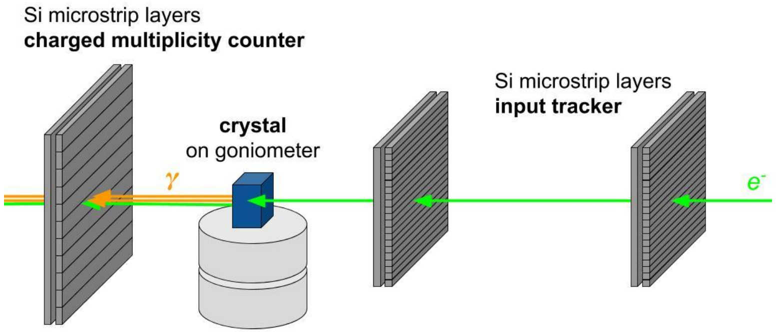
output charged multiplicity counter
pair of ~10×10 cm² single-sided Si microstrip sensors, with 242 µm readout pitch, analog readout and an overall ~35 µm single-hit resolution

goniometer
fine-grained, remote-controlled movements along x, y, θ_x and θ_y with ~5 µm/µrad resolution

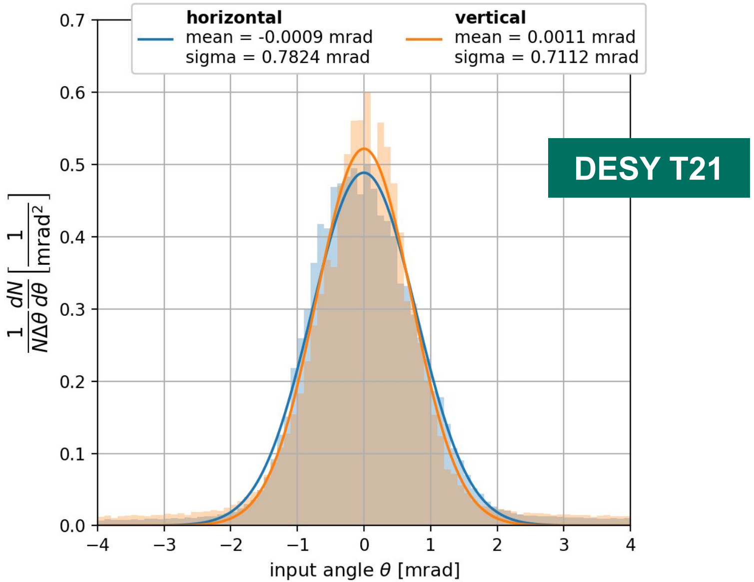


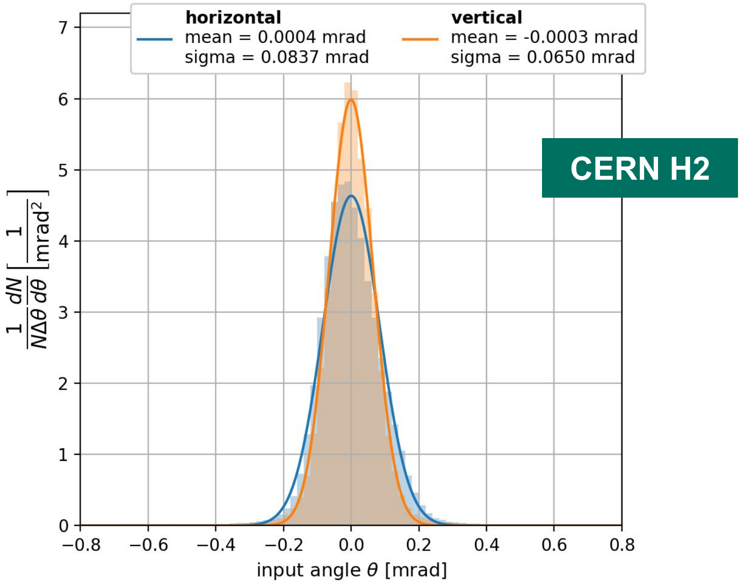


the setup the beams



input angle distributions
divergences differ by a factor ~10





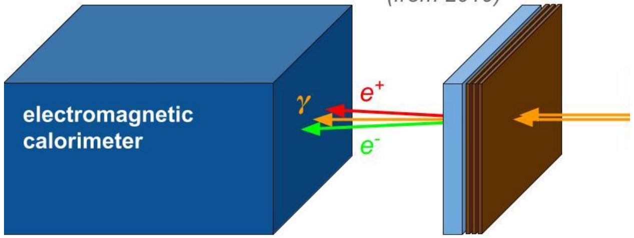
the setup **output stage**

different **calorimeters** have been exploited:

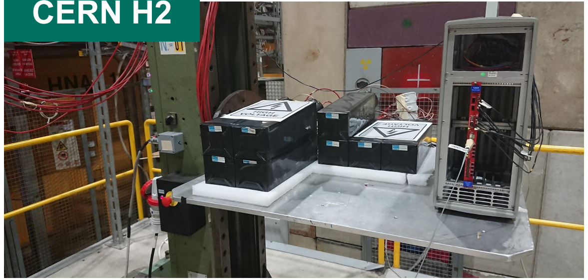
- CERN H4: 3×3 matrix of PWO blocks from the CMS endcap, SiPM-based readout
- CERN H2: (OPAL) Pb glass blocks read out by PMTs
- DESY T21: 3×3 matrix of BGO blocks from the PADME calorimeter, PMT-based readout

a **photon multiplicity counter** was installed and tested for the first time during the 2019 beamtest at DESY T21, to ensure better sensitivity to the samples lattice axes on a statistical basis

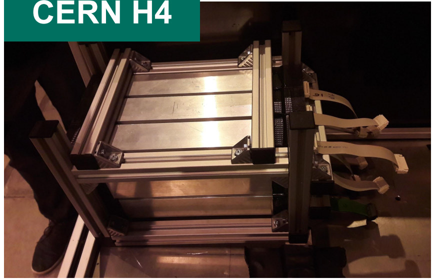
bulk + plastic scintillator
photon multiplicity counter
(from 2019)



CERN H2

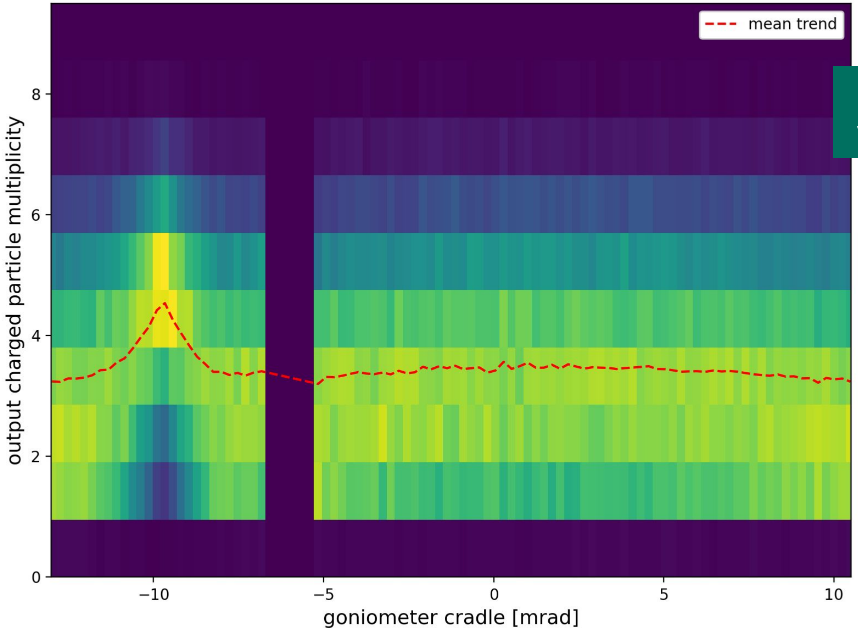


CERN H4

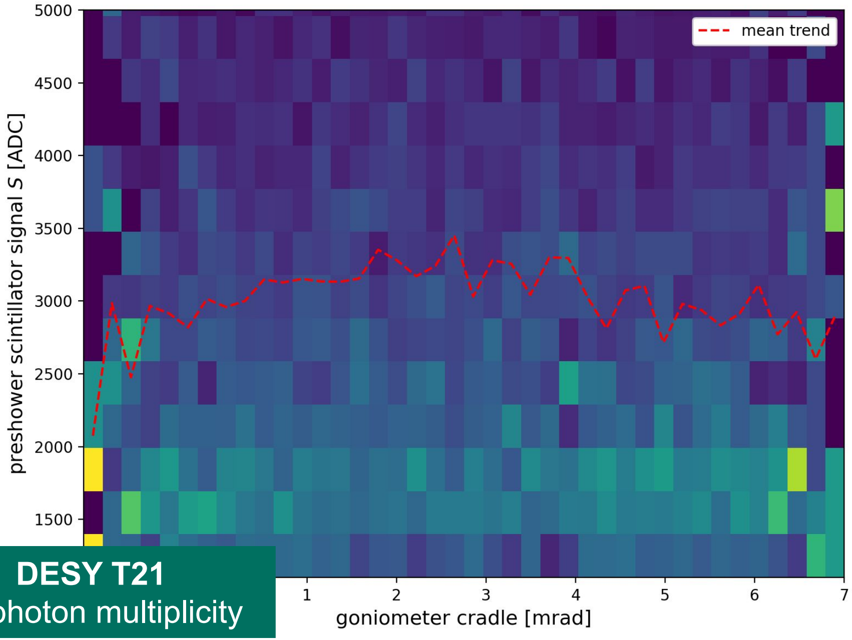


DESY T21

the setup **sample alignment**



CERN H2
via charged multiplicity



DESY T21
via photon multiplicity

sampling vs homogeneous detectors

light-emitting crystals

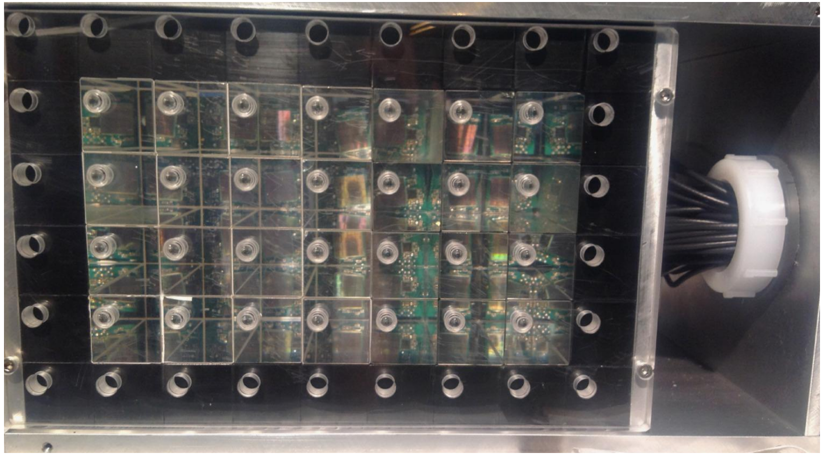
- commercial samples have very small mosaicity, which is also much smaller than the SF angular range
- can be grown *easily* up to any size
- cheap
- *slightly* weaker lattice effects

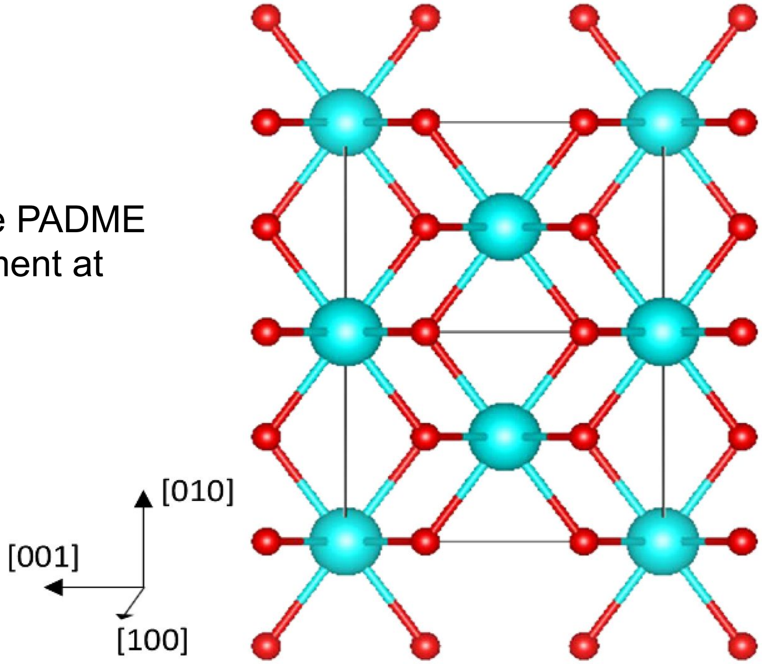
metallic crystals

- very strong lattice effects
- easy machining
- limited to small-size samples → ok for radiators/photoconverters

PbF_2 (lead fluoride)

- transparent, Cherenkov light emitter
- high density, high *Z*
- X_0 = 9.3 mm (slightly higher than $PbWO_4$)
- suitable for the development of a fast calorimeter
- already exploited (with random orientation) by the PADME experiment at LNF and by the E989 (*g*-2) experiment at Fermilab





K_L Experiment for **VE**ry **R**are events

$$BR(K_L \to \pi^0 \nu \overline{\nu}) \longrightarrow$$

new physics!

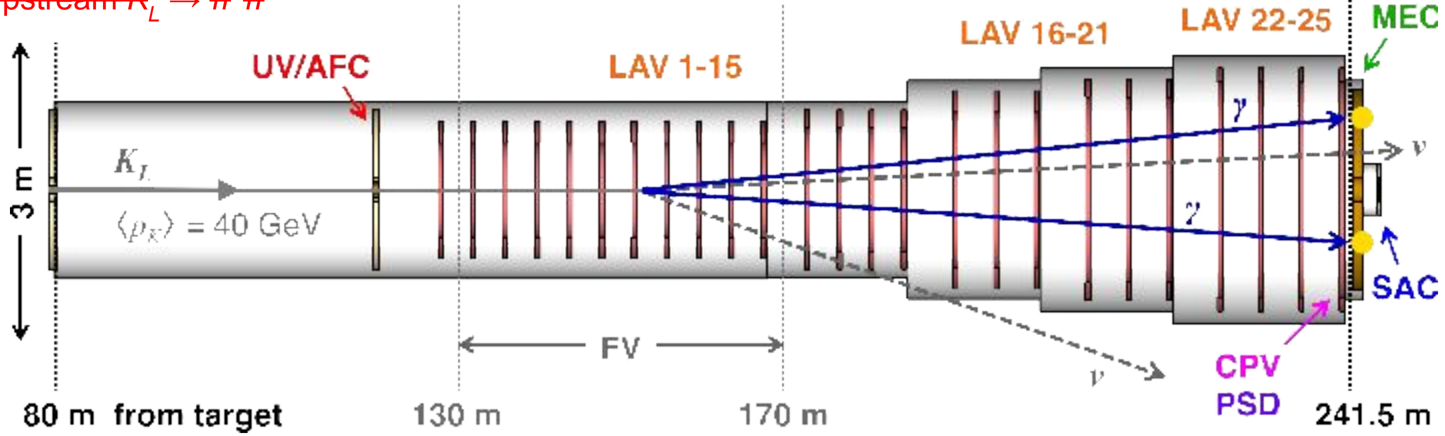
measurement goal: SBR = 100%

→ top-quality background rejection is mandatory:

~~charged products~~ ~~photons in the input beam~~

~~$K_L \to \pi^0\pi^0$ with some photons at large angle~~

~~upstream $K_L \to \pi^0\pi^0$~~



~~$K_L \to \pi^0\pi^0$ with some photons at small angle~~

~~$\Lambda \to \pi^0 n$~~

~~photons and (some) neutral hadrons in the input beam~~

~~charged products~~ ~~$K_L \to \pi^0\pi^0$ with missing photons from different pions~~

M. Moulson **KLEVER: An experiment to measure BR($K_L \to \pi_0 \nu \underline{\nu}$) at the CERN SPS** *J. Phys. Conf. Ser.*, 1526(1):012028, 2020