R&D on a high-performance **electromagnetic calorimeter** based on **oriented crystalline scintillators**

CALOR 2024

Tsukuba
つくば市

May 21th, 2024

Mattia Soldani

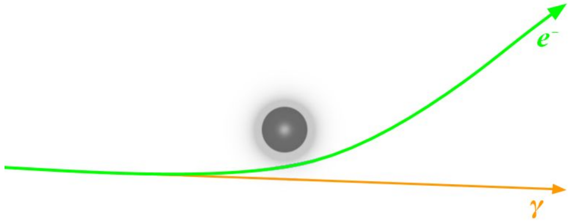
on behalf of the OREO project

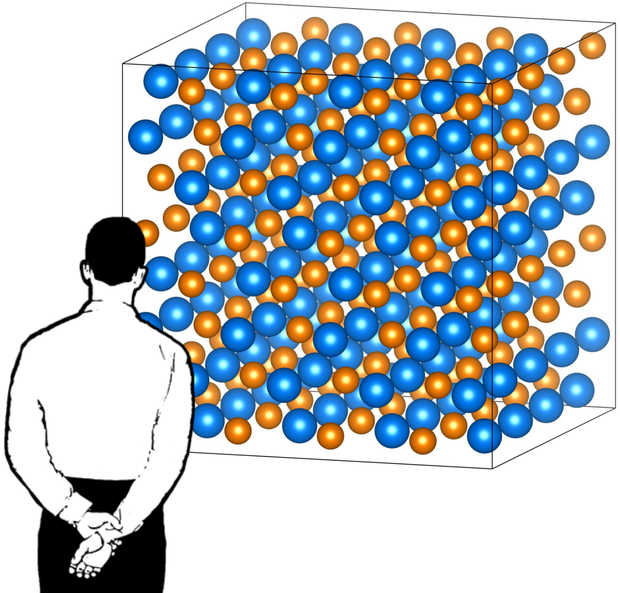
mattia.soldani@lnf.infn.it

lattice **random orientation**

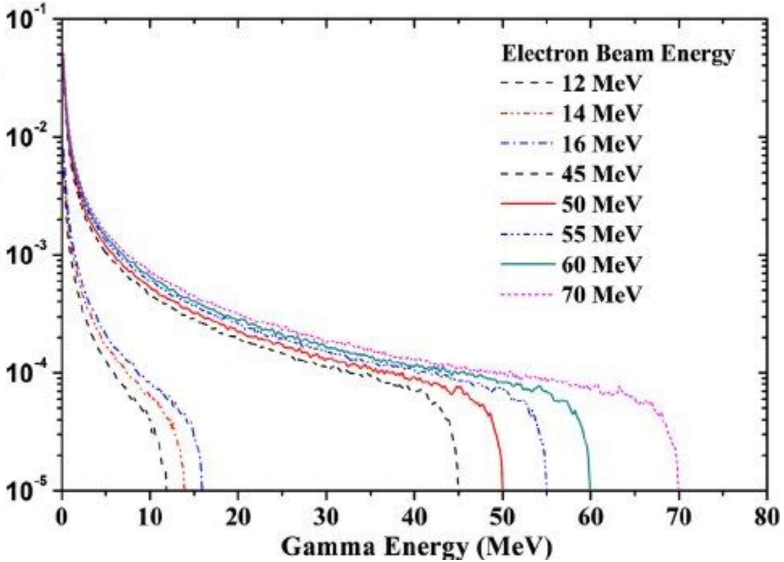
in amorphous media and randomly oriented crystals

electromagnetic interactions occur with one particle at a time, in an incoherent succession of mutually independent events





features of **both bremsstrahlung and pair production** are well-known since Bethe & Heitler (1934)



Naik *et al.* (2013)

lattice **on axis**

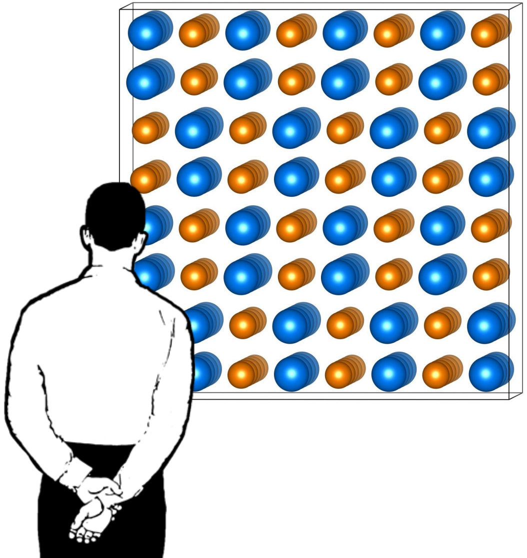
single-atom potentials from the same string sum up coherently ⇒ continuous potential along the direction of the lattice axes

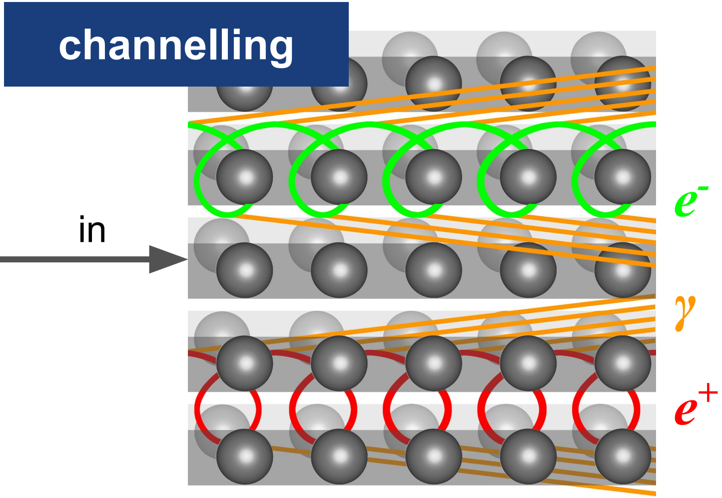
$$\psi_L \xrightarrow[v \to c]{} \sqrt{\frac{2U_0}{E_0}}$$

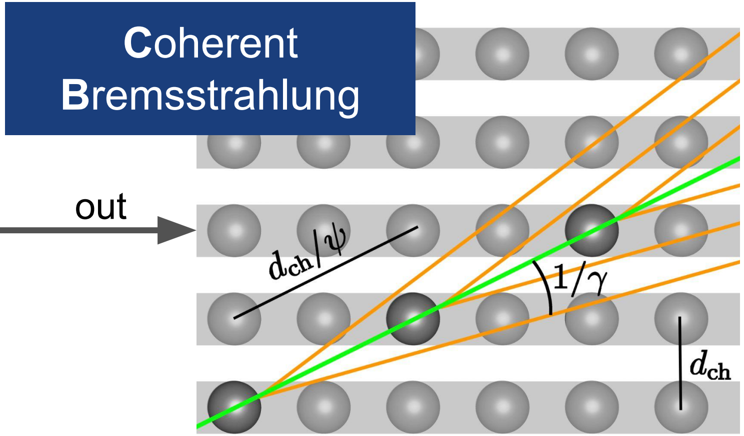
lattice potential

projectile energy

Lindhard (1965)







lattice on axis

energy threshold

Lorentz boost, lattice field in the lab

$$\chi = \frac{\gamma E}{E_0} > 1$$

only depends on Nature's constants

$$E_0 = \frac{m^2 c^3}{e\hbar} = 1.32 \cdot 10^{18} \frac{\mathrm{V}}{\mathrm{m}}$$

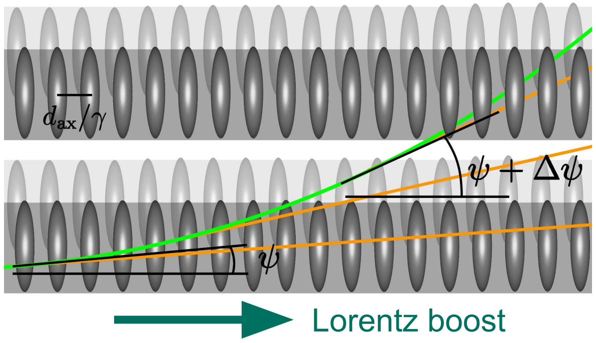
⇒ ≳ 10-20 GeV in high-Z, high-density crystals

⇒ limited effects already for χ≳0.1 i.e. already at the GeV scale

angular acceptance

lattice potential

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



⇒ independent on the energy and, when above threshold, much larger than ψ_L

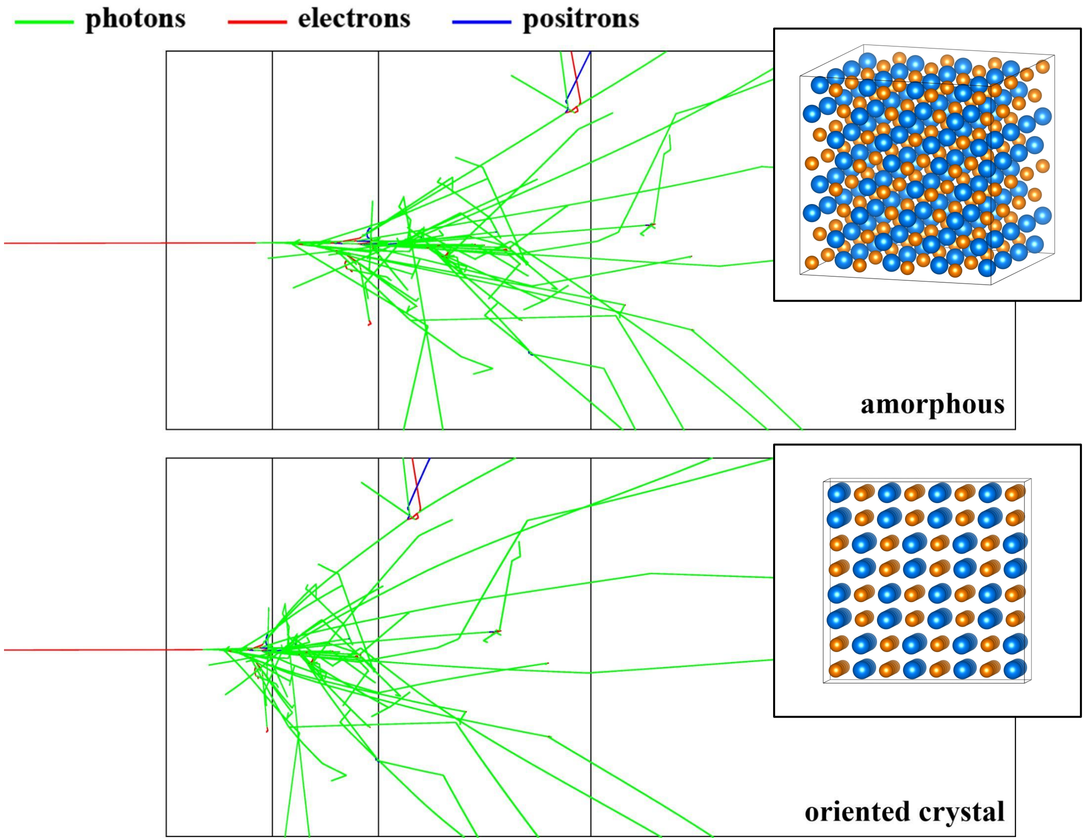
⇒ ≲ 1 mrad in high-Z, high-density crystals but CB contributes up to ~1°

⇒ Strong Field

enhanced hard photon emission (= quantum synchrotron radiation)

enhanced pair production

the on-axis em cascade



(*not an actual G4 event – for visualisation only*)

overall

electromagnetic shower development is **accelerated**

or equivalently

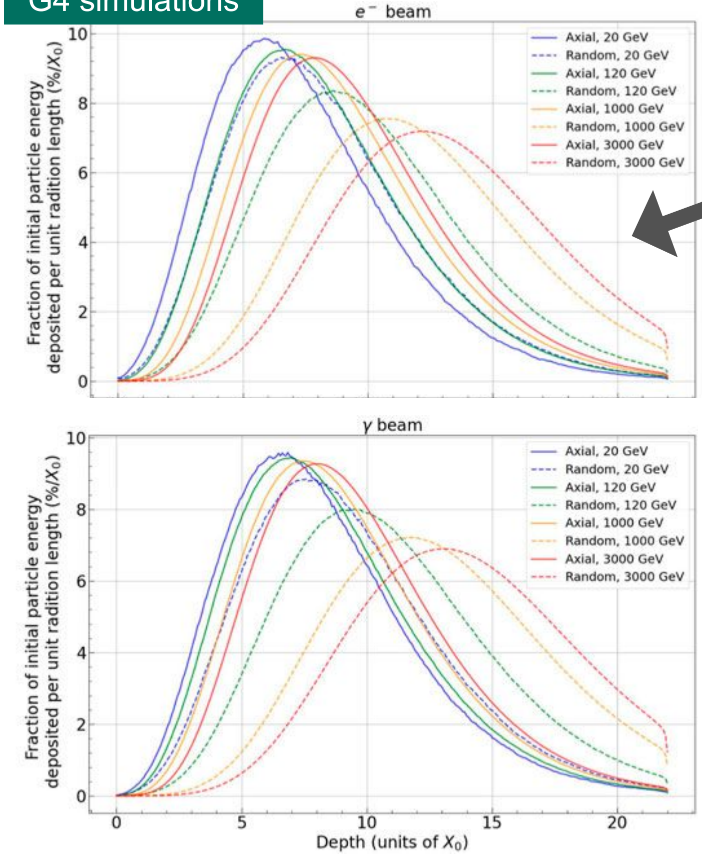
effective radiation length X_0 is **much shorter**

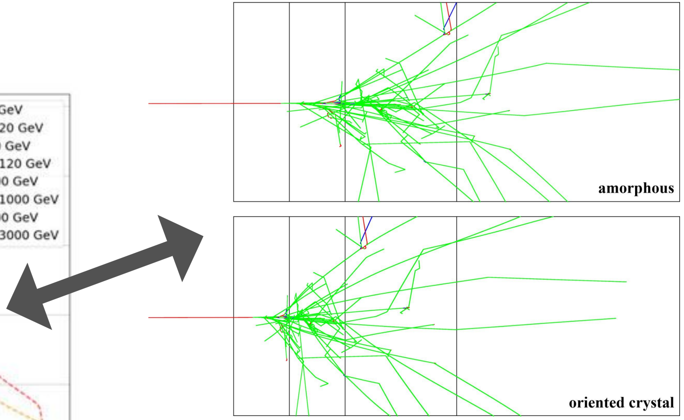
appealing in view of <u>next-generation ECALs</u>

…

the on-axis em cascade

G4 simulations





- shower front is shorter due to the SF effects on the primary and early core
- peak is at smaller depth
- peak depth is essentially independent on the primary energy and type
- effect gradually decreases as the shower develops ⇒ shower tail is unaffected by the lattice orientation

Bandiera *et al.* (2023)

the ORientEd calOrimeter project

aim

from the full characterisation of lattice-borne effects to the shower development in oriented PWO (lead tungstate)

- simulation models
- measurements with different particles at increasing thickness

to the development and test of an oriented crystal-calorimeter demonstrator

- compactness
- improved energy resolution
- improved particle ID

$PbWO_4$ as a scintillator

main light component @ 420 nm
⇒ good match for e.g. NUV SiPMs

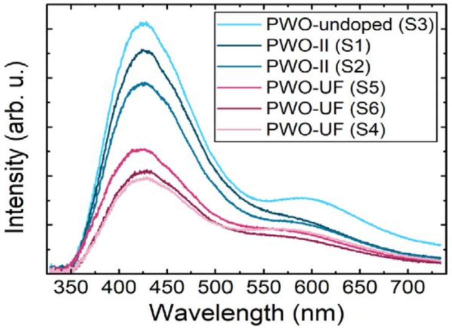
original **PWO-I** (as in CMS ECAL):
- quite radiation hard
- rather low relative output 0.3% of NaI
- moderately fast ~10 ns

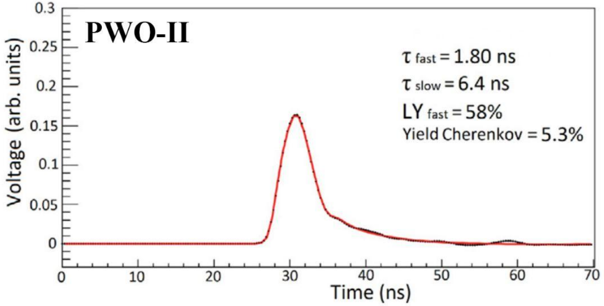
Annenkov *et al.* (2002)

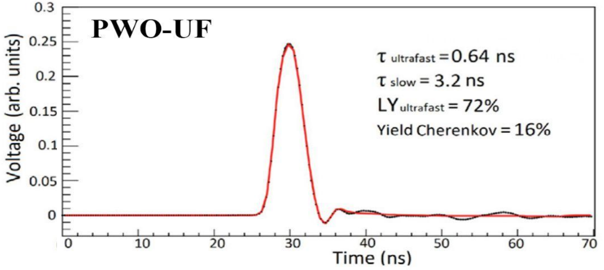
appealing for future detectors…

PWO-II (for P̅ANDA)
- ○ about same decay time
- ↗ twice the light yield 0.6% of NaI

PWO-Ultra **F**ast
- ↘ slightly worse light yield 0.2% of NaI
- ↗ impressive decay time ~640 ps!



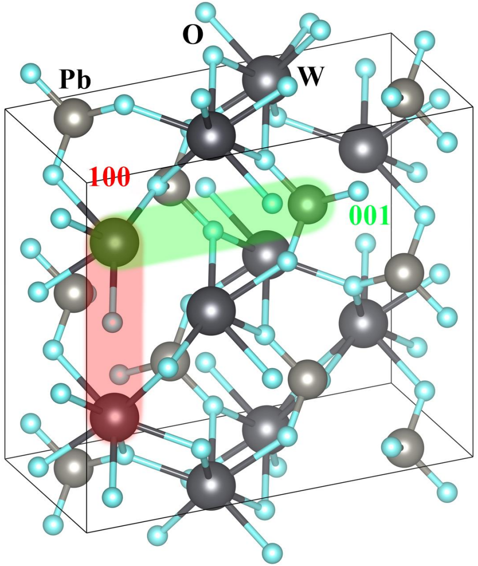




BRAND NEW! in Korzhik *et al.* (2022)

$PbWO_4$ as a crystal

two of the highest-field axes:



axis	100	001
interatomic pitch [Å]	5.456	12.020
U_0 [eV]	464	420
energy threshold [GeV]	23.45	25.90
Θ_0 [mrad]	0.908	0.822
□ @ 5.6 GeV	0.24	0.22
□ @ 120 GeV	5.12	4.63
Ψ_L @ 5.6 GeV [mrad]	0.407	0.387
Ψ_L @ 120 GeV [mrad]	0.088	0.084

limited SF down to a few GeV

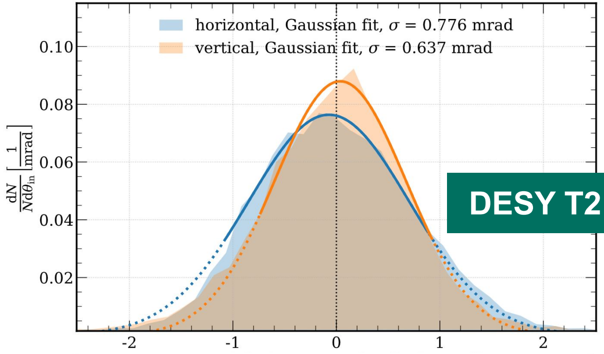
but other coherent effects hold up to ~1°

unbound motion: angular acceptance significantly larger than that of channelling (under-barrier)

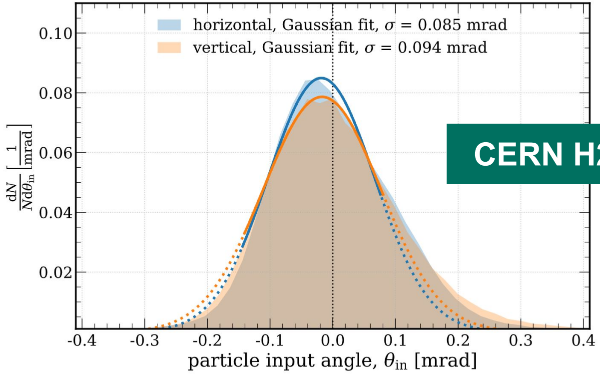
our measurement campaign

intrinsic resolution between 10-40 μm

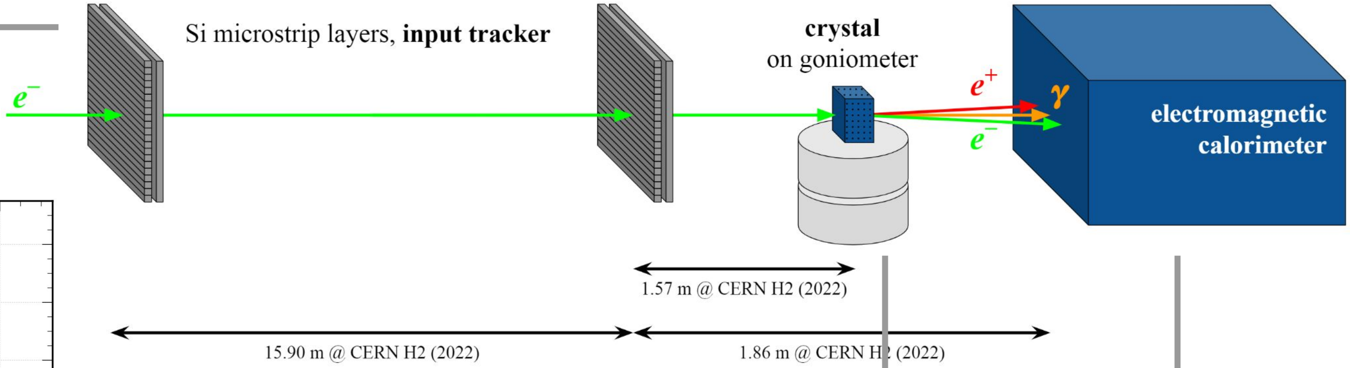
⇒ e^- beam angles:



DESY T21



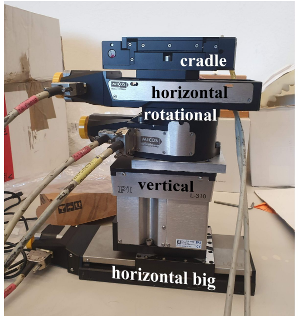
CERN H2

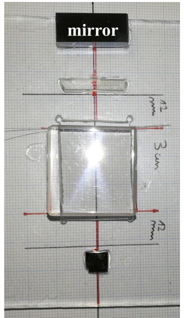


angular (transverse axes) stages with precision ≲ 5 μrad

⇒ beam-lattice misalignment angle

lead glass blocks or BGO/PWO arrays





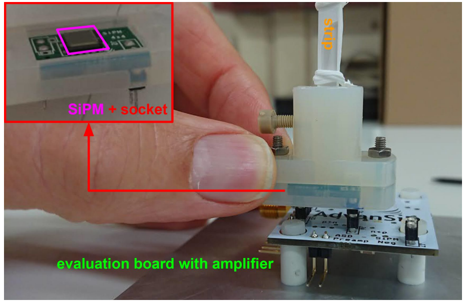
our measurement campaign

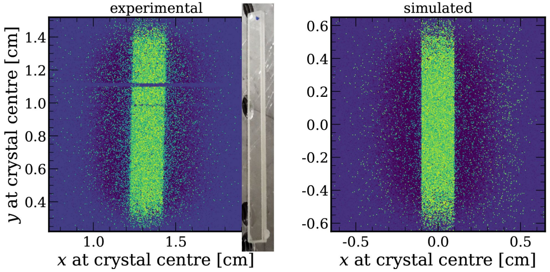
first observation of SF effects to radiation in oriented PWO: Bandiera *et al.* (2018)

2017-19

0.45 X_0 proof of concept

- probed with 120 GeV/*c* e⁻ @ CERN SPS H2
  5.6 GeV/*c* e⁻ (no SiPMs) @ DESY T21
- SiPM: AdvanSiD ASD-NUV4S-P Soldani *et al.* (2022)



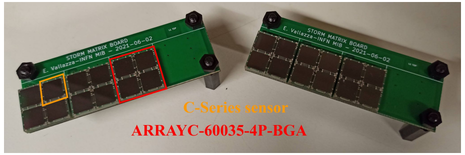


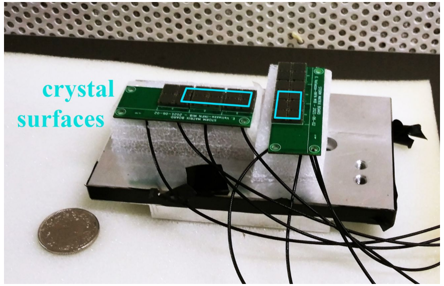
2021

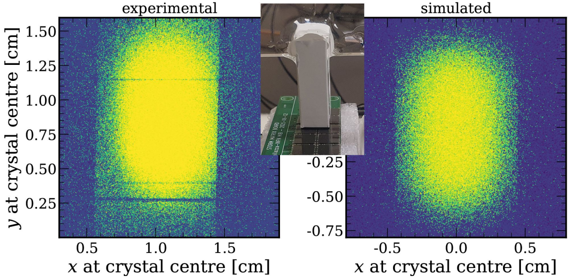
1, 2 X_0 getting thicker

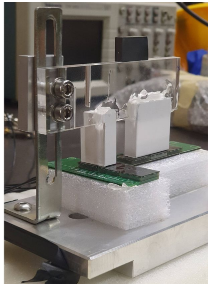
- probed with 120 GeV/*c* e⁻ @ CERN SPS H2
  1-100 GeV γ @ CERN SPS H2
- SiPM: onsemi ARRAYC-60035-4P-BGA arrays

⇒ standardisation
Selmi *et al.* (2023)









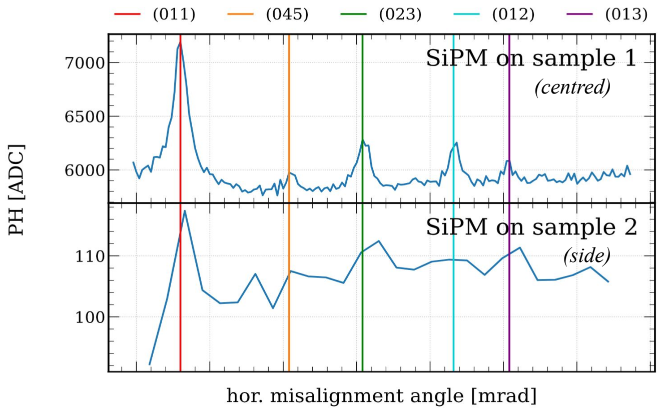
our measurement campaign

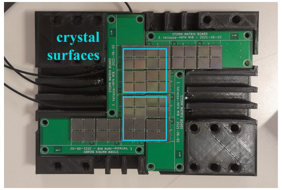
putting everything together:
Soldani *et al.* (2024)

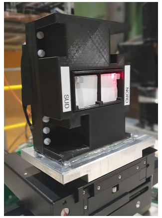
2022

4.6 X_0 THICKER

- probed with 100, 120 GeV/*c* e^- @ CERN SPS H2
- SiPM: onsemi ARRAYC-60035-4P-BGA arrays on the back
- preliminary test of (purely mechanical) mutual alignment between 2 identical samples and shower sharing



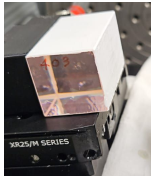




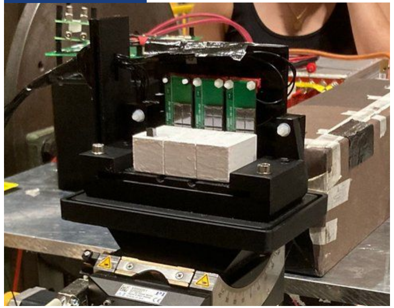
2023

5 X_0 arrays time to go multi-cell

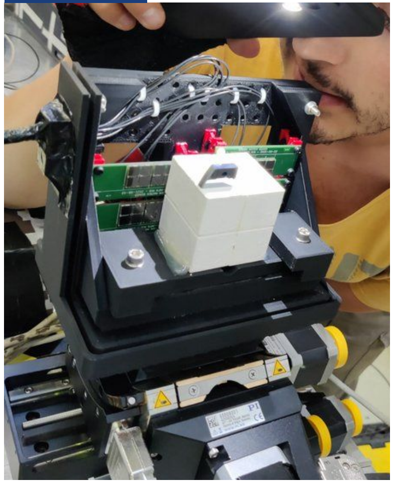
- probed with 5-15 GeV/*c* e^- @ CERN PS T9
  40-150 GeV γ @ CERN SPS H2
- SiPM: onsemi ARRAYC-60035-4P-BGA arrays
- cells glued to one another and optically isolated



3×1



2×2

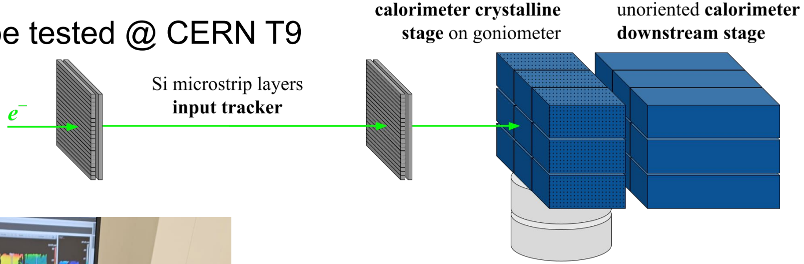


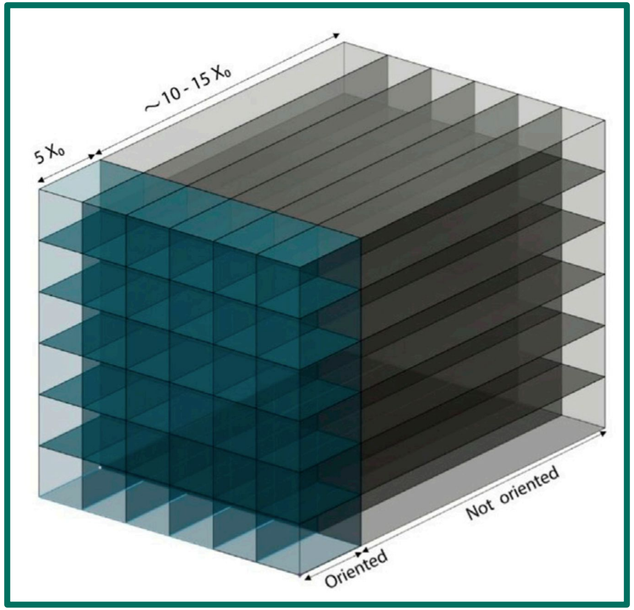
towards a fine-segmentation ECAL

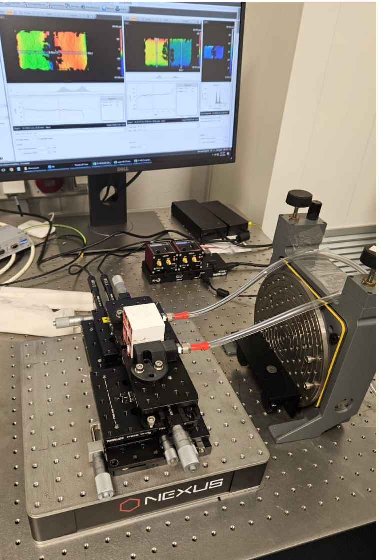
2024-25

the OREO prototype

to be tested @ CERN T9



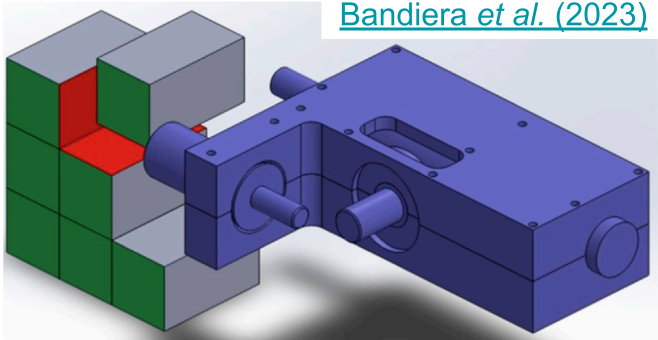




3×3 oriented layer ~5 X_0
and 3×3 unoriented layer ≫ 5 X_0

surface (not axis) non-projective geometry

Bandiera *et al.* (2023)



crystals mutually aligned within ~$\Theta_0/2$ maximum

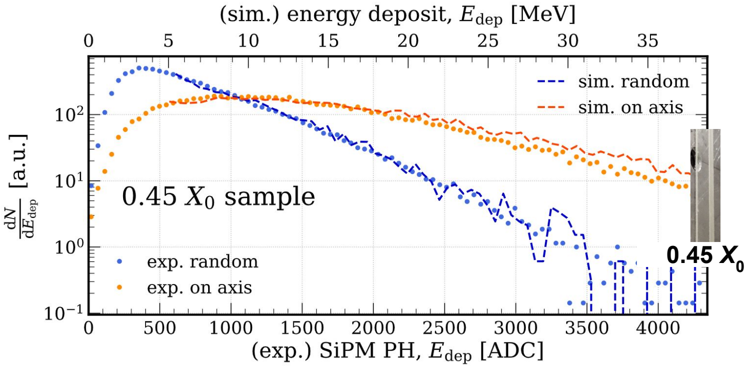
gluing procedure

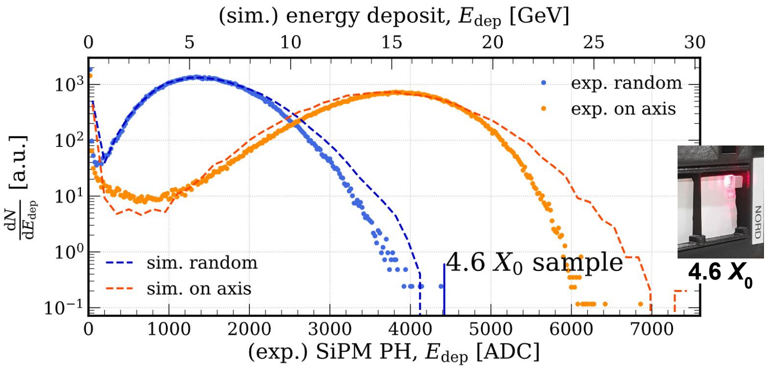
- preliminary lattice characterisation with laser autocollimator and HRXRD
- on roto-translational adjusters → real-time corrections of relative miscut
- Fizeau interferometry for real-time check

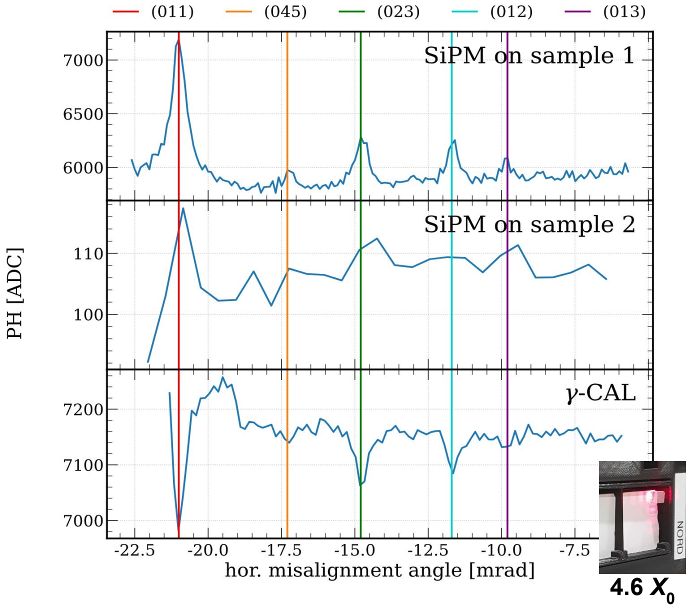
a selection of our results

LY enhancement

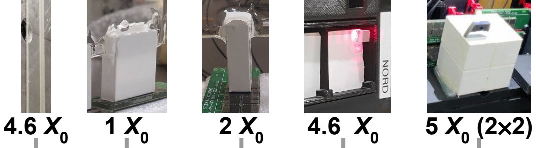
- light output is highly sensitive to the lattice effects
  - → not only the strong axes, also higher-order planes
  - → light spectrum modification even at < X_0
- excellent agreement with G4 simulations (energy deposit)



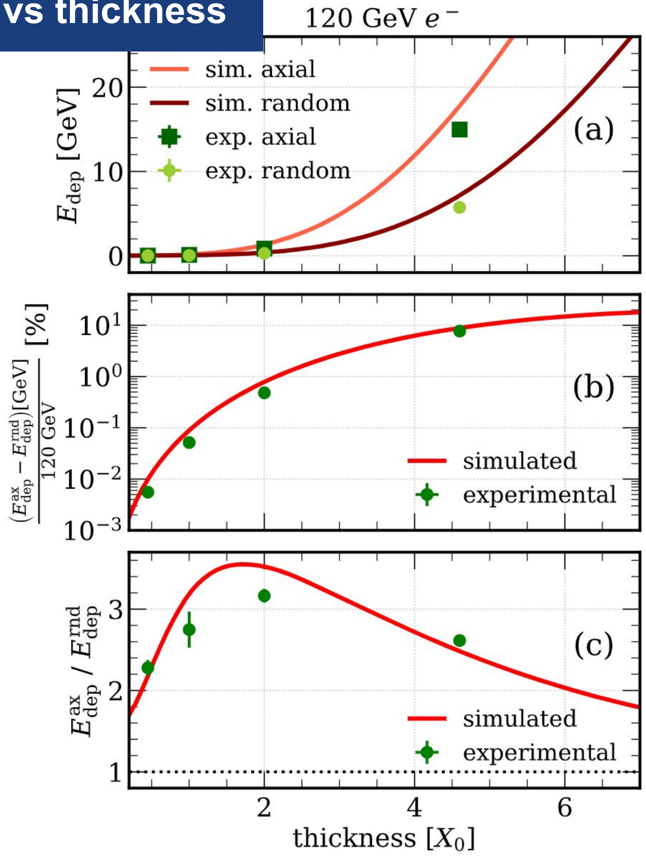




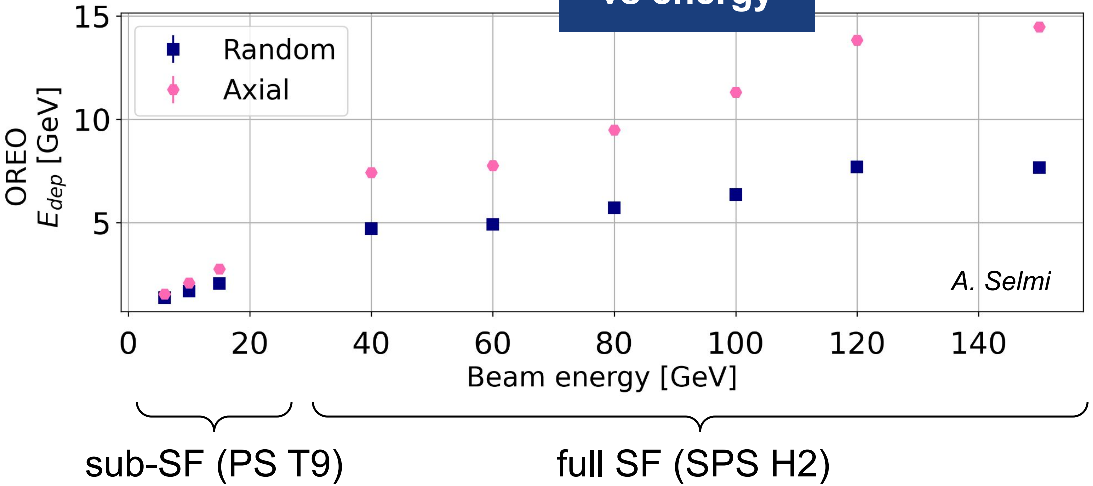
shower acceleration



vs thickness



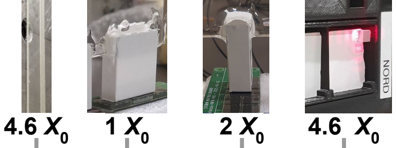
vs energy



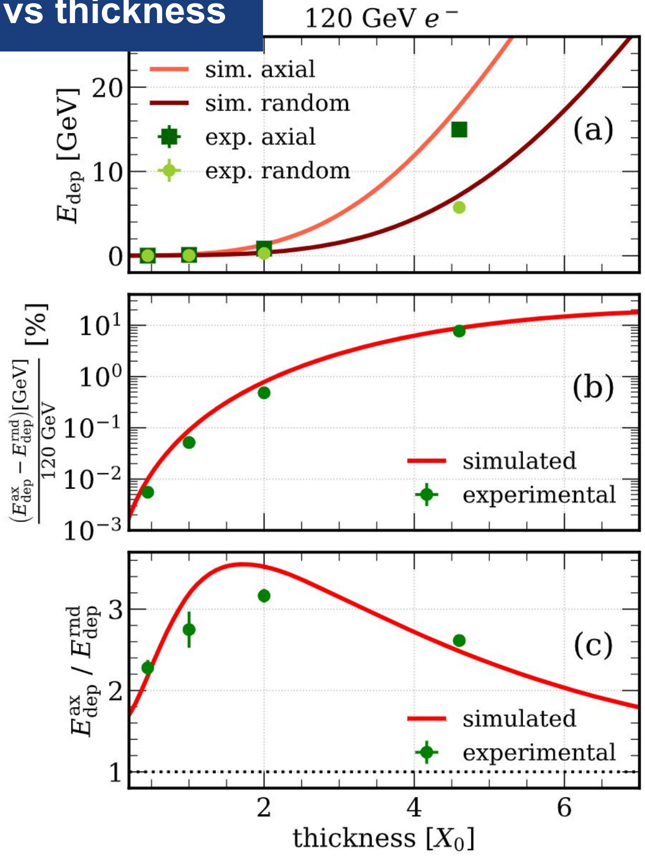
with electrons

- on-axis energy deposit curve is steeper → shower is accelerated
- axis-random fractional energy deposit difference spans over 4 orders of magnitude!
- axis-random enhancement
  - → is peaked at ~1.5 X_0 at 120 GeV/*c*
  - → grows with the incident electron energy

shower acceleration



vs thickness

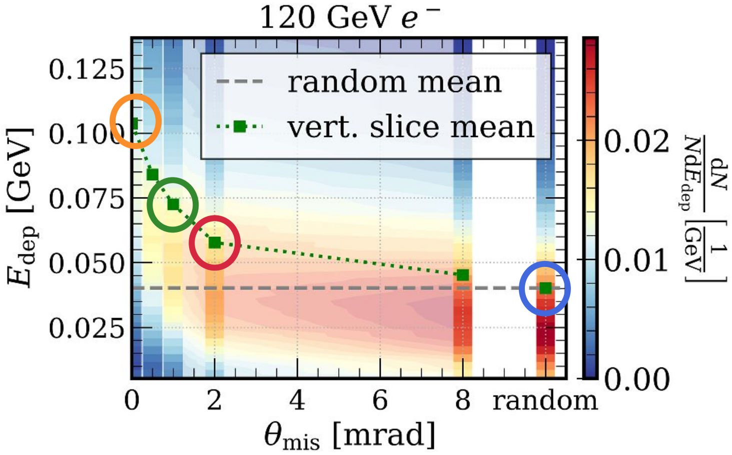


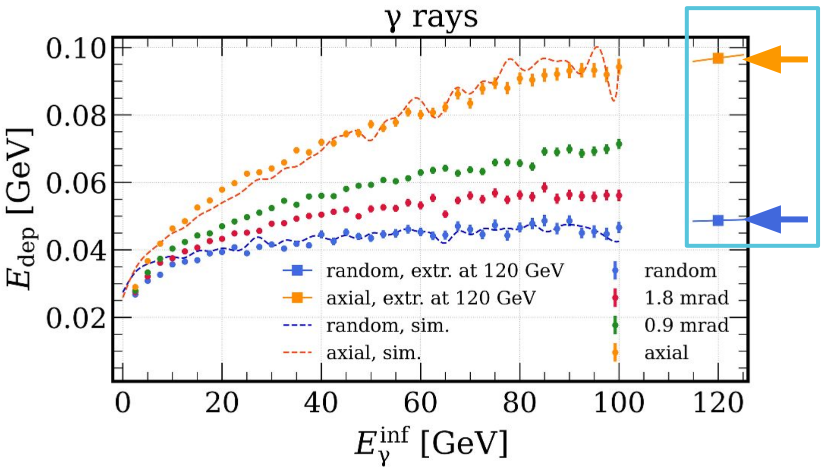
thickness [X_0]	effective thickness [X_0]	thickness enhancement [%]
0.45	0.745	165.48
1	1.520	151.98
2	2.923	146.17
4.6	6.208	134.96

reduction of the effective X_0!

electrons vs photons

1 X_0





- data with bremsstrahlung photons between 1 and 10 GeV
- extrapolation to 120 GeV

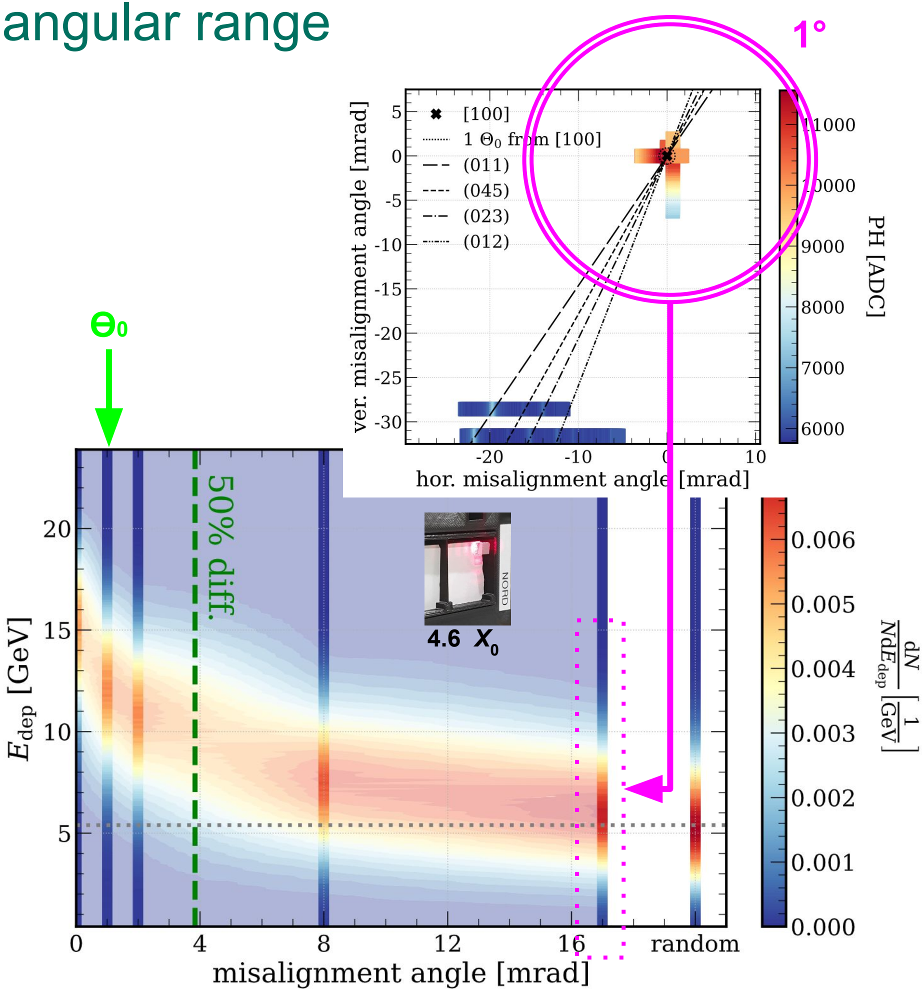
$$a \cdot \log\left(bE_\gamma - c\right)$$

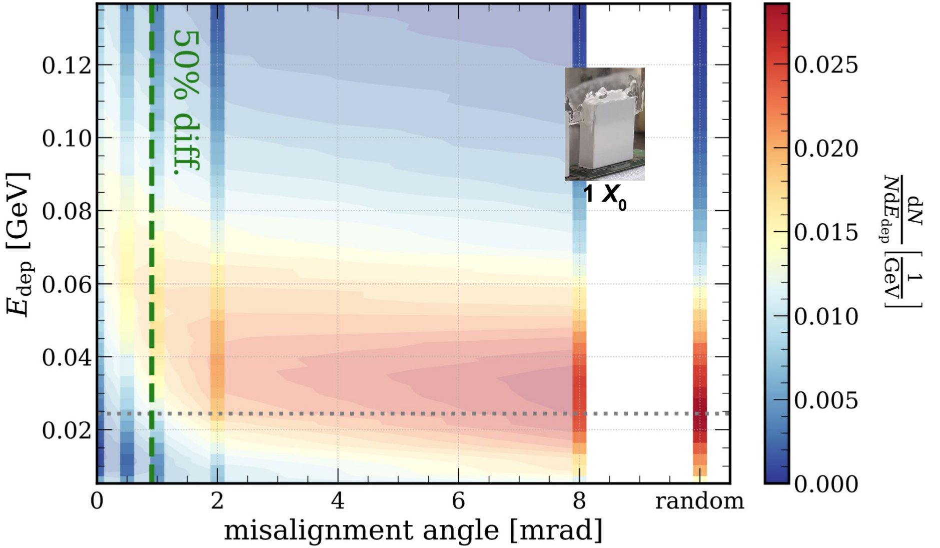
→ consistent with the data collected with 120 GeV/c electrons at different misalignment angles

(accounting for the $e^{\mp}$/γ development difference)

angular range

- enhancement is angle-dependent
  - → sharp peak at $\lesssim \Theta_0 \sim 1$ mrad
  - → still different from random at ~1°
- width is sample dependent
  - → depends on sample mosaicity
  - → shower develops more in thicker samples ⇒ more lower-energy secondaries, within range of channelling (ψ_L) and CB (~$10\psi_L$)





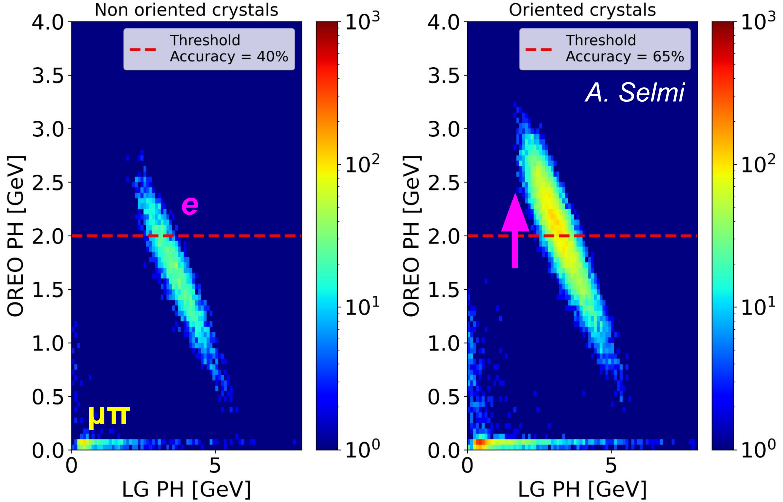
vs hadronic interactions

X_0 (em) is reduced, whereas λ_{int} (hadronic) is unaffected ⇒ **γ/hadron discrimination**

PRELIMINARY measurements

5 X_0 (2×2)

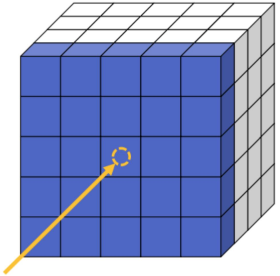
PWO preshower on goniometer in front of Pb glass block



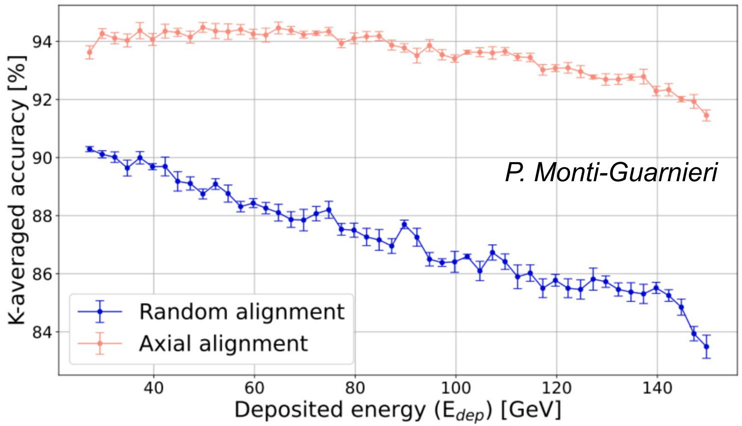
G4 simulation studies

γ/n populations with initial energy 26-151 GeV in a highly segmented PWO full calorimeter:

5×5×4 crystals of size 1×1×4 cm^3



random forest classification



exciting times ahead!

several progress throughout the years in
- probing crystalline SF effects
- developing sound simulation tools + integration with Geant4
- designing an operational longitudinally segmented, oriented-calorimeter prototype

getting ready for integration in

keep track of the lattice orientation to avoid uncontrolled lattice effects when building a crystal calorimeter!

space-borne γ-ray (VHE/UHE) detectors with pointing systems

à la Fermi LAT

- reduced thickness ⇒ more payload available for transverse size increase ⇒ acceptance
- improved shower containment ⇒ less longitudinal leakage
- higher γ efficiency
- better γ/hadron discrimination

see e.g. Bandiera *et al.* (2023), Gaitskell *et al.* (2023)

forward-geometry accelerator-based experiments

fixed-target **collider forward region**

- improved shower containment ⇒ energy resolution
- higher γ efficiency ⇒ ideal for γ vetoes
- better γ/hadron discrimination ⇒ ideal for γ/n in small-angle calorimeters on neutral hadron beamlines e.g. HIKE CERN-SPSC-2022-031

thank you! どうもありがとう!

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

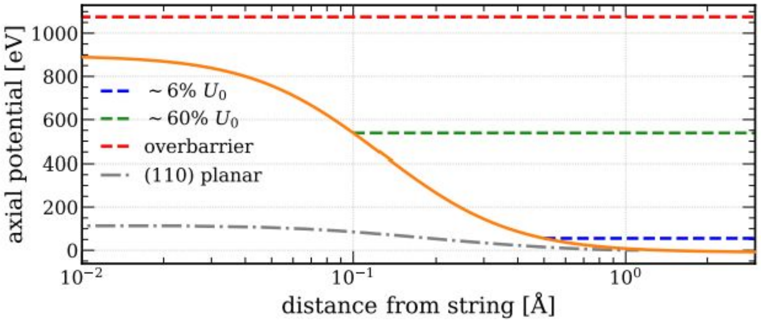
supplemental material

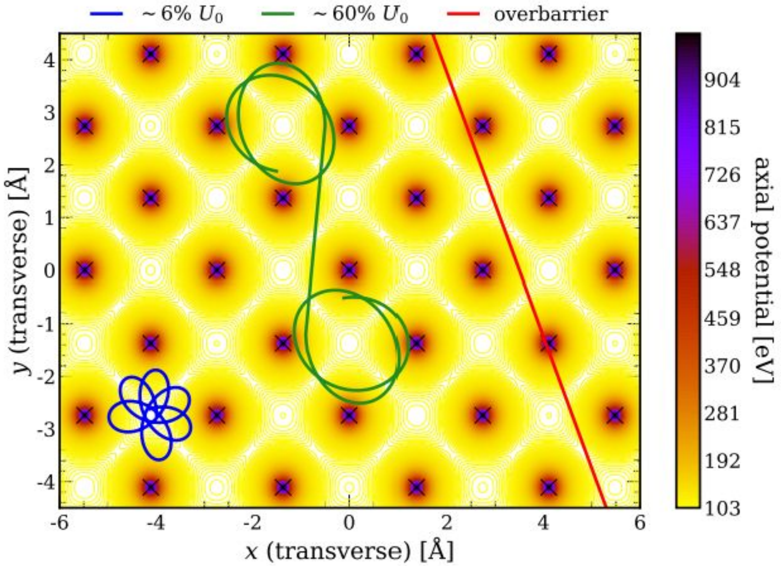
the **OREO** team

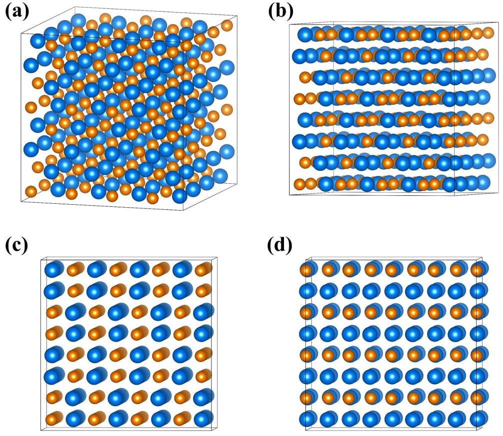
N. Argiolas[a,b], L. Bandiera[c], V. Baryshevsky[d], L. Bomben[e,f], C. Brizzolari[e,f], N. Canale[c], S. Carsi[e,f], S. Cutini[g], F. Davì[h,c], D. De Salvador[a,b], A. Gianoli[c], V. Guidi[i], V. Haurylavets[d], M. Korjik[d], G. Lezzani[e,f], A. Lobko[d], F. Longo[j,k], L. Malagutti[c], S. Mangiacavalli[e,f], V. Mascagna[e,f], A. Mazzolari[c,i], L. Montalto[h], P. Monti-Guarnieri[c,i,**], M. Moulson[1], R. Negrello[c,i], G. Paternò[c], L. Perna[e,f], C. Petroselli[e,f], M. Prest[e,f], D. Rinaldi[h,1], M. Romagnoni[c,i], F. Ronchetti[e,f,*], G. Saibene[e,f], A. Selmi[e,f], F. Sgarbossa[a,b], M. Soldani[1], A. Sytov[c], V. Tikhomirov[d], E. Vallazza[f]

[a] *Università degli Studi di Padova, Padua, Italy*
[b] *INFN Laboratori Nazionali di Legnaro, Legnaro, Italy*
[c] *INFN Sezione di Ferrara, Ferrara, Italy*
[d] *Institute for Nuclear Problems, Belarusian State University, Minsk, Belarus*
[e] *Università degli Studi dell'Insubria, Como, Italy*
[f] *INFN Sezione di Milano Bicocca, Milan, Italy*
[g] *INFN Sezione di Perugia, Perugia, Italy*
[h] *Università Politecnica delle Marche, Ancona, Italy*
[i] *Università degli Studi di Ferrara, Ferrara, Italy*
[j] *Università degli Studi di Trieste, Trieste, Italy*
[k] *INFN Sezione di Trieste, Trieste, Italy*

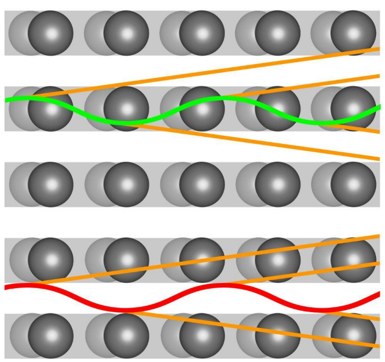
planes vs axes

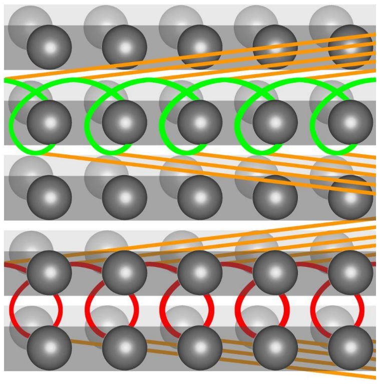






a) amorphous
b) planar
c) axial, [100]-like
d) axial, [001]-like





scintillating media

inorganic (crystals)

↗ high-Z → homogeneous calorimeters

↘ typically slow > ns, up to μs
& tradeoff between LY and timing
↘ many technological challenges
(growth, machining, support…)
↘ expensive
↘ LY depends on temperature $O(\%/°C)$

organic (plastic)

↘ low density and Z

↗ fast response $\lesssim$ ns
↗ easy to handle and scale
↗ comparatively easier to craft
↗ comparatively cheaper

⇒ ideal active medium <u>in sampling calorimeters</u>

(common) inorganic scintillators

Parameter:	ρ	MP	X_0^*	R_M^*	dE^*/dx	λ_I^*	τ_{decay}	$\lambda_{\max}$	$n^\natural$	Relative output†	Hygro-scopic?	$d(\mathrm{LY})/dT$
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%/°C‡
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9	245	410	1.85	100	yes	−0.2
BGO	7.13	1050	1.12	2.23	9.0	22.8	300	480	2.15	21	no	−0.9
BaF_2	4.89	1280	2.03	3.10	6.5	30.7	650^s	300^s	1.50	36^s	no	-1.9^s
							0.9^f	220^f		4.1^f		0.1^f
CsI(Tl)	4.51	621	1.86	3.57	5.6	39.3	1220	550	1.79	165	slight	0.4
CsI(Na)	4.51	621	1.86	3.57	5.6	39.3	690	420	1.84	88	yes	0.4
CsI(pure)	4.51	621	1.86	3.57	5.6	39.3	30^s	310	1.95	3.6^s	slight	−1.4
							6^f			1.1^f		
$PbWO_4$	8.30	1123	0.89	2.00	10.1	20.7	30^s	425^s	2.20	0.3^s	no	−2.5
							10^f	420^f		0.077^f		
LSO(Ce)	7.40	2050	1.14	2.07	9.6	20.9	40	402	1.82	85	no	−0.2
PbF_2	7.77	824	0.93	2.21	9.4	21.0	-	-	-	Cherenkov	no	-
CeF_3	6.16	1460	1.70	2.41	8.42	23.2	30	340	1.62	7.3	no	0
$LaBr_3$(Ce)	5.29	783	1.88	2.85	6.90	30.4	20	356	1.9	180	yes	0.2
$CeBr_3$	5.23	722	1.96	2.97	6.65	31.5	17	371	1.9	165	yes	−0.1

* Numerical values calculated using formulae in this review.
♮ Refractive index at the wavelength of the emission maximum.
† Relative light output measured for samples of 1.5 X_0 cube with a Tyvek paper wrapping and a full end face coupled to a photodetector. The quantum efficiencies of the photodetector are taken out.
‡ Variation of light yield with temperature evaluated at the room temperature.
f = fast component, s = slow component

more on PWO and its generations

Z/A	0.41315
ρ [g/cm^3]	8.3
Standard X_0 [mm]	8.903
Standard R_M [mm]	19.59
E_C for e^- [MeV]	9.64
E_C for e^+ [MeV]	9.31
Nuclear collision length [mm]	121.2
Nuclear interaction length [mm]	202.7
Pion collision length [mm]	152.1
Pion interaction length [mm]	240.4

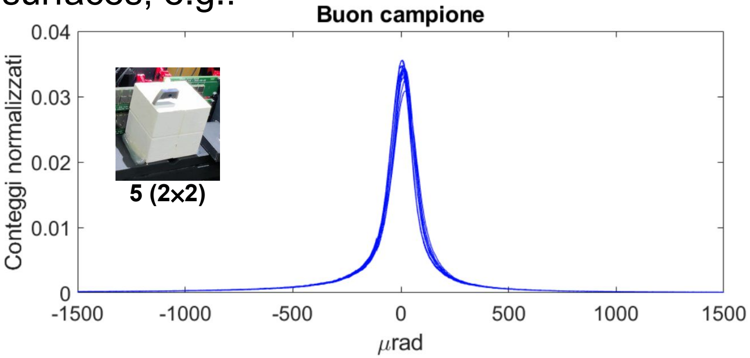
	PWO-I	PWO-II	PWO-UF
ρ [g/cm^3]	8.28 [30]	8.28 [198]	8.27 [201]
Scintillation max. [nm]	420 [30]	420 [198]	420 [201]
LY [ph.e^-/MeV]	8–12 [205]	17–22 [205]	7 [201]
LY rel. to NaI [%]	0.3 [30]	0.6 [198]	about 0.2
τ_{decay} [ns]	10–30 [30, 205] 6.5 [198]	10–30 [30, 205] 6.5 [198]	0.64 [201]
$-$dLY/dT [%/°C]	2.5 [30]	3 [205]	about 0.4 [201]
dk [1/m]	1.5 [205]	1 [205]	0.3 [201]

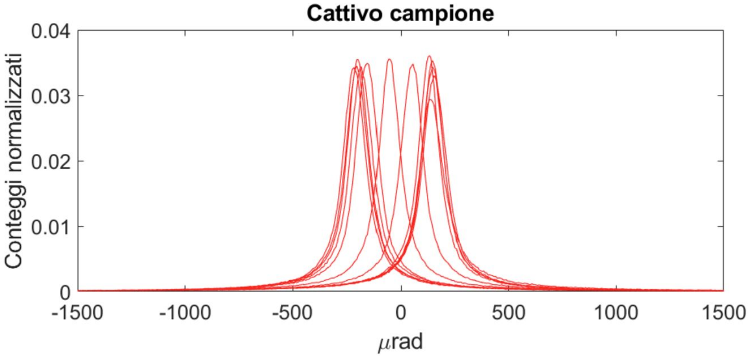
see Soldani, PhD thesis (2023) and references therein

our PWO samples

characterisation w/ HRXRD scanning the sample front/back surfaces, e.g.:

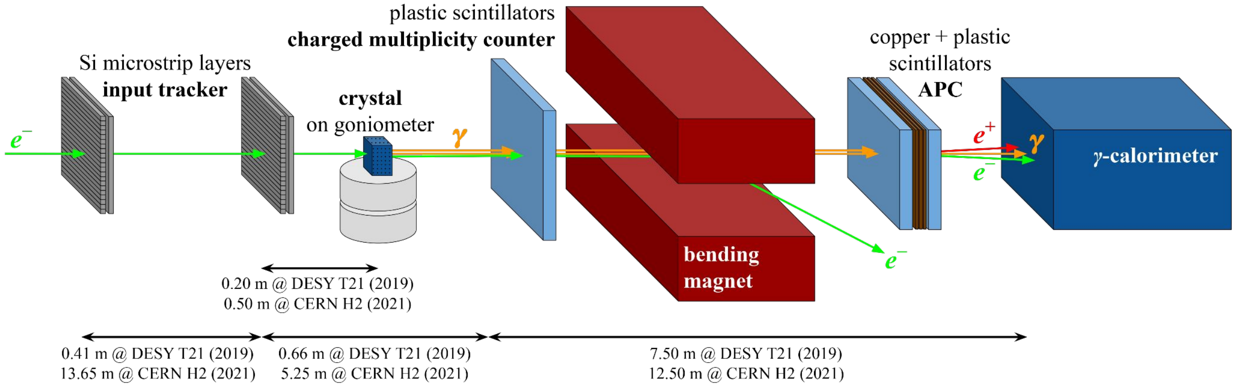
Thickness $[X_0]$	**0.45**	**1**	**2**	**4.6**
Thickness [mm]	4	9	18	41
Transv. size [mm^2]	2×55	$\sim 30 \times 30$	9×27	$\sim 30 \times 30$
Axis	001	100	001	100
Generation	I	II	I	I
Surface mosaicity [μrad]	~ 100	~ 250	~ 350 (hor.) ~ 550 (ver.)	~ 250
Tested on CERN H2/H4	2016-2018	2021	2021	2022
Tested on DESY T21	2019	2019	no	no



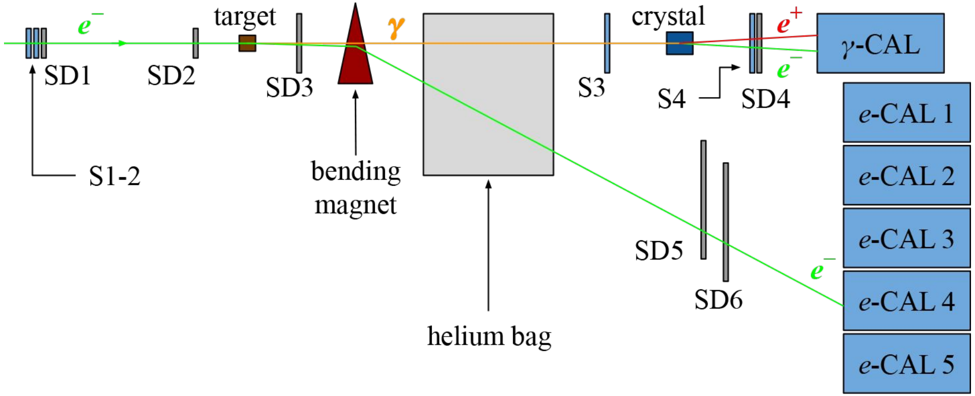


other beamtest setups

e⁻



γ

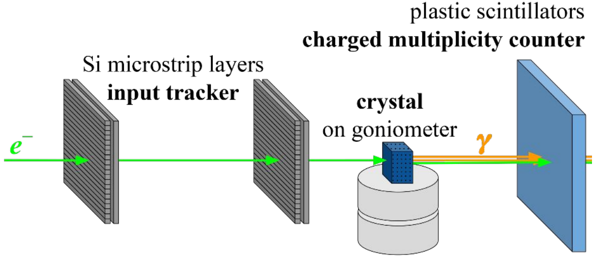


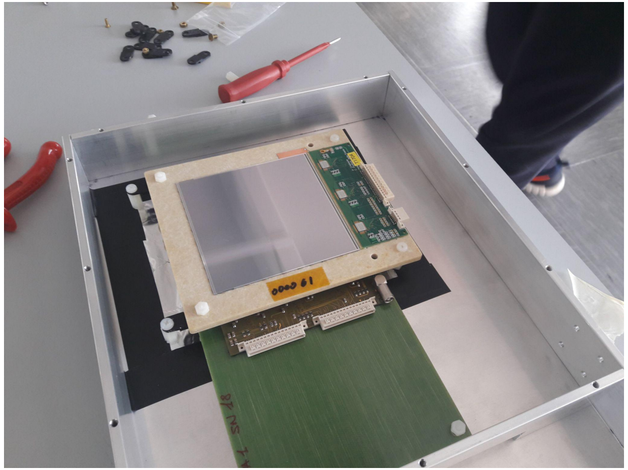
beamtest setup

input tracking modules

≃2×2 cm^2 *xy* double-sided Si microstrip sensors, with 50 μm readout pitch, analog readout and an overall ≃10 μm single-hit resolution

pairs of ≃10×10 cm^2 single-sided Si microstrip sensors, with 242 μm readout pitch, analog readout and an overall ≃35 μm single-hit resolution



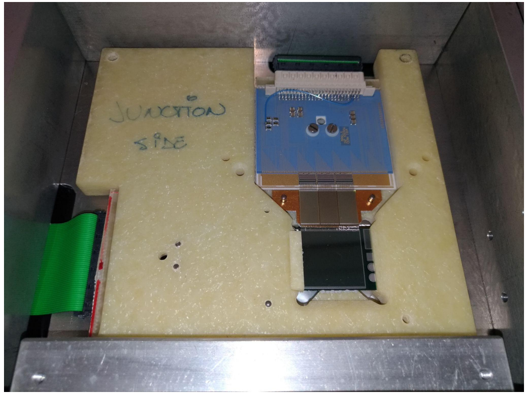


output charged multiplicity counter

one or more ≃10×10 cm^2 plastic scintillator pads read out by PMTs

goniometer

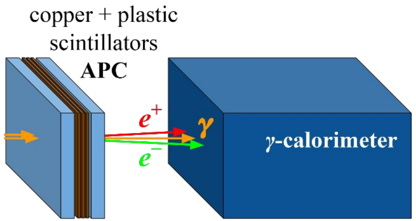
fine-grained, remote-controlled movements along x, y, θ_x and θ_y with ≃5 μm/μrad resolution



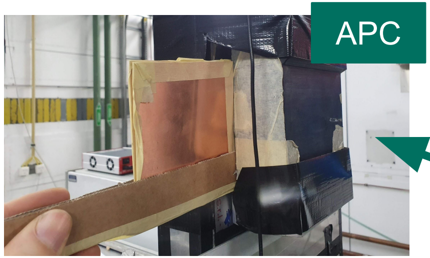
beamtest setup

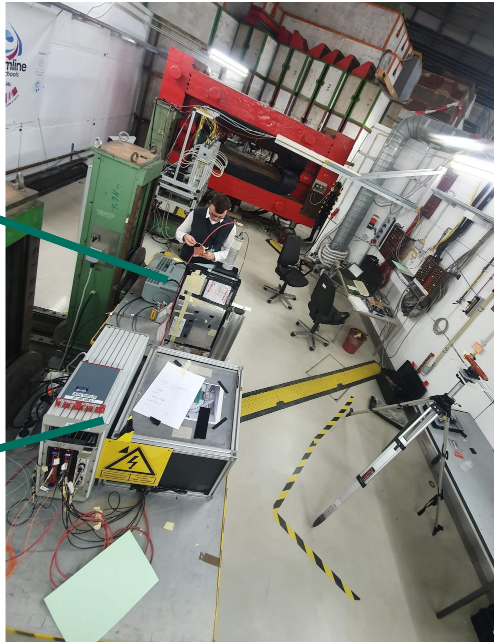
different **calorimeters** along the years:

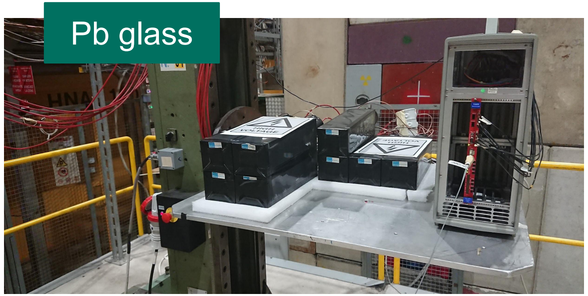
- Stefi: 3×3 matrix of PWO blocks from the CMS endcap, SiPM-based readout
- Genni: 3×3 matrix of BGO blocks from the PADME calorimeter, PMT-based readout
- (OPAL) Pb glass blocks read out by PMTs

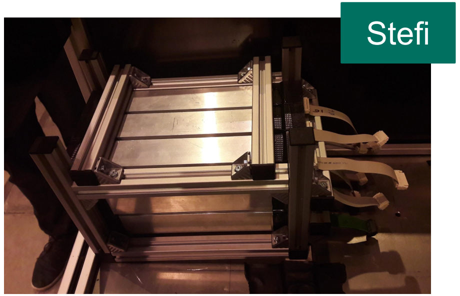


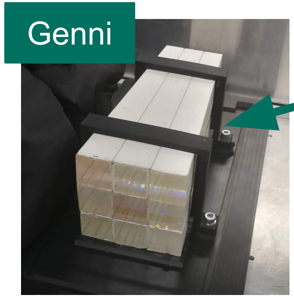
the **Active Photon Converter** was installed and tested for the first time during the 2019 beamtest at DESY T21 → scintillating pads and a Cu converter layer, statistical information on the output photon number distribution



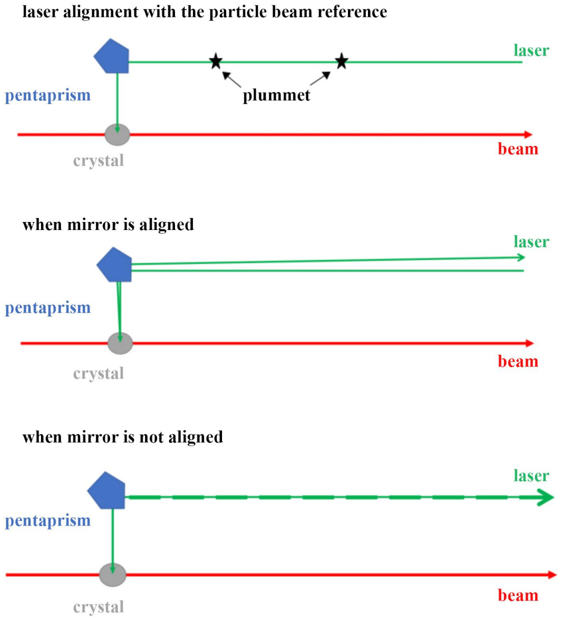


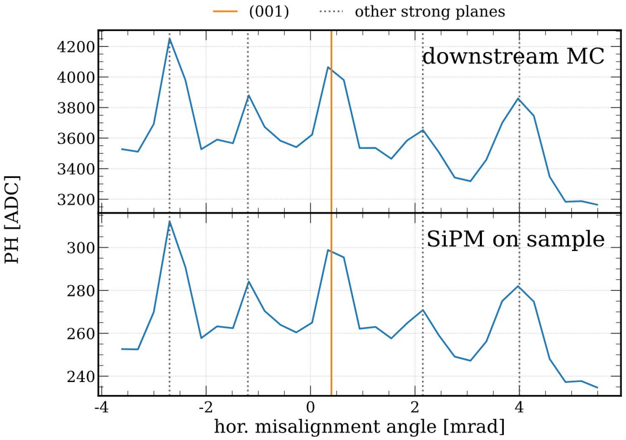


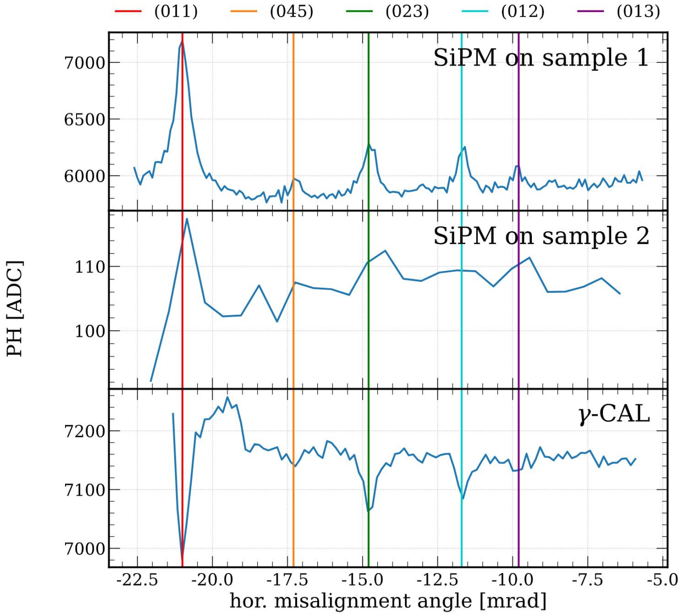




sample (pre-)alignment







crystal simulation framework

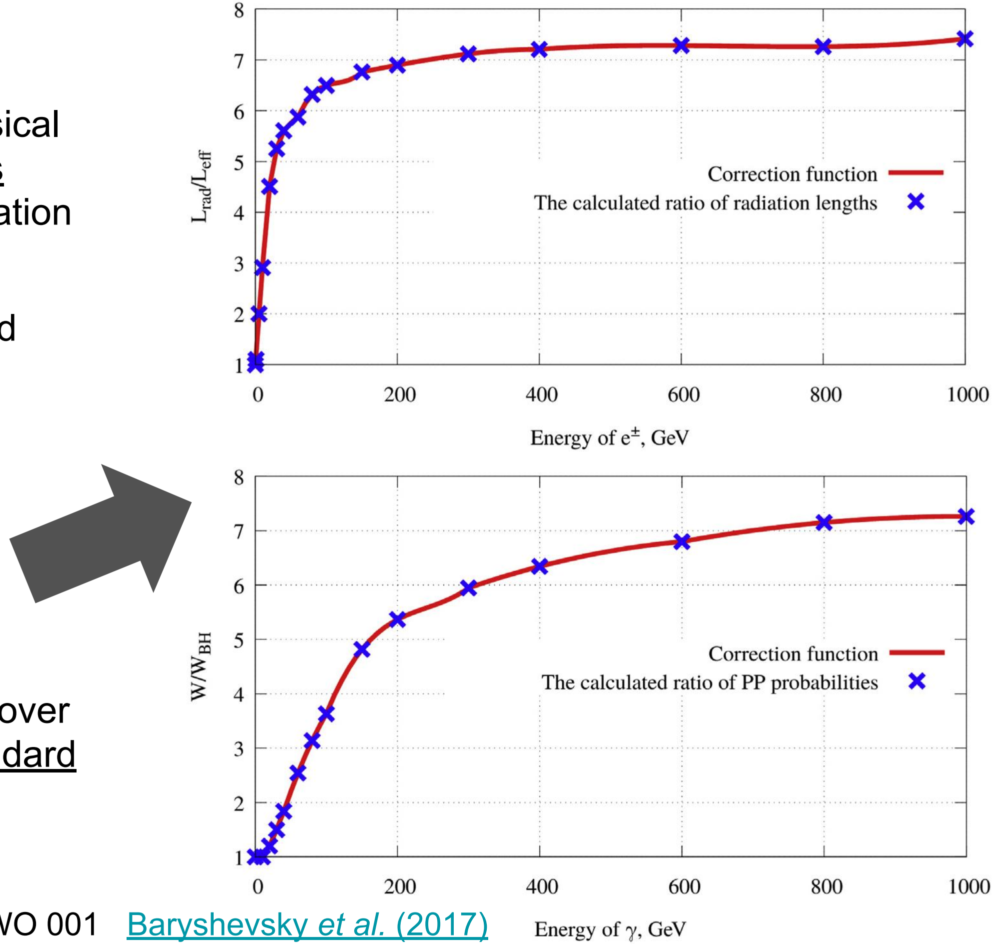
sub-X_0 crystals

Baier, Katkov & Strakhovenko (1998) semiclassical method: simulation of the (classical) trajectories inside the crystalline lattice with (quantum) radiation emission

⇒ **D**irect **I**ntegration of the **B**aier-**K**atkov method implemented by INP BSU & INFN Ferrara

multi-X_0 crystals

DIBK applied to thin crystal slices at different energies and angles ⇒ radiation and PP probabilities at different energies are averaged over the angles and used to rescale the Geant4 standard cross sections

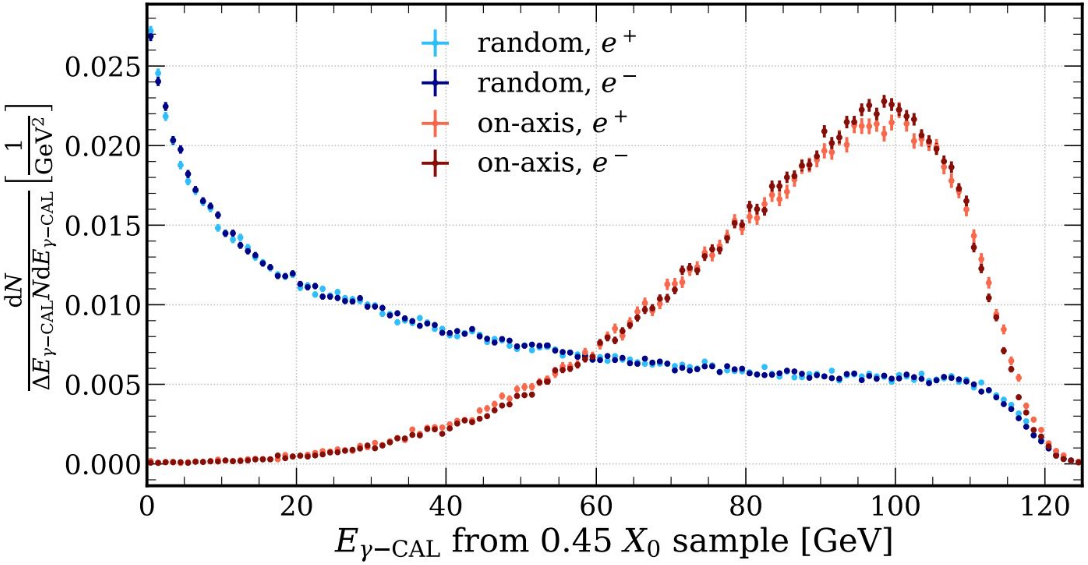


Geant4 rescaling factors for PWO 001 Baryshevsky *et al.* (2017)

electrons vs positrons

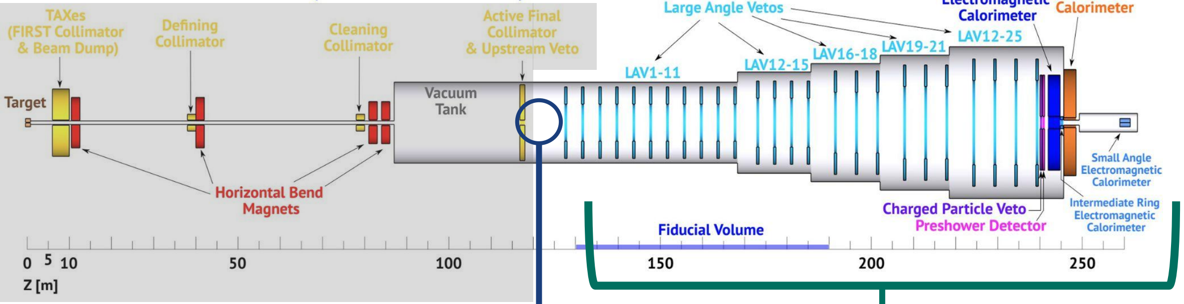
120 GeV/c
electrons/positons on

0.45



the HIKE Small Angle Calorimeter

HIKE Phase 3 (KLEVER)



phase 3 signal: $K_L \to \pi^0 \nu \overline{\nu}$

i.e. two detected photons and missing momentum

main harmful background channels:

- $K_L \to \pi^0 \pi^0$ where two photons get lost
- $\Lambda \to \pi^0 n$ from upstream

photon reconstruction is critical!

at this point:

140 MHz (mean ≃27 GeV/*c*) K_L
vs
440 MHz neutrons
198 MHz photons >1 GeV
53 MHz photons >5 GeV
4.1 MHz photons >30 GeV

many neutrons in the beam!

fully hermetic, high-efficiency photon detection apparatus

along the beam path: **S**mall **A**ngle **C**alorimeter

⇒ very low photon inefficiency $<10^{-4}$ at > 30 GeV, <1% between 5 and 30 GeV
⇒ insensitivity to neutrons
⇒ good photon/neutron disambiguation capability
⇒ high time resolution ≲100 ps
⇒ two-pulse disambiguation ≃ ns
⇒ radiation hardness

CERN-SPSC-2022-031