Istituto Nazionale di Fisica Nucleare

Electromagnetic Processes in Strong Crystalline Fields: Toward a High-Performance Calorimeter for Future HEP Experiments

Laura BandieraINFN Ferrara

On behalf of the OREO collaboration

bandiera@fe.infn.it

Channeling2024

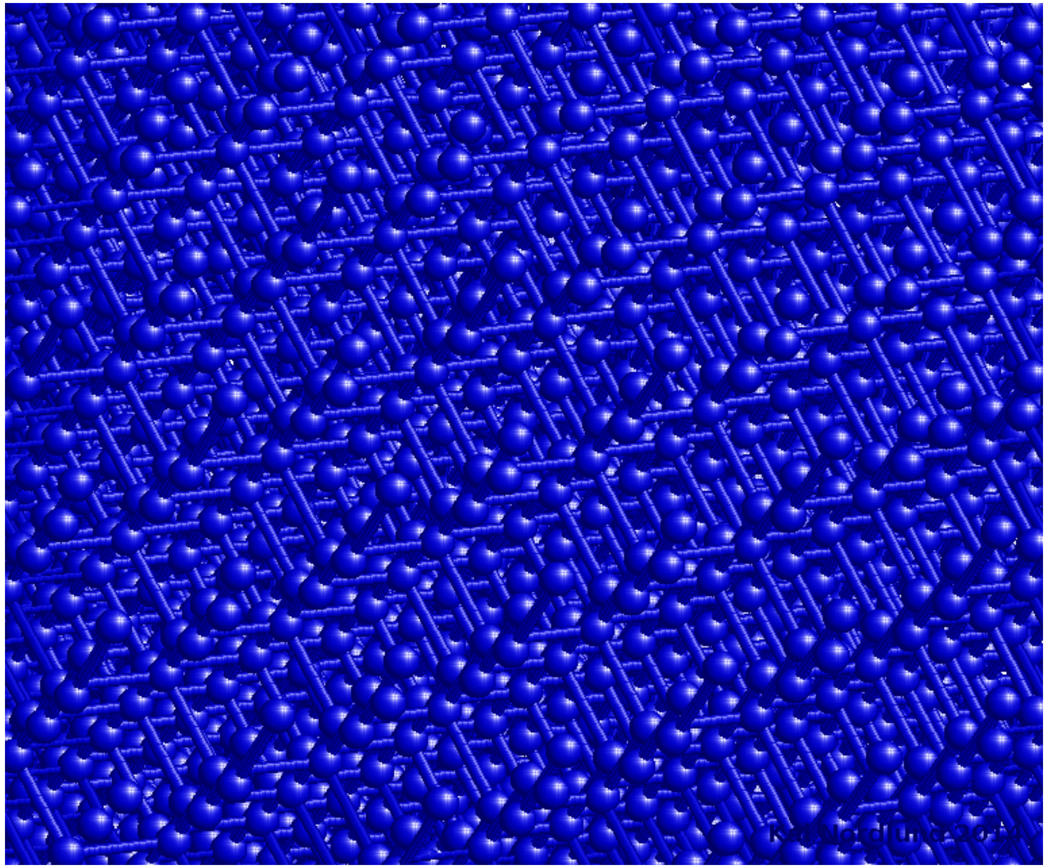
Riccione 12/09/2024

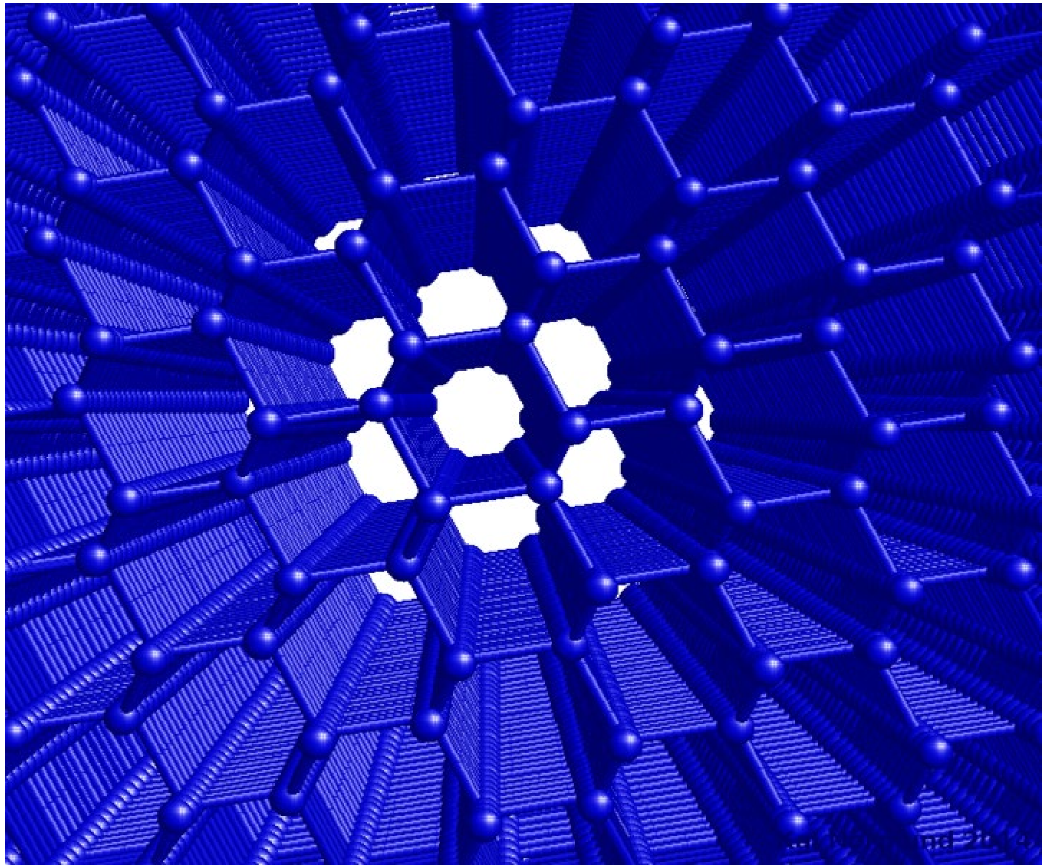
R&D financed by INFN CSN5 2023-2025

Included in **H2020AidaInnova WP8 task 3.1**

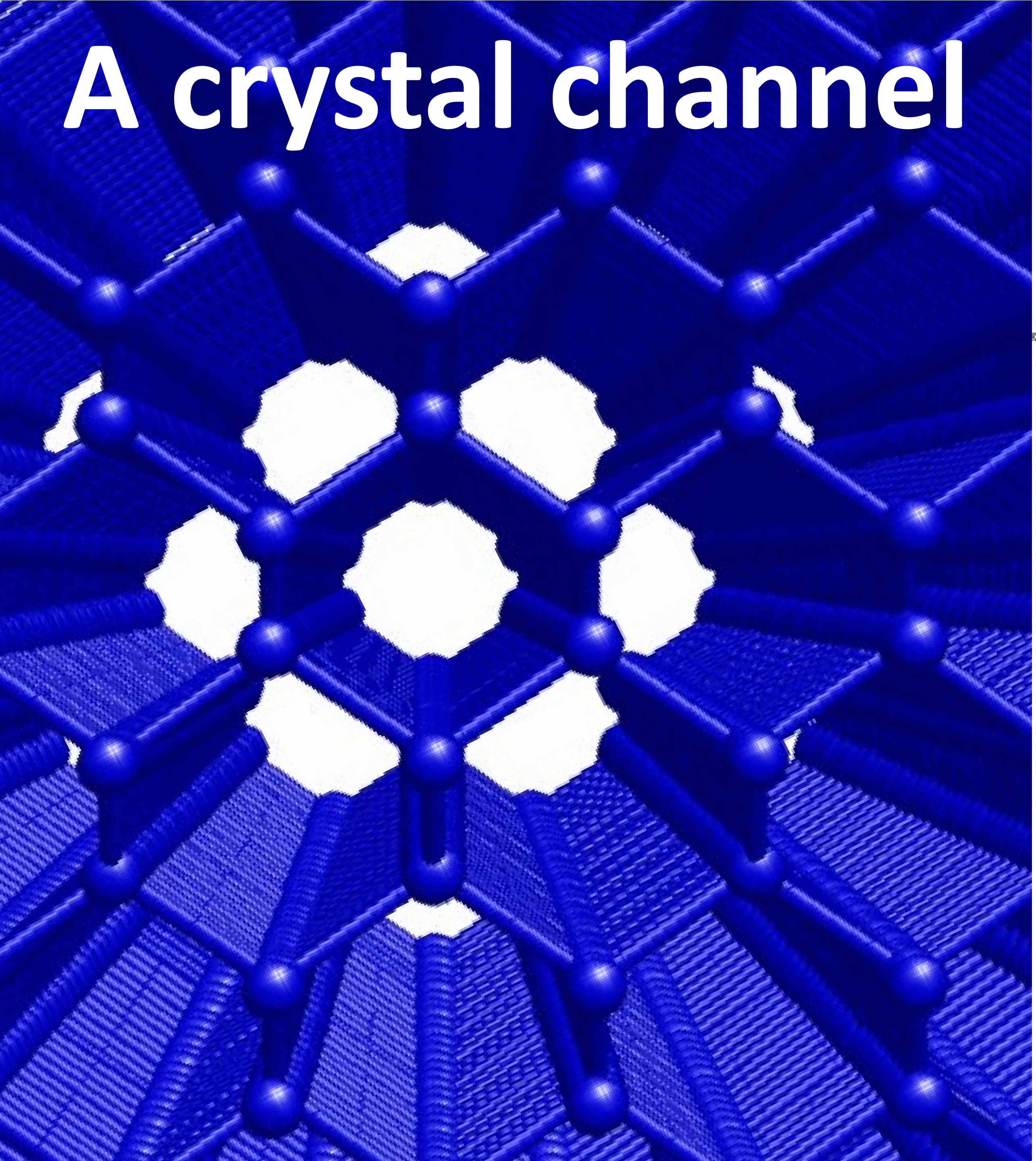
DRD6 Calorimetry WP3 task 3.1

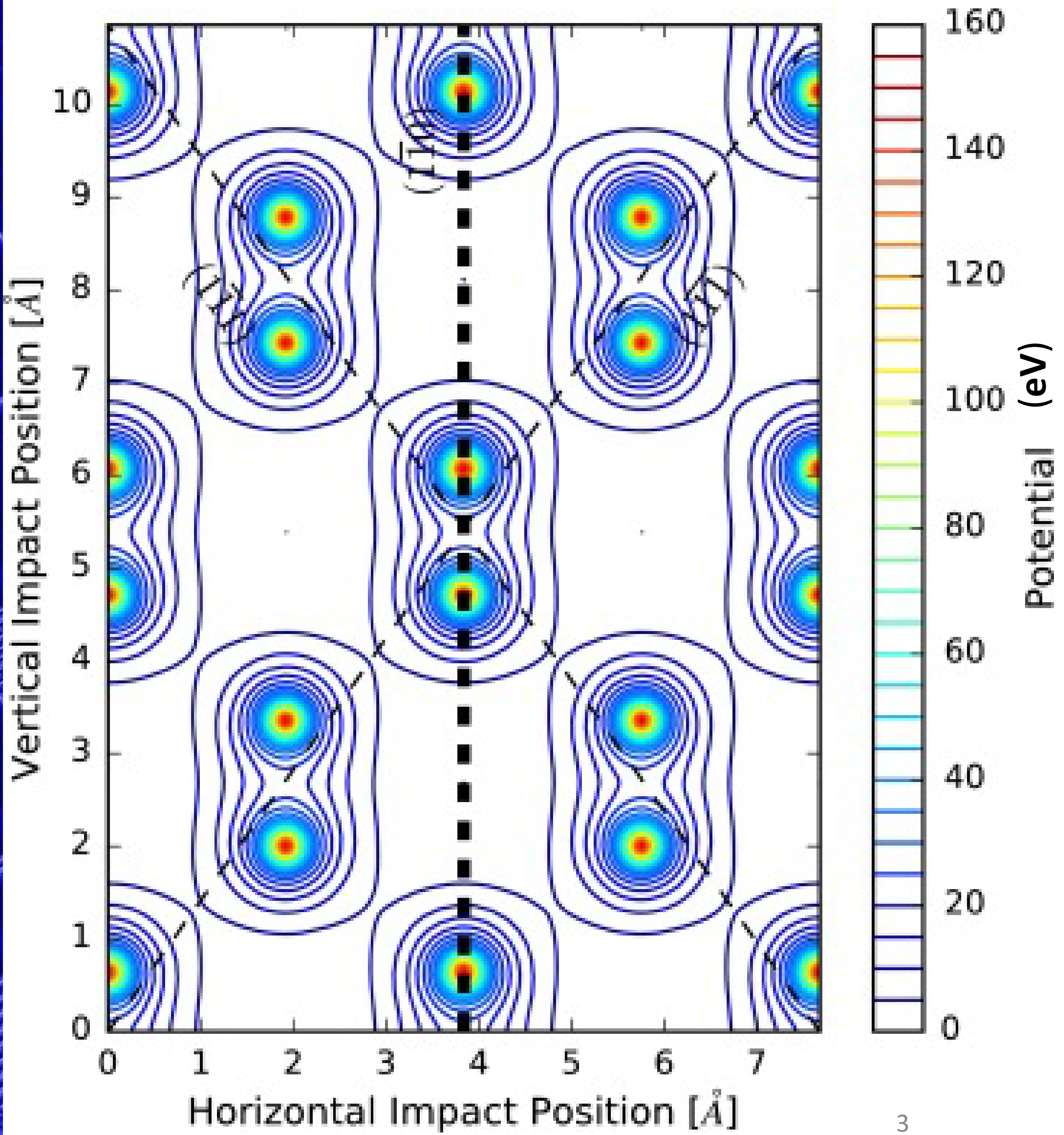
Crystal strong electrostatic potential



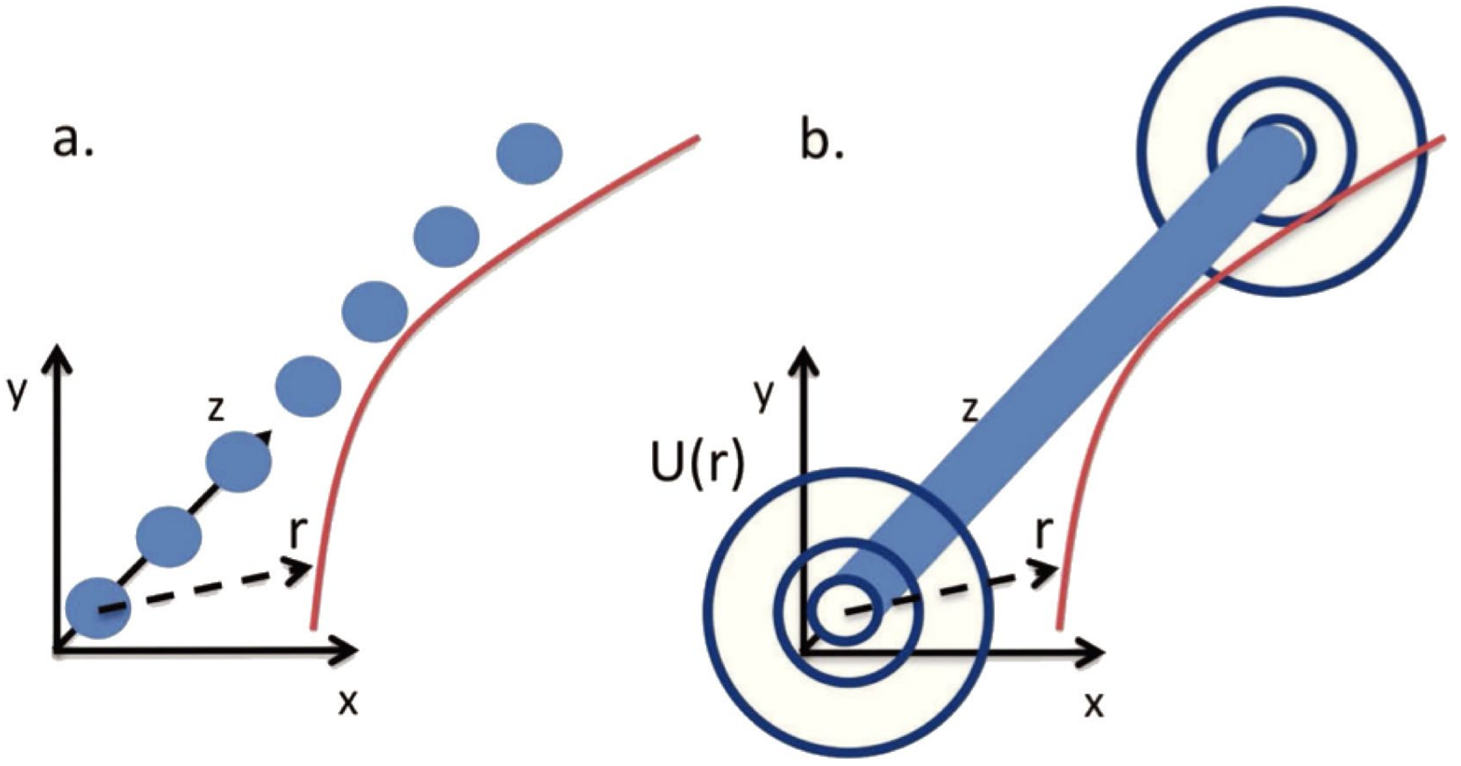


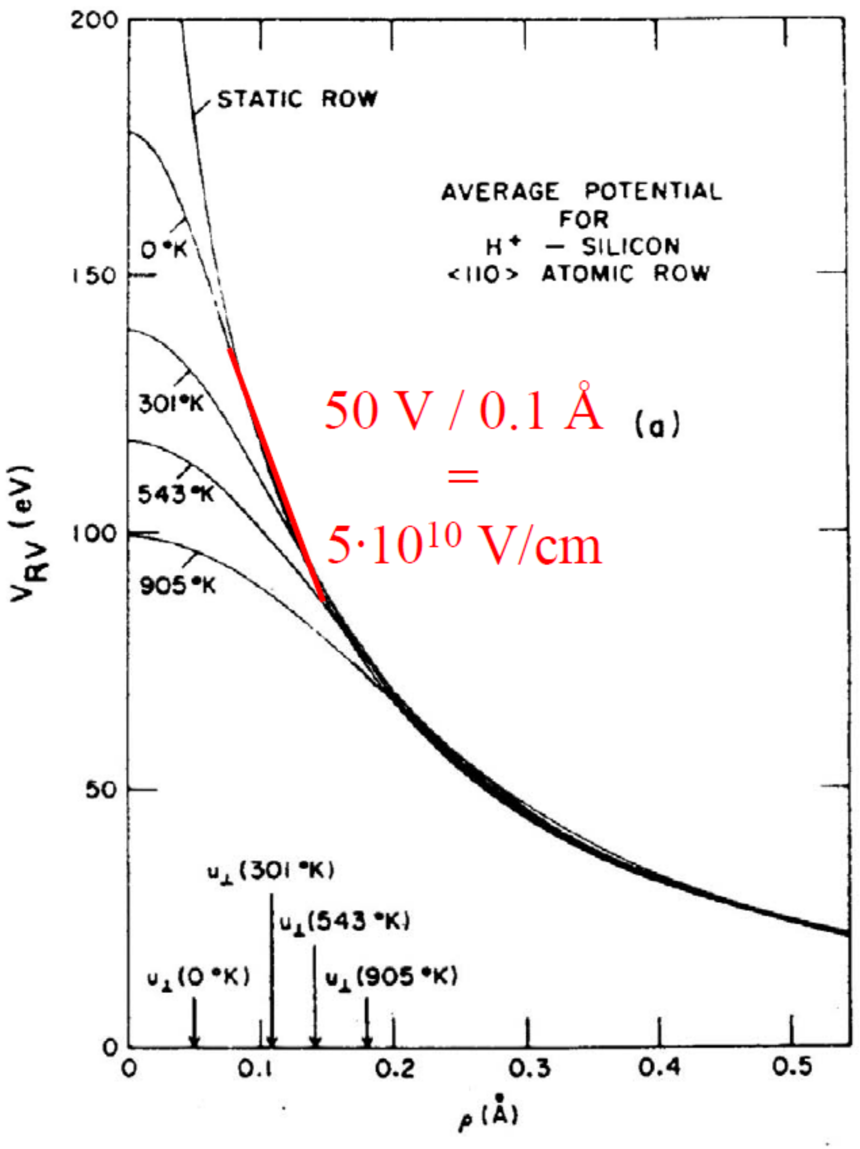
A crystal channel



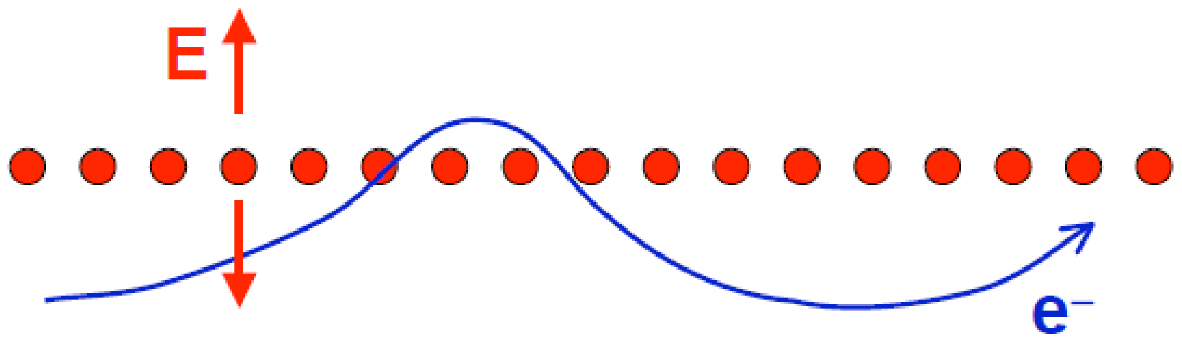


Extremely strong electric fields

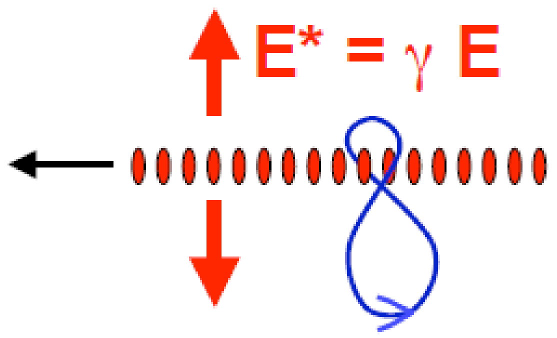




Strong Field regime of Radiation in Crystals



lab. frame



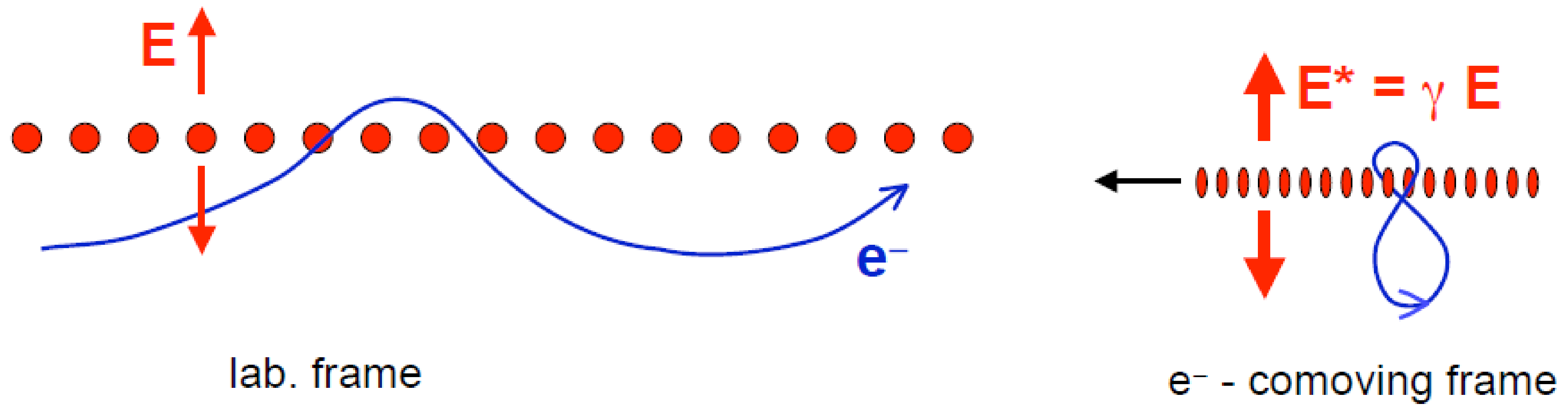
e⁻ - comoving frame

In the comoving frame, the **Lorentz contracted Electric field** can be computed as:

$$E^* = \gamma E$$

Being the Axial field of high-Z crystals $E \approx 10^{11}$ V/cm

Strong Field regime of Radiation in Crystals



In the comoving frame, the **Lorentz contracted Electric field** can be computed as:

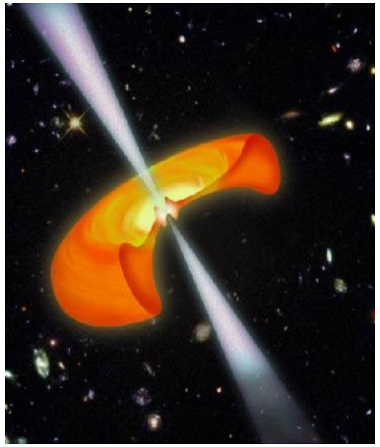
$$E^* = \gamma E$$

Being the Axial field of high-Z crystals $E \approx 10^{11}$ V/cm

At beam energies > 10 GeV, E* can reach the **Critical Schwinger QED field**:

$$E_0 = m^2c^3/e\hbar \simeq 1.3 \times 10^{16} V/cm$$

above which electrodynamics becomes non linear

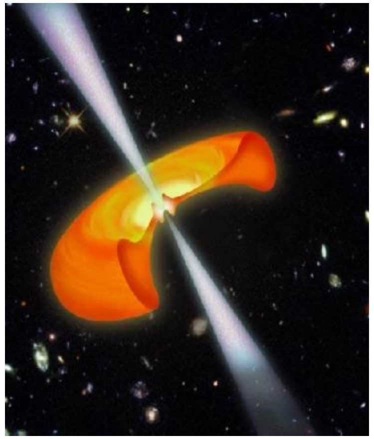


Magnetars

$B \approx 10^{10}$ T

Strong fields in Nature and Labs

Magnetars
$B \approx 10^{10}$ T



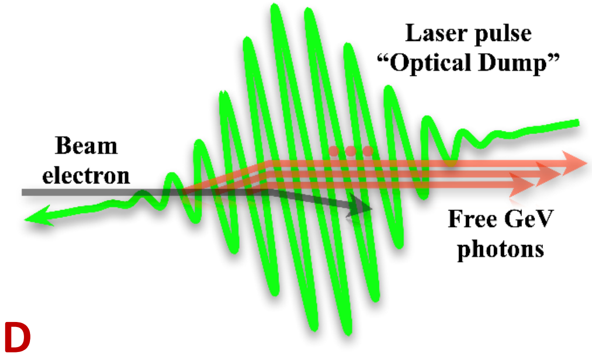
Beamstrahlung in future linear colliders

ILC/CLIC

Heavy ion collider

RHIC/LHC

Strong lasers

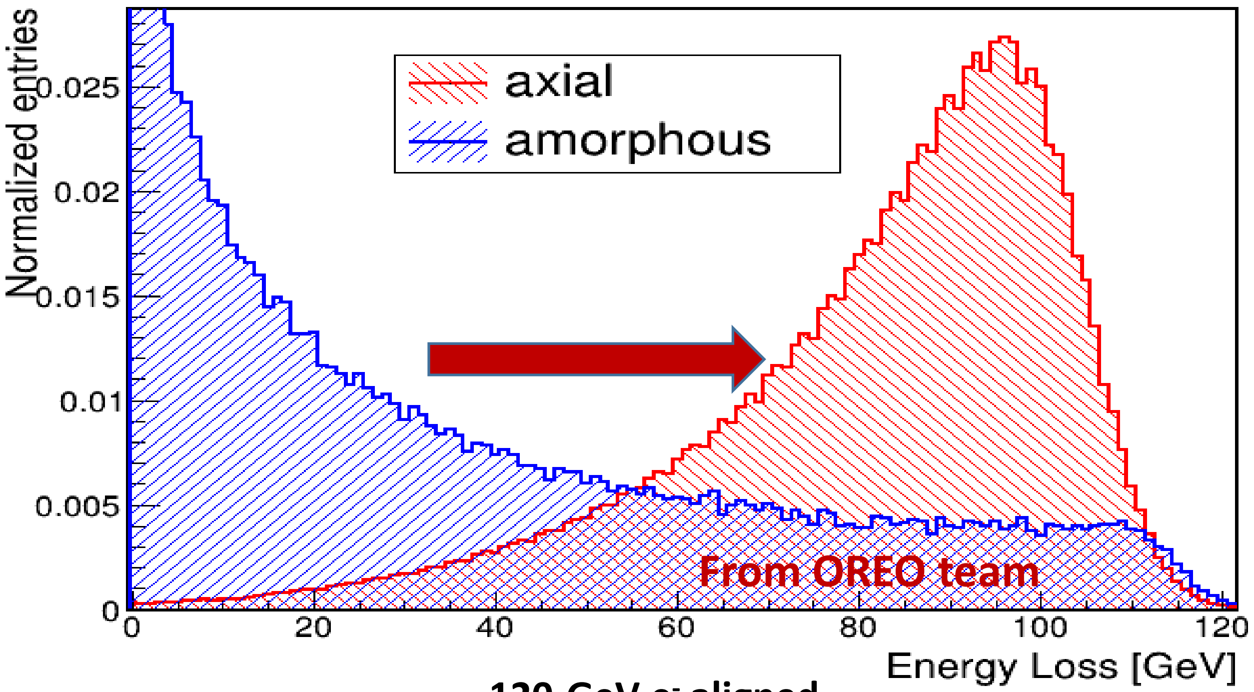


Many experiments worldwide dedicated to investigate Strong Field QED
NA63 @CERN (crystals), E-320 @SLAC (Stanford, US) and LUXE @EU XFEL/DESY (Hamburg)

With crystals, the **Critical Schwinger Field** is accessible with no need of multi-TeV beams or ultra-intense lasers
Crystals are powerful tools to test Strong Field QED!!

Enhanced radiation emission ..

Effect of axial orientation in the radiation spectrum



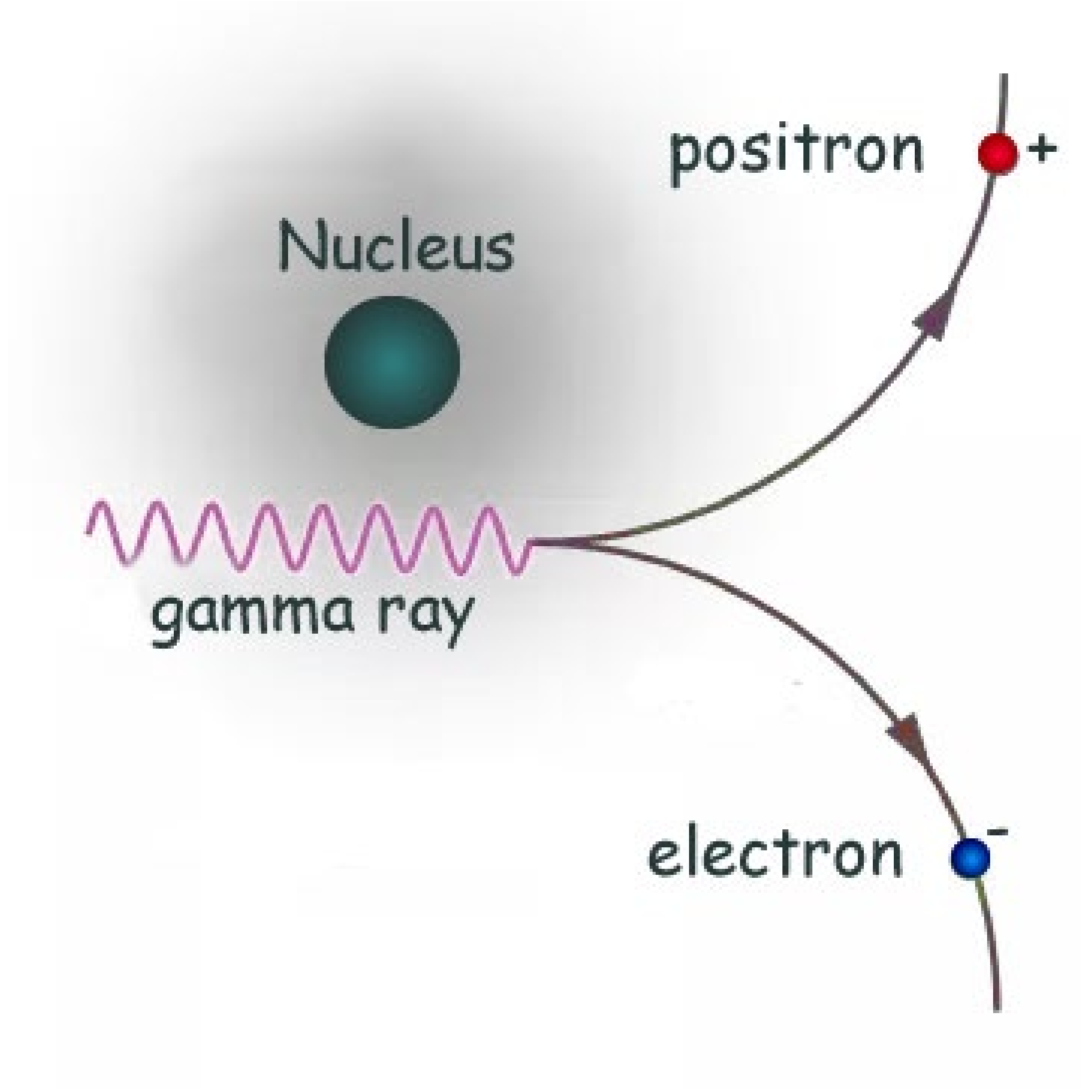
120-GeV e⁻ aligned
with the <110> axis of a 2.8 mm long Ge crystal

- **The Strong Field effect increase with initial particle energy**
- **Angular range*:***
  - up to 1° of misalignment between particle direction and crystal axes

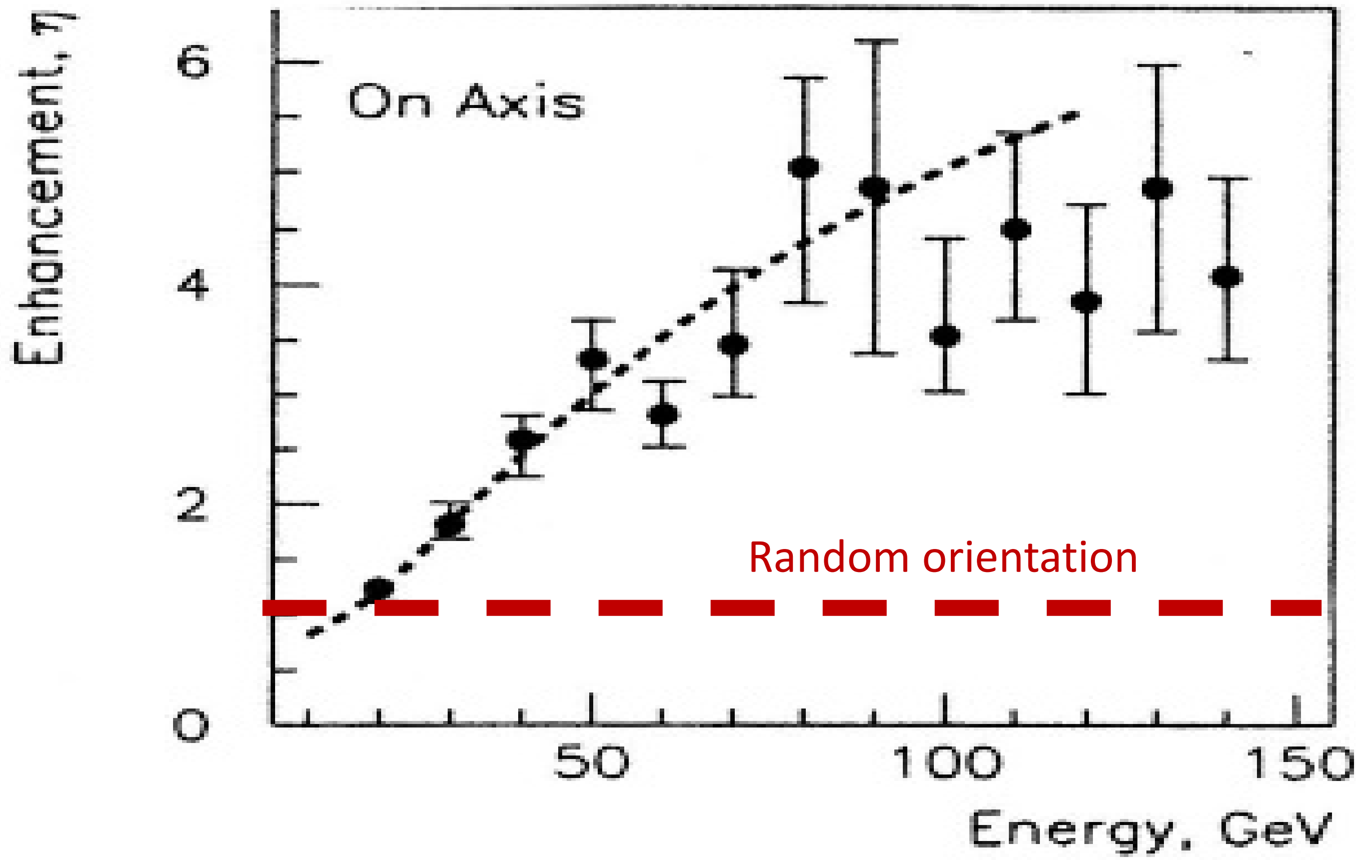
Strong increase in the energy radiated by the electrons!

First observation in a Ge crystal at CERN by A. Belkacem et al. Phys. Rev Lett. 54 (1985) 25

..and what about photons…



…increased e^+e^- pair production by high-energy photons



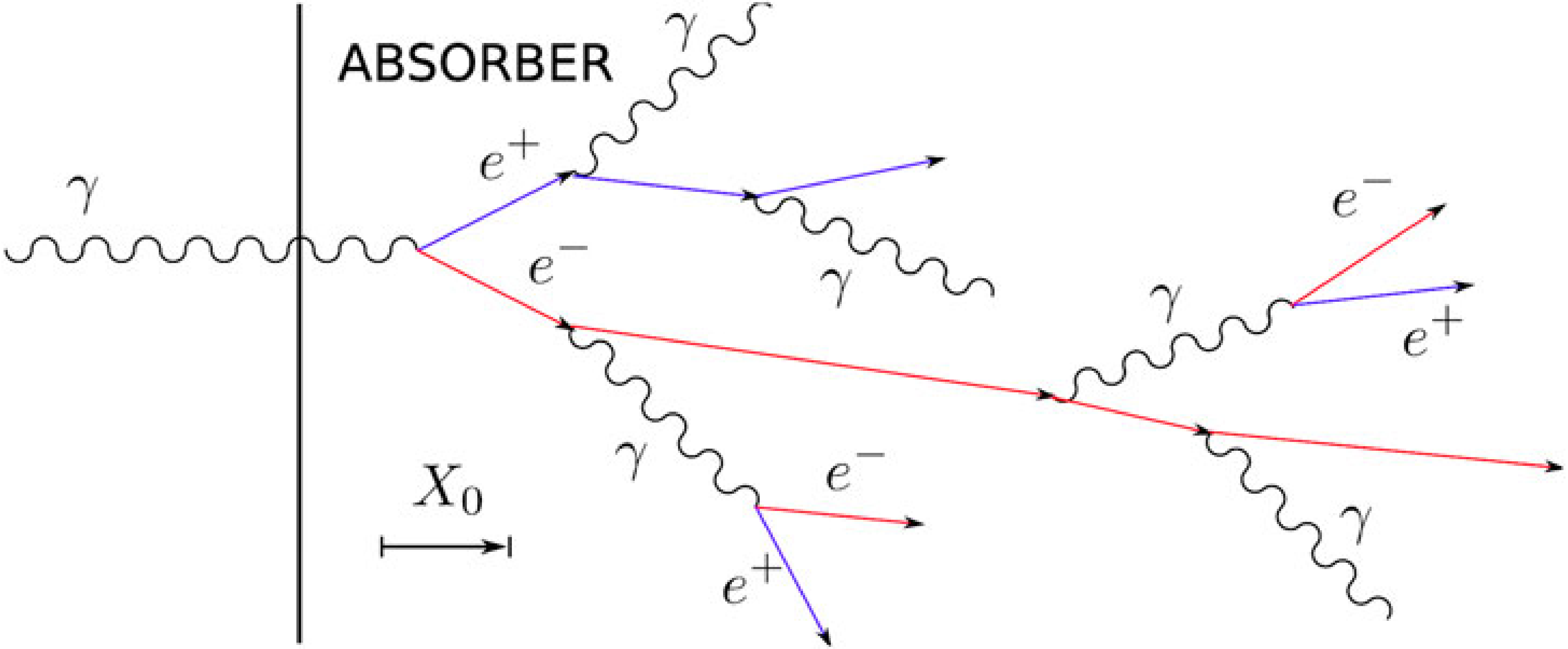
**Enhancement of e+e- pair production in a Tungsten crystal axially oriented – compared to random orientation
Vs. photon energy**

NA43 & NA48 @CERN

Strong increase of the pair production probability by High-energy photons in an oriented crystal

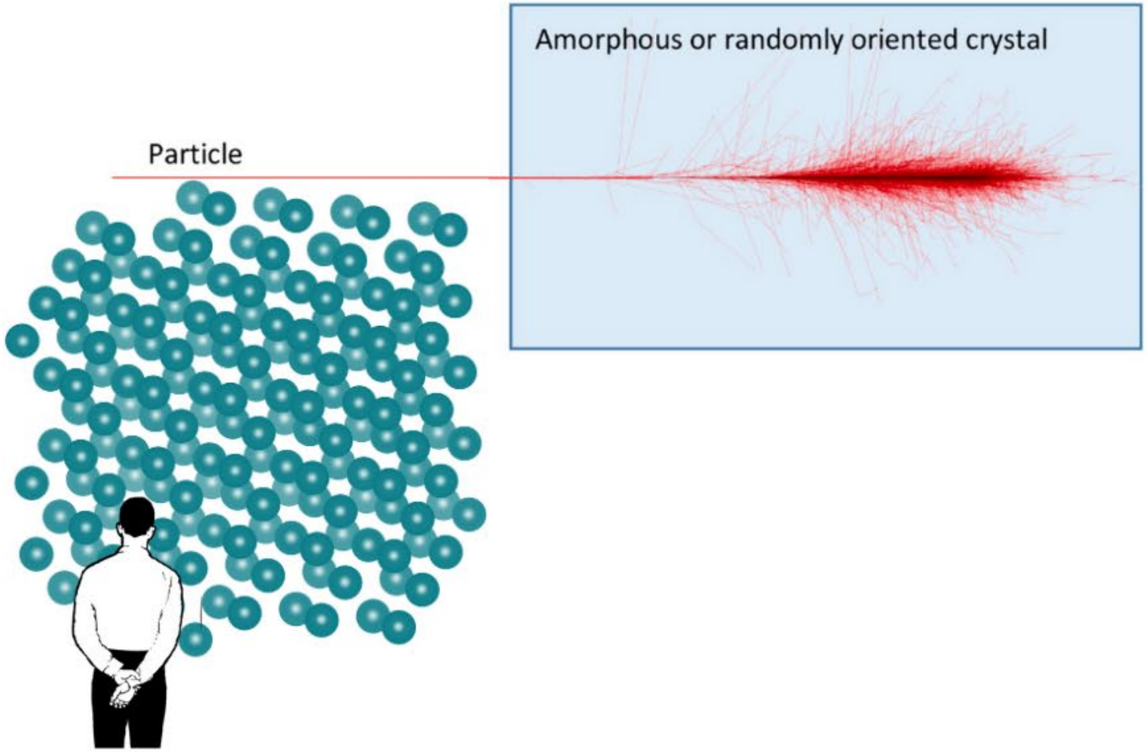
First observation in a Ge crystal at CERN by A. Belkacem et al., Phys. Rev. Lett. 58 (1987) 1196

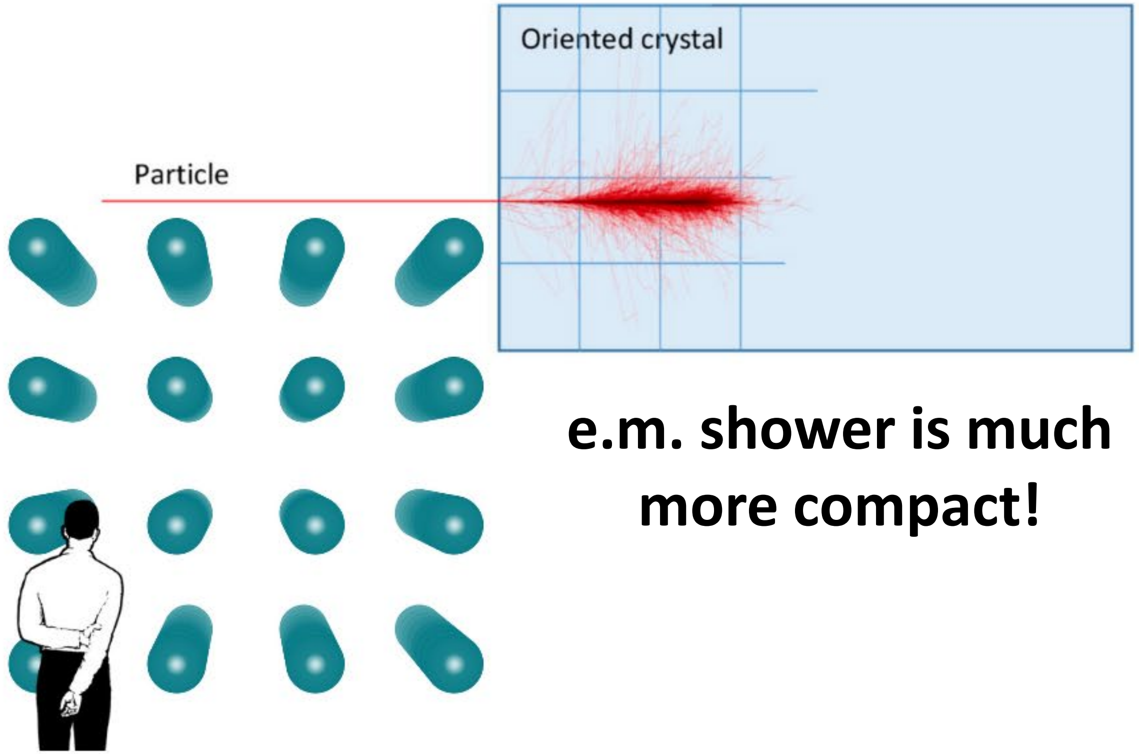
Electromagnetic shower



Radiation Length X_0 **of a medium is defined as: distance over which electron energy reduced to *e* times. Characterizes the shower depth.**

Strong Crystal Fields:
Electromagnetic shower acceleration…..





e.m. shower is much more compact!

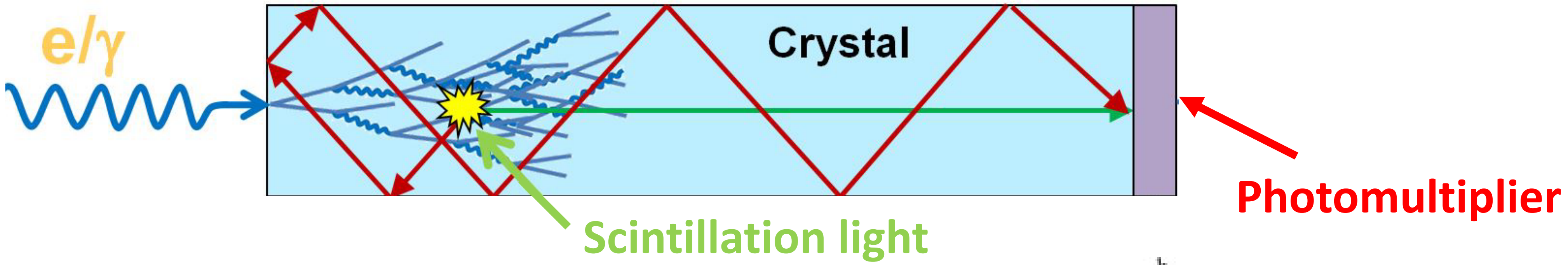
Radiation length reduction

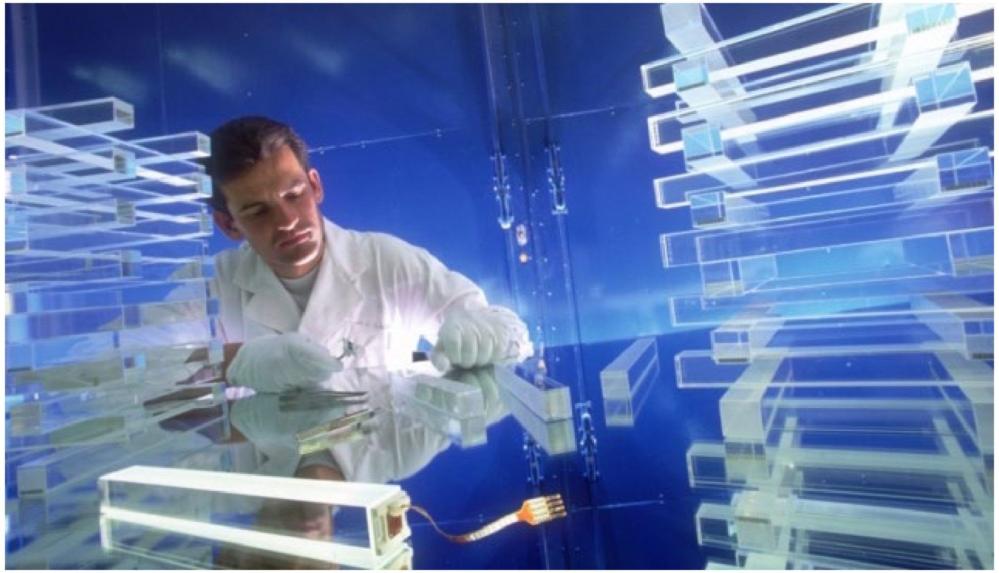
- **X_0 decreases with Energy increase.**

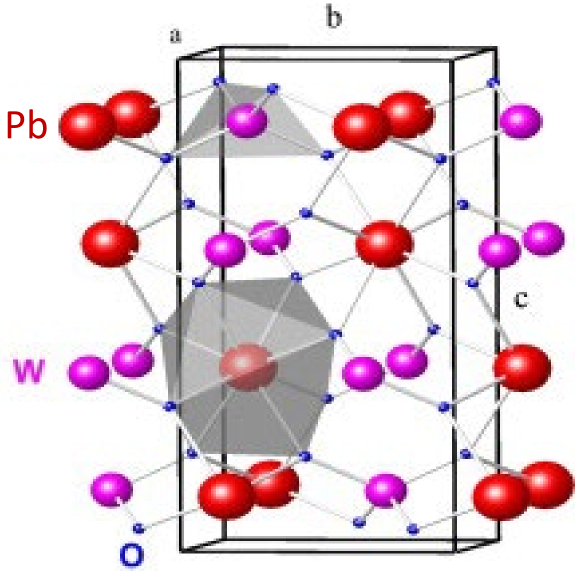
Angular range:

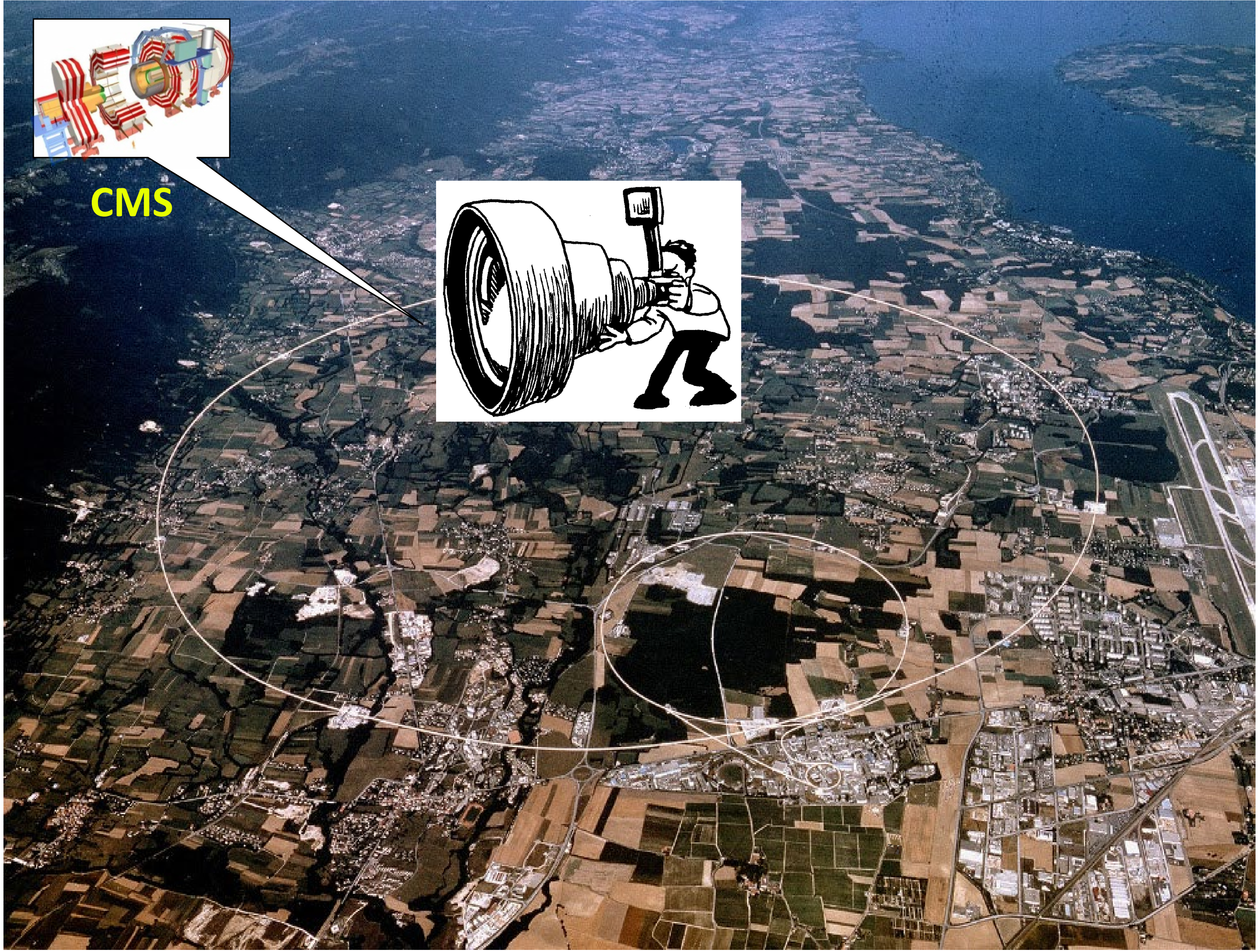
- **$\Theta_{max} = V_0/m$ (mrad)**
- **few mrad up to 0.5°-1°**
- Depends poorly on particle energy.

… Strong Crystalline Field in inorganic crystal scintillators used in electromagnetic calorimeters



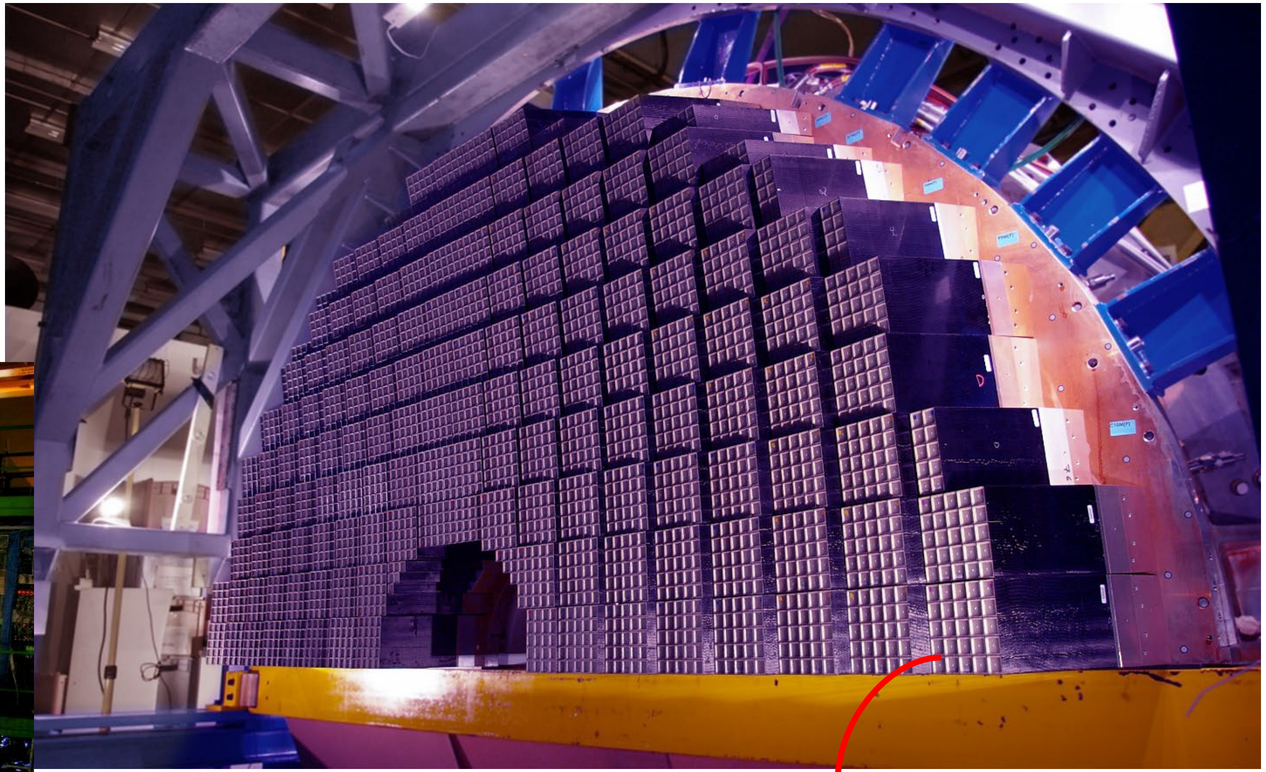


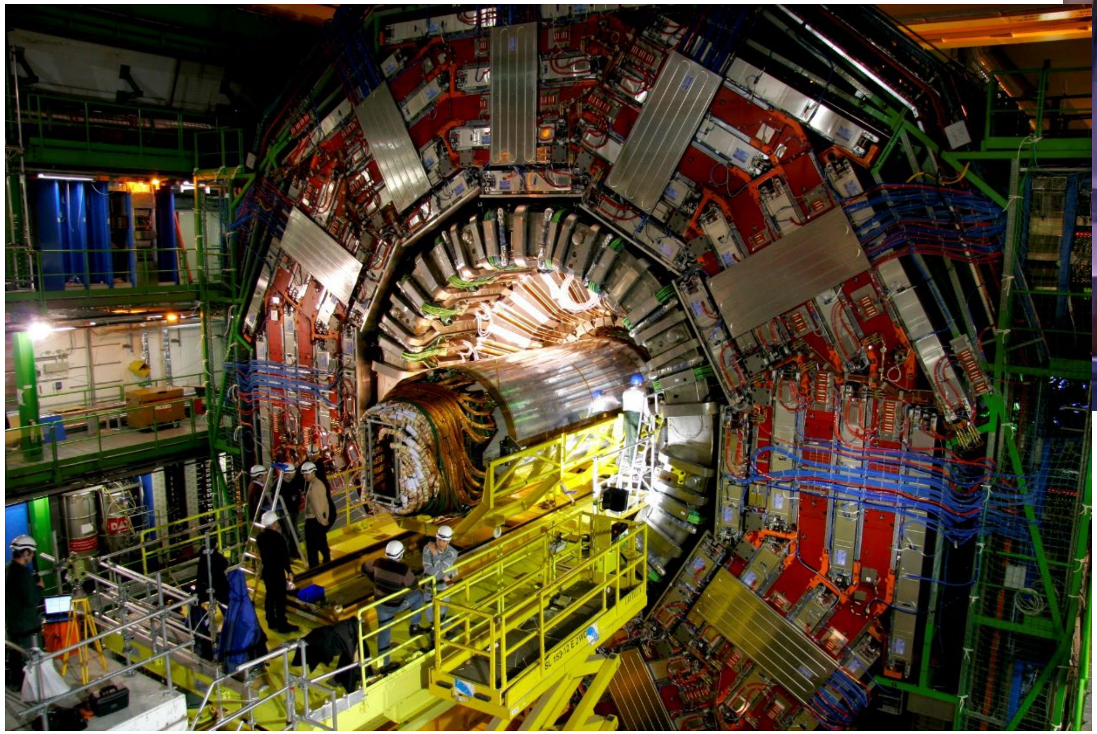


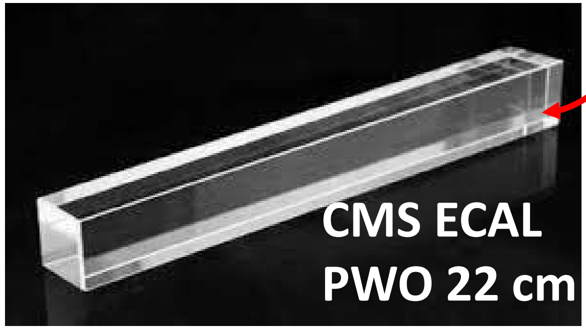

CMS

The CMS Crystal ECAL

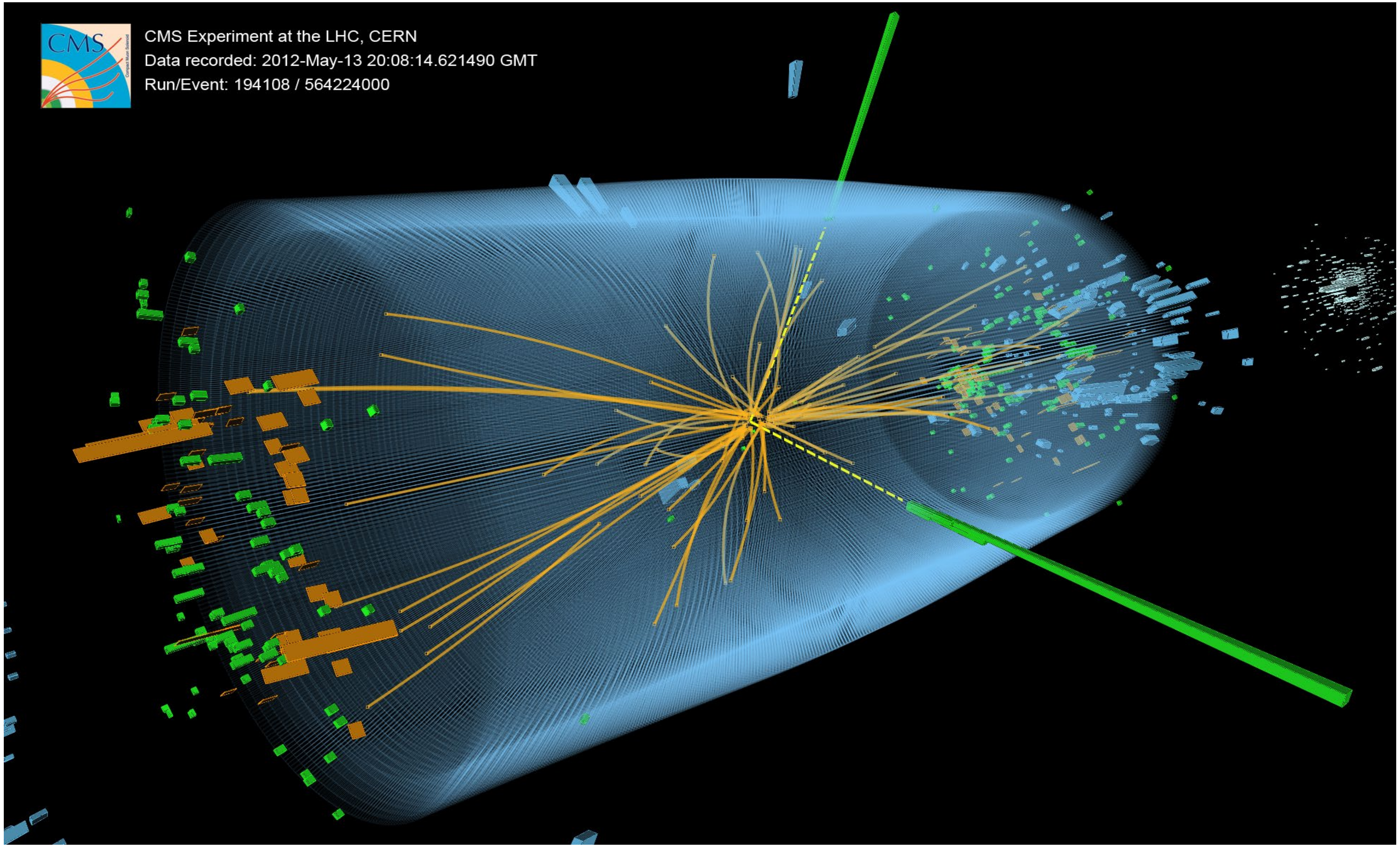
The CMS Electromagnetic Calorimeter at CERN LHC is composed of 77200 lead tungstate (PbWO4 or PWO) scintillator crystals





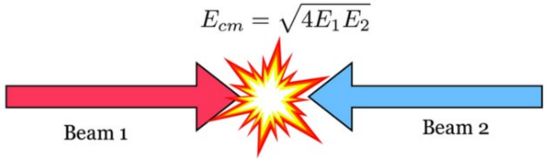


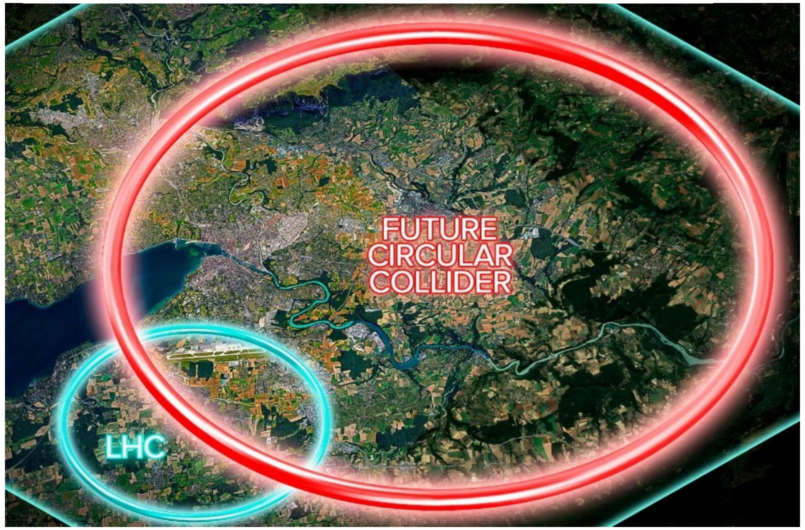
Higgs boson decay in two photons



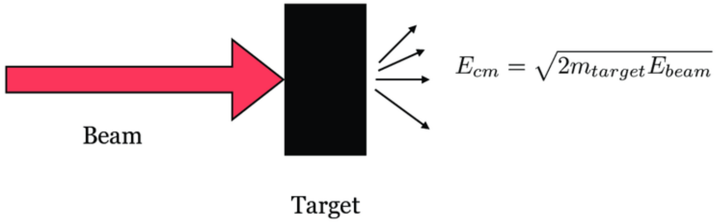
Crystal Electromagnetic Calorimeter

At the highest energies in future colliders (FCC, CEPC, Muon Collider…)

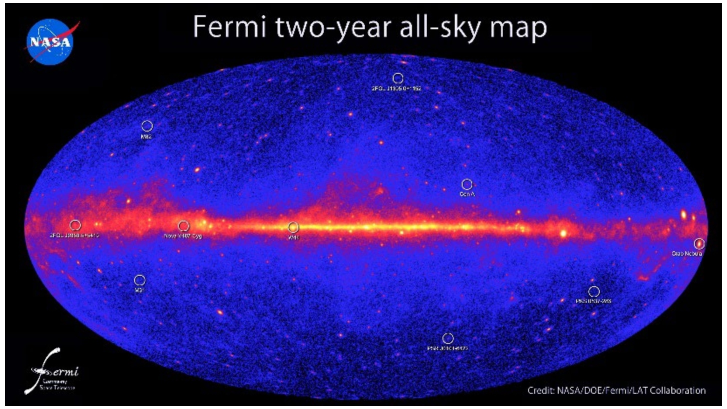




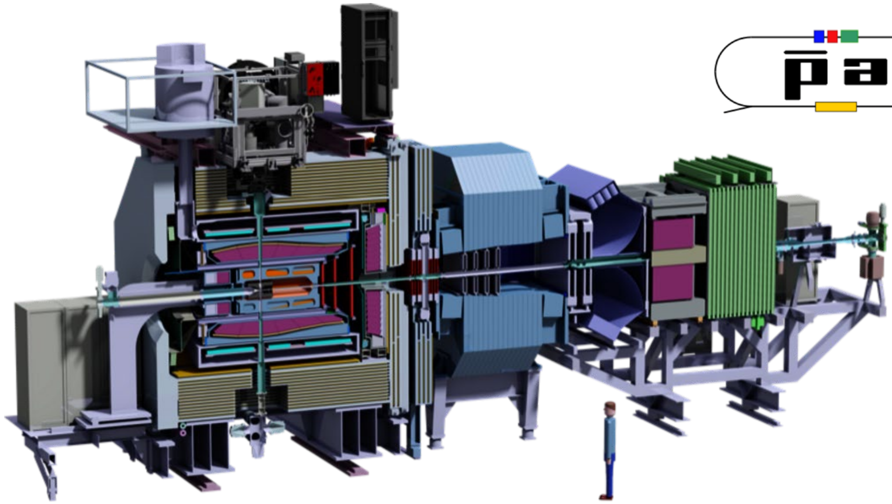
At the precision frontiers in fixed target experiments and for light dark matter search in Beam Dump



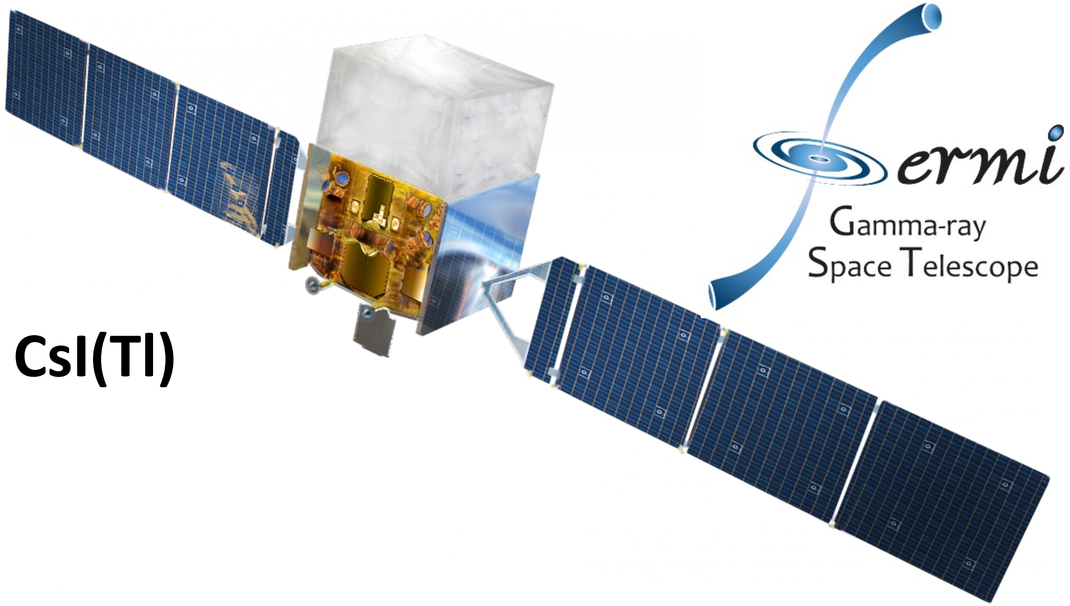
In space-borne telescope for VHE and UHE gamma-ray observation



p̄anda

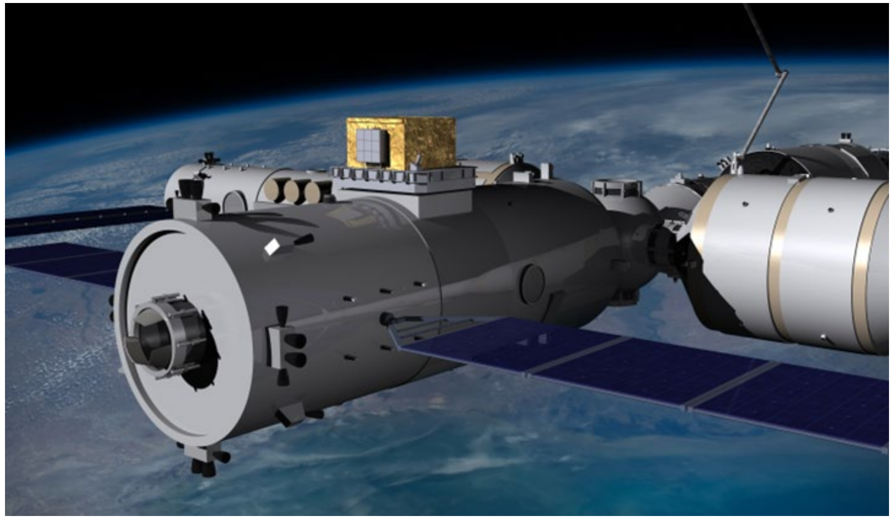


PWO



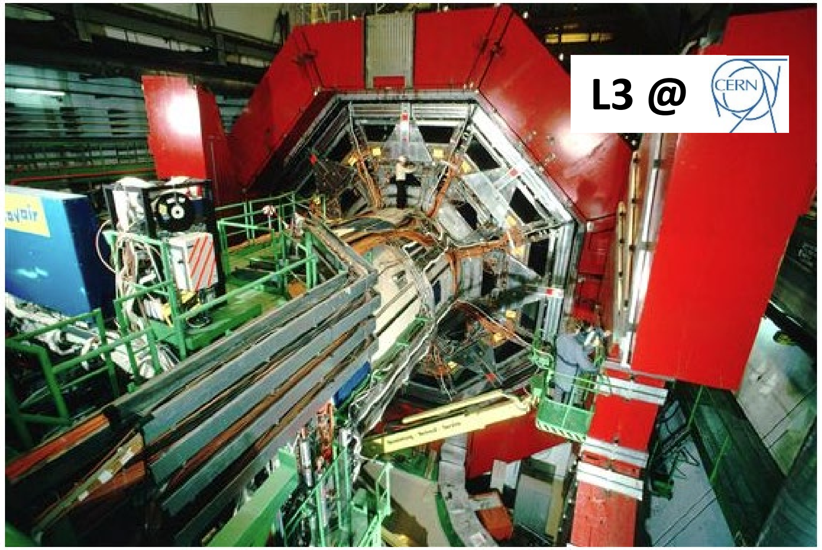
CsI(Tl)

HERD



LYSO

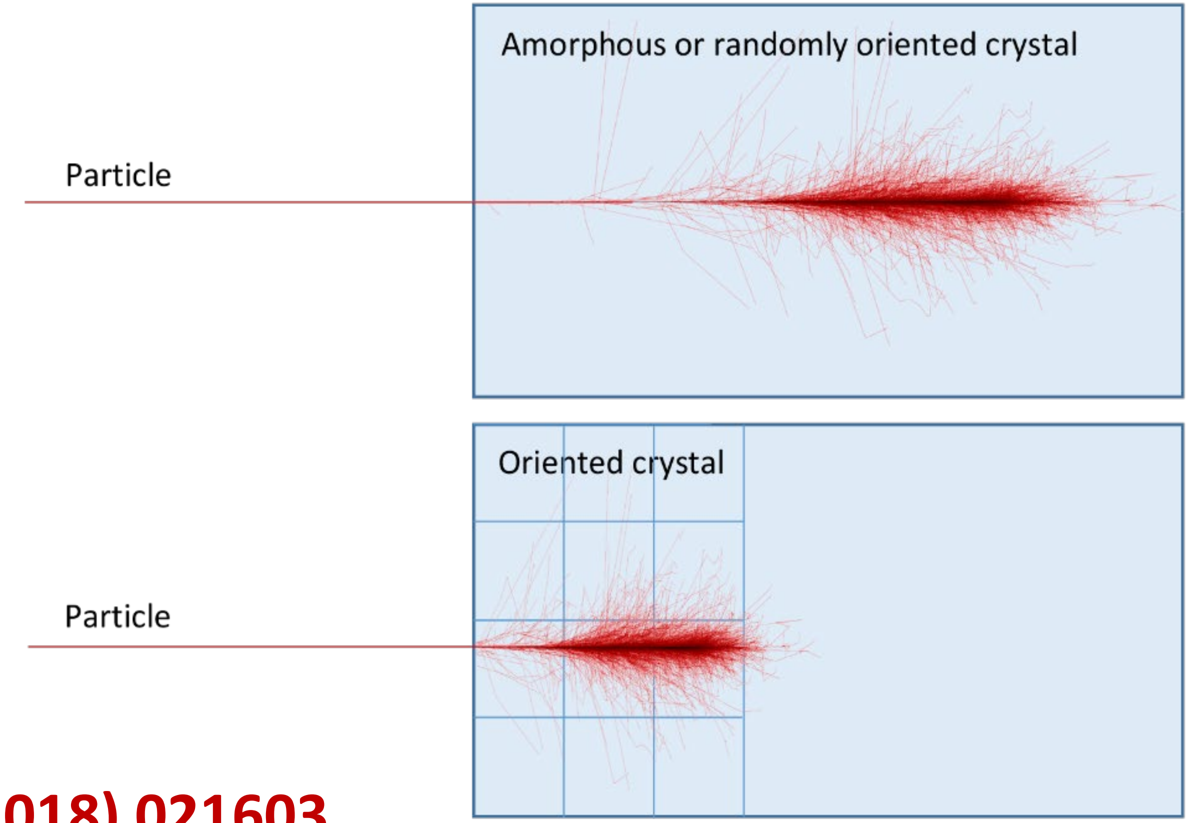
BGO



Orienting the e.m. calorimeter

The input photon or e^-/e^+ showers can fully develop in a much lower thickness with respect to the current state-of-the-art detectors

- ➢ enhanced compactness
- ➢ budget-saver
- ➢ n/γ discrimination



L. Bandiera et al., Phys. Rev. Lett. 121 (2018) 021603

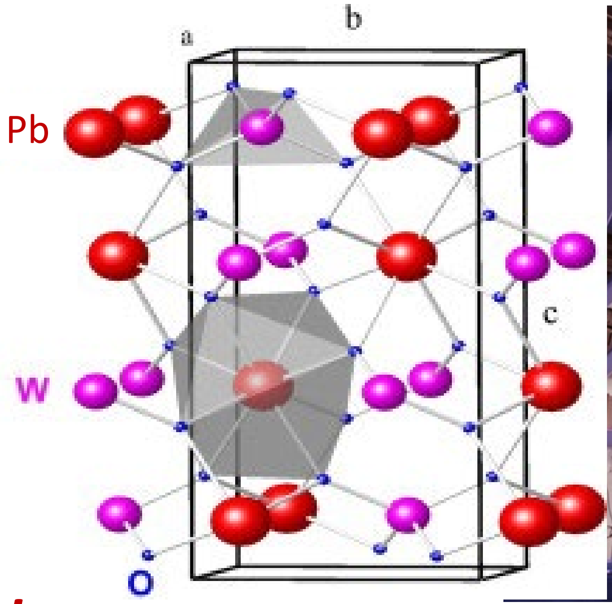
Crystal investigated: Lead tungstate ($PbWO_4$)

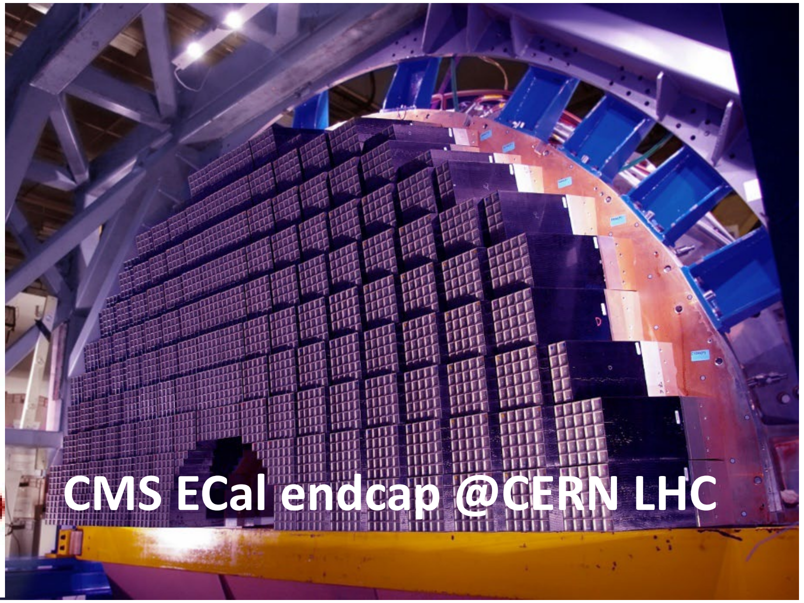
- Scintillator, with well-peaked light emission in the blue
- Optically transparent
- Exploited by the CMS ECal → well known
- High density, high *Z* ***X_0 = 8.9 mm***
- Radiation hard
- Cheap fabrication into big samples
- **Good crystalline quality (mosaic spread 0.1 mrad)**
- Axes properties:

Maximum of Strong Field V_0/m ≈1 mrad

	[100]	[001]
interatomic pitch	5.456 Å	6.01 Å
U_0	~700 eV	~600 eV
SF threshold	~25 GeV	

High-Z crystal for compact detectors

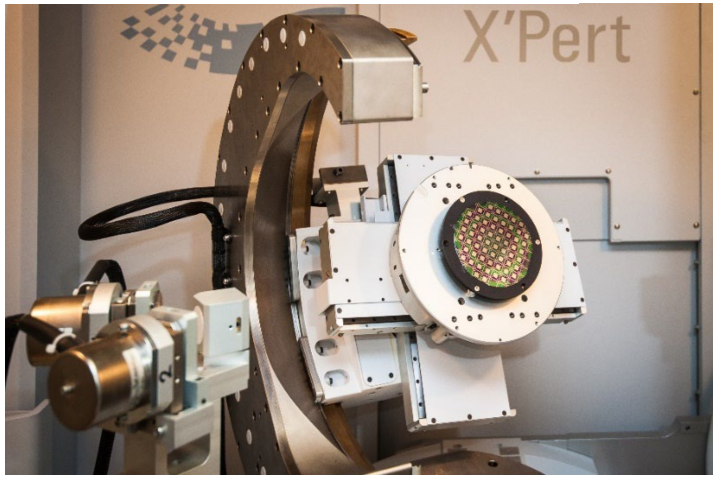




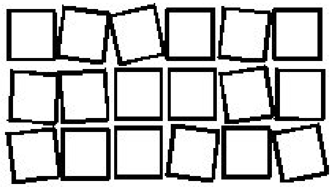
PWO-I, PWO-II**, PWO-UF****
Moltech, M. Korjik** and Crytur****

Crystal Characterization

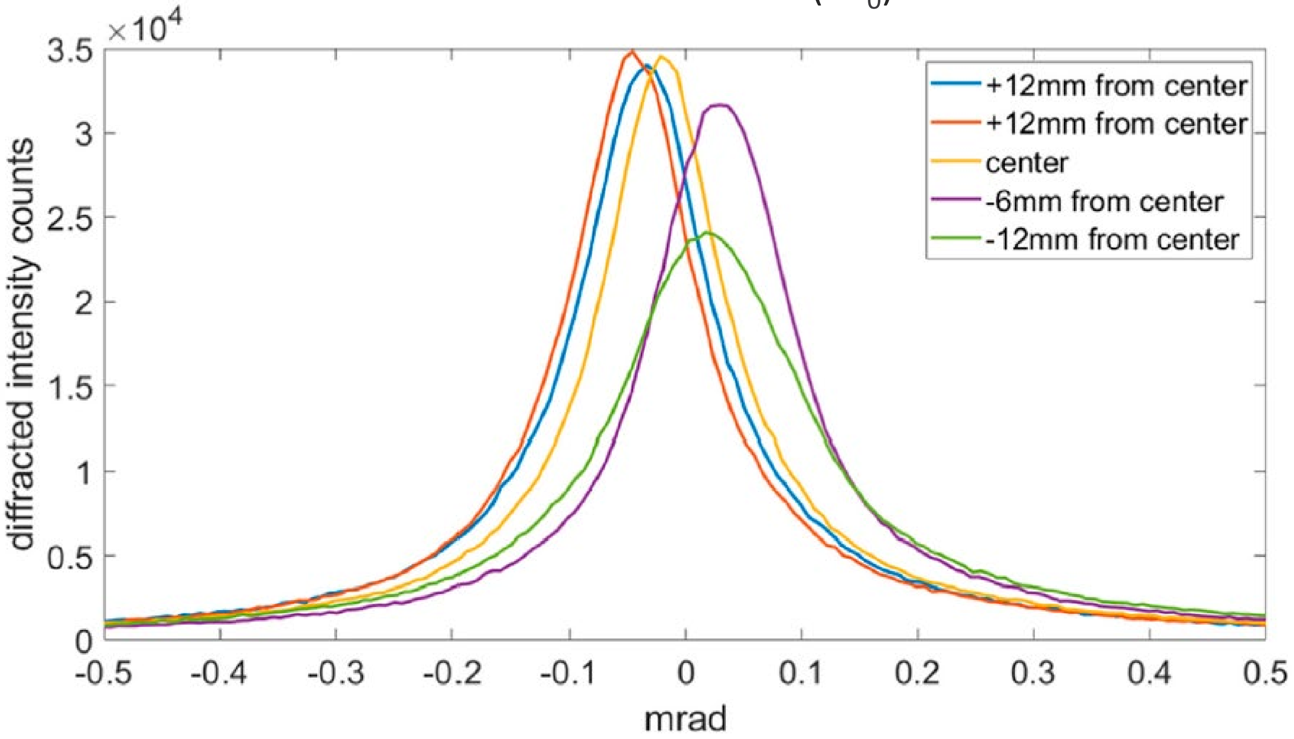
X-ray characterization



surface mosaicity and
crystal orientation

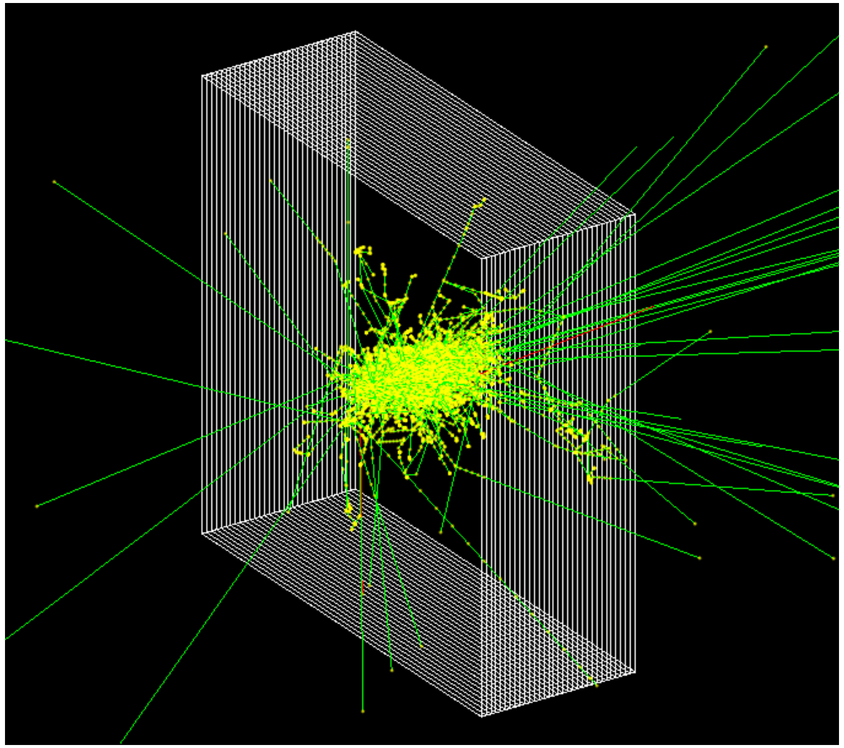


Series of rocking curves on the 27 × 27 mm^2 face of the 71-mm ($8X_0$) thick PWO-UF

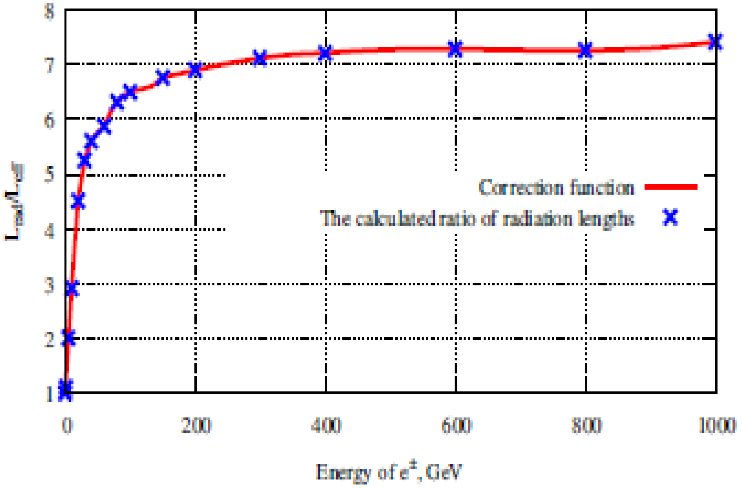


- Mosaicity spread ≤ 0.1 mrad;
- axis alignment on different position changes of < 0.2 mrad << V_0/m

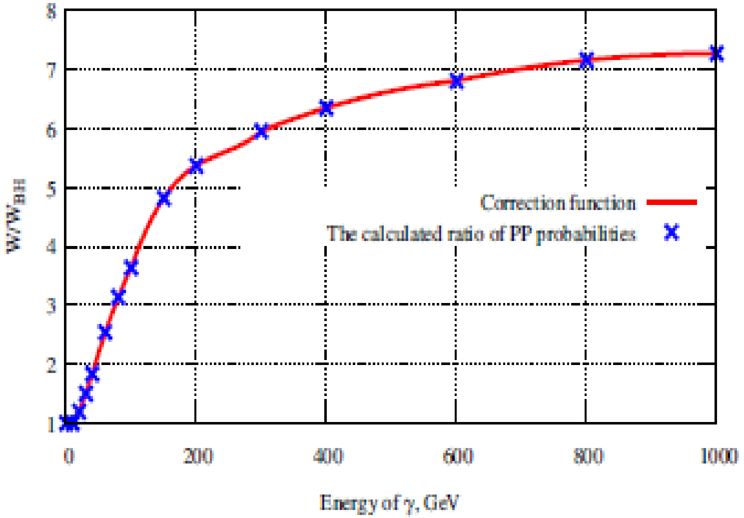
Oriented crystals in Geant4 simulations

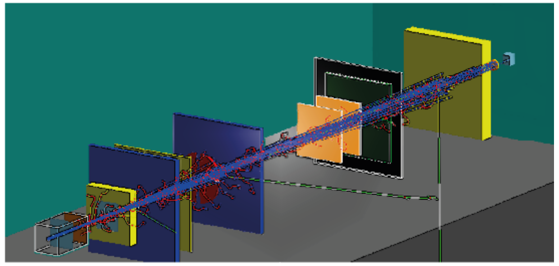


bremsstrahlung



Pair production





The electromagnetic shower is simulated using the **Geant4** toolkit in which the cross sections for **bremsstrahlung and pair production are rescaled** in agreement with a full Monte Carlo code including the strong field effects in crystals.

L. Bandiera, V.V.Haurylavets, V. Tikhomirov NIM A 936 (2019) p.124-126

GEANT I.N.F.N.

European Commission

Trillion

Marie Curie Individual fellow

https://www.fe.infn.it/trillion/

E.m. shower development in an oriented PWO

- <u>peak is at smaller depth</u>
- peak depth is essentially <u>independent on the primary energy and type</u>
- effect gradually decreases as the shower develops

L. Bandiera et al., NIM A 936 (2019) p.124-126

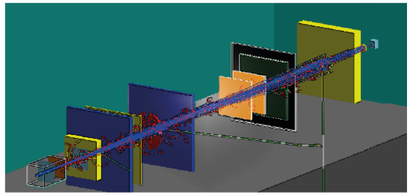
L. Bandiera et al., Front. Phys. (2023) doi.org/10.3389/fphy.2023.1254020

European Commission

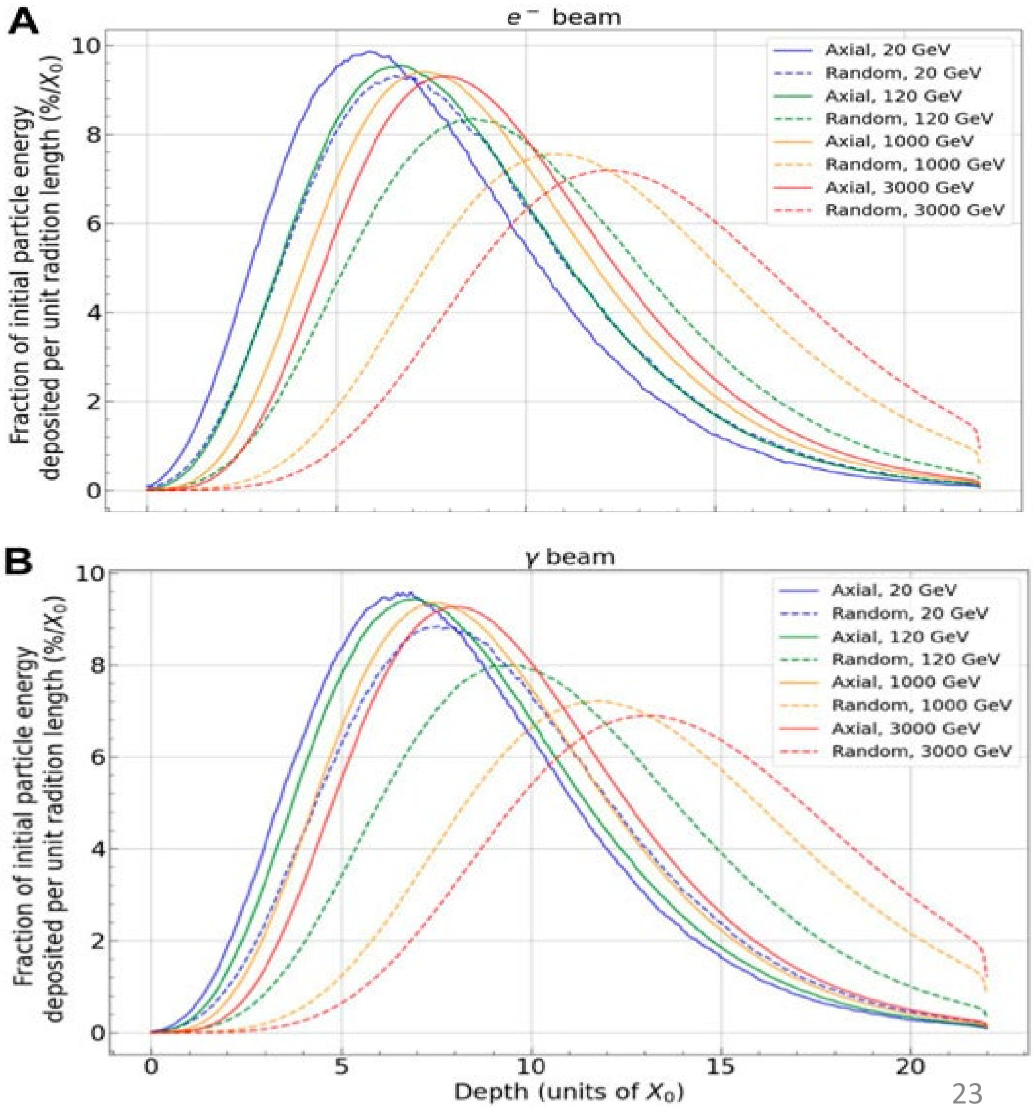
Trillion

I.N.F.N.

GEANT



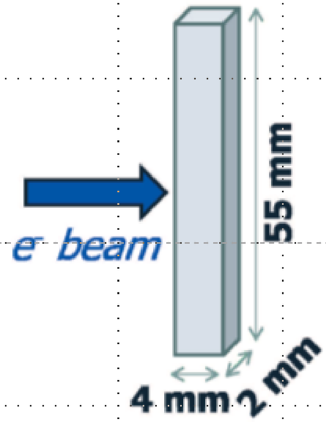
On axis Geant4 simulations

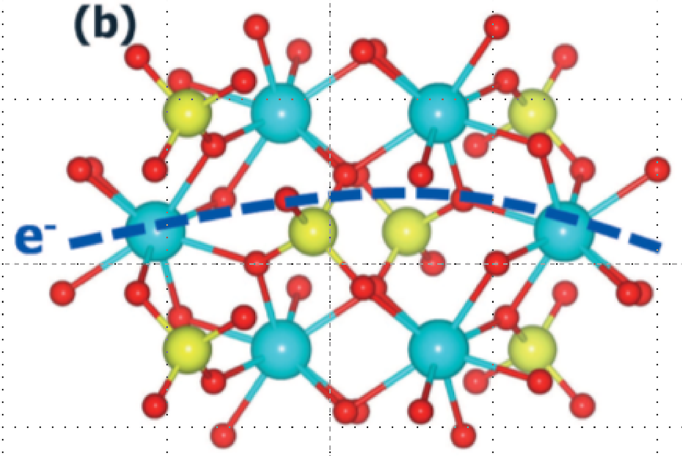


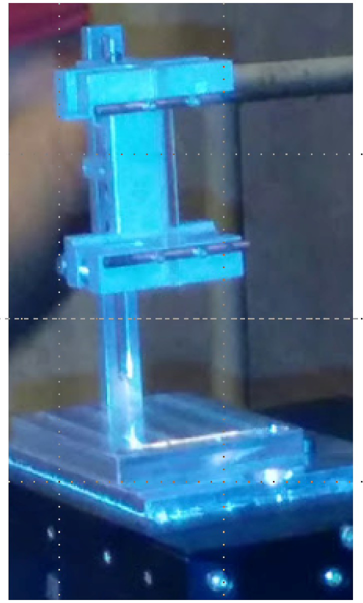
Where we started…
first result presented at Channeling2018

L. Bandiera, INFN Sezione di Ferrara Channeling 2018, 27 September 2018

Experiment with 120 GeV/c electrons

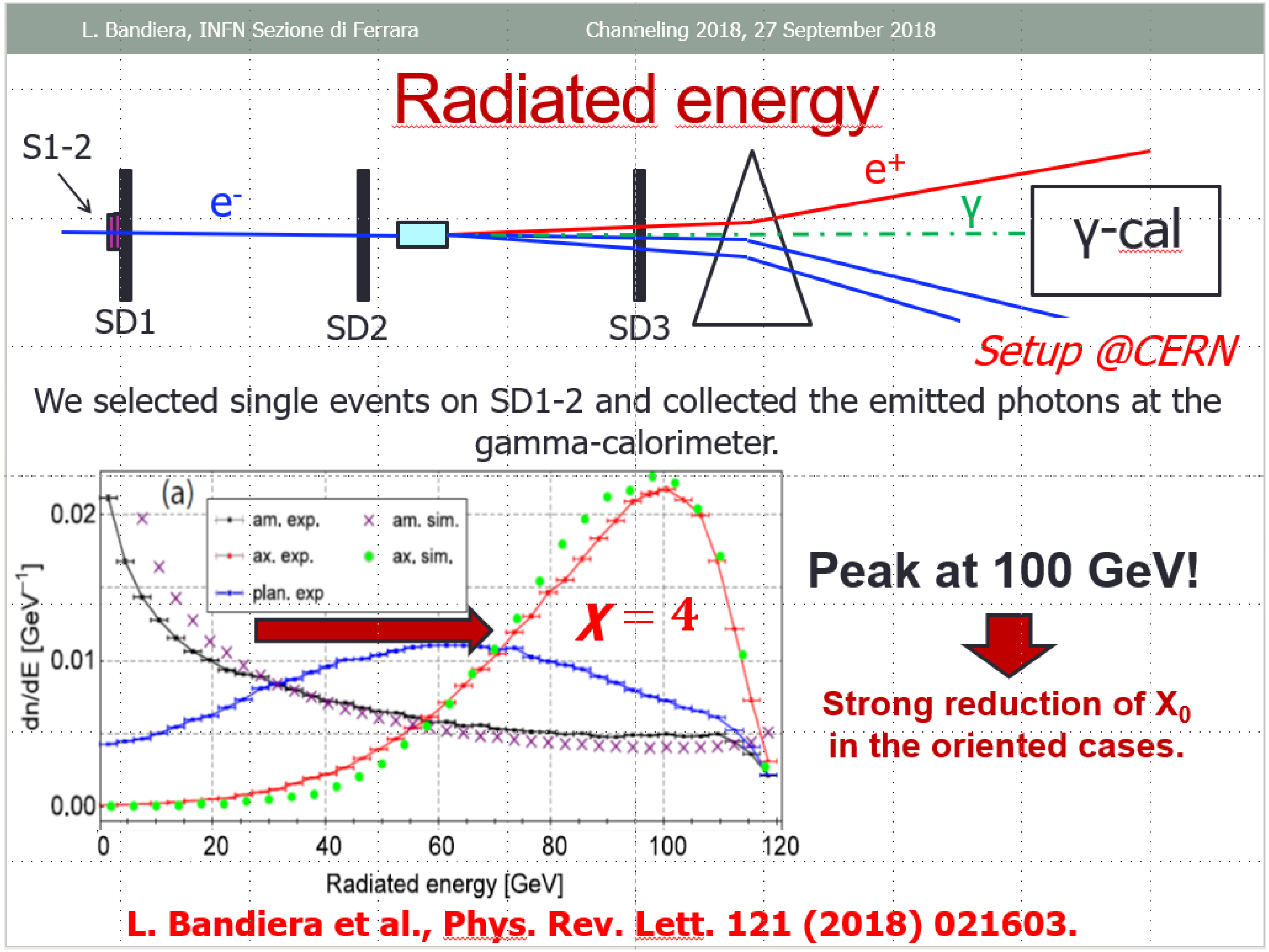






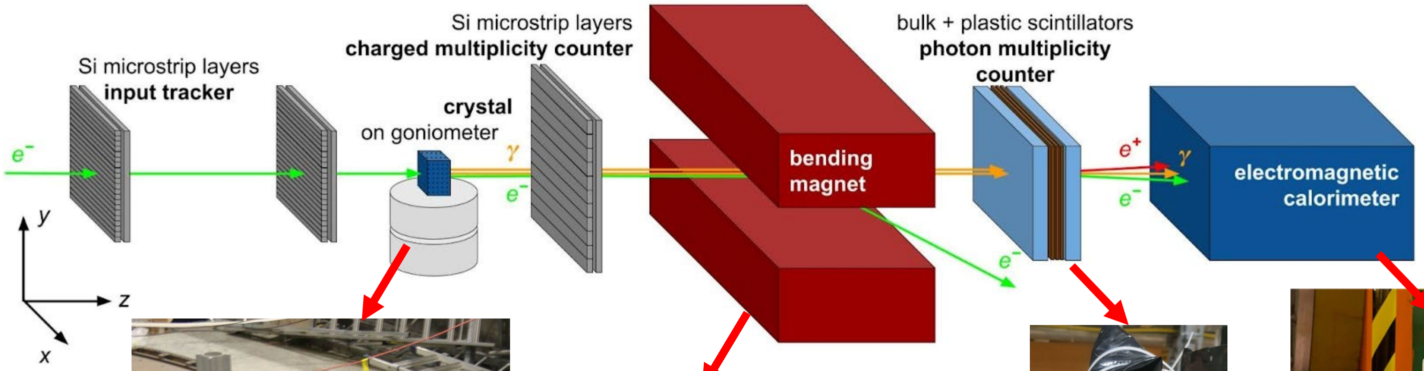
A 2x55x4 mm^3 strip-like PWO crystal with the largest faces oriented parallel to the (100) planes was selected for the experiment. **4 mm length** along the beam direction corresponds to about **0.45 X_0**.

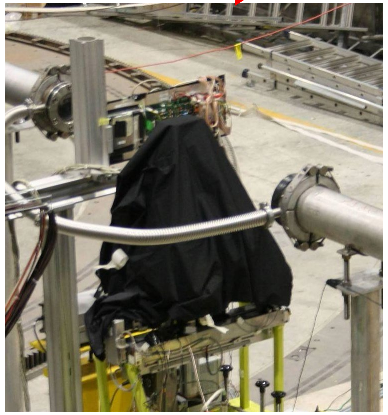
Where we started…
first result presented at Channeling2018

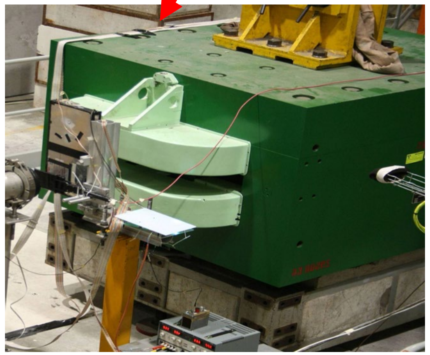


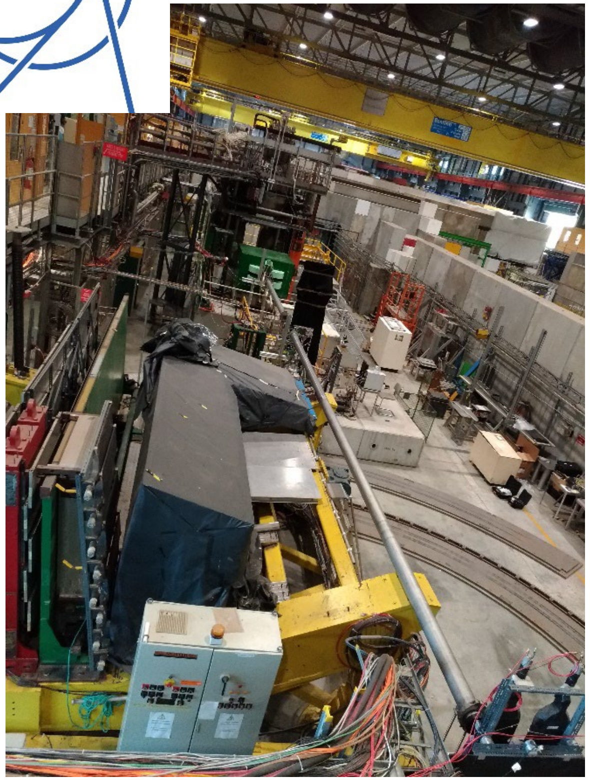
Test on single oriented crystals with e- @CERN SPS

A. Selmi, et al. NIM A 1048 (2023) 167948









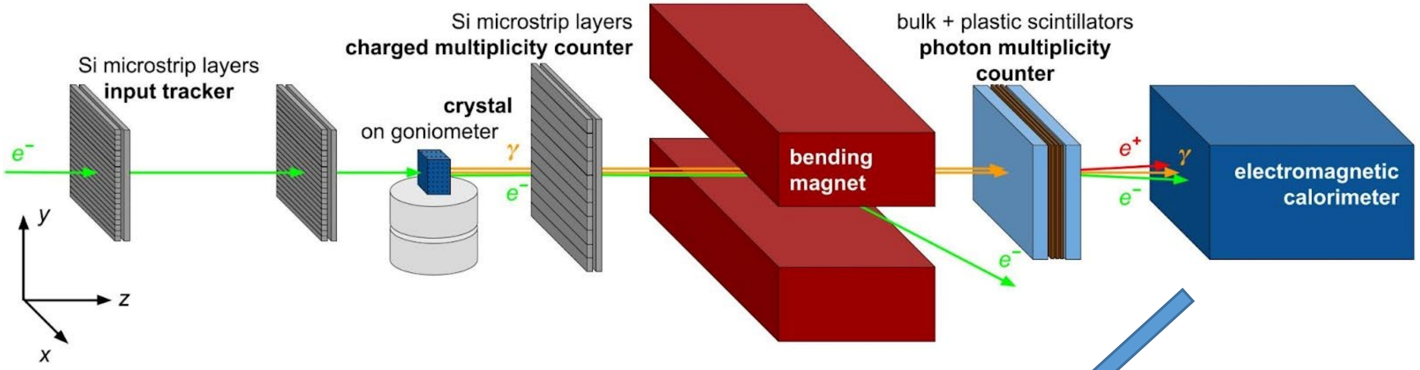
e^- & γ @ 10-150 GeV
CERN SPS NA H2
(Geneve)

STORM

CSN5
Ricerca
Tecnologica

STORM – STrOng cRystalline electroMagentic field
2021-2022 project financed by INFN

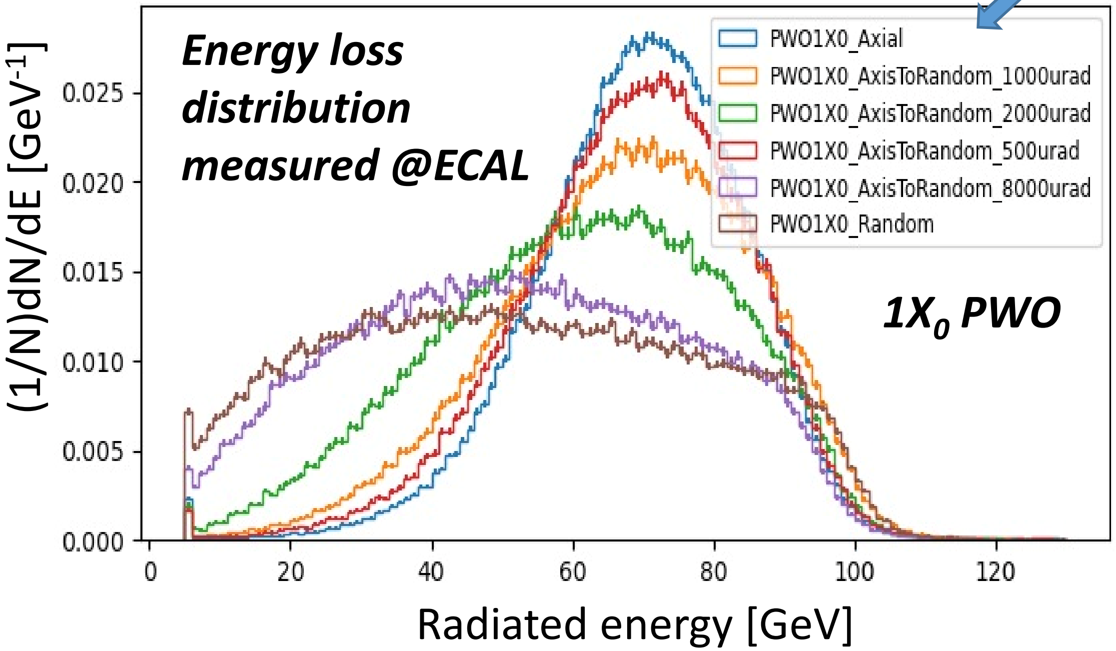
Experiment & Monte Carlo – Calorimeter data

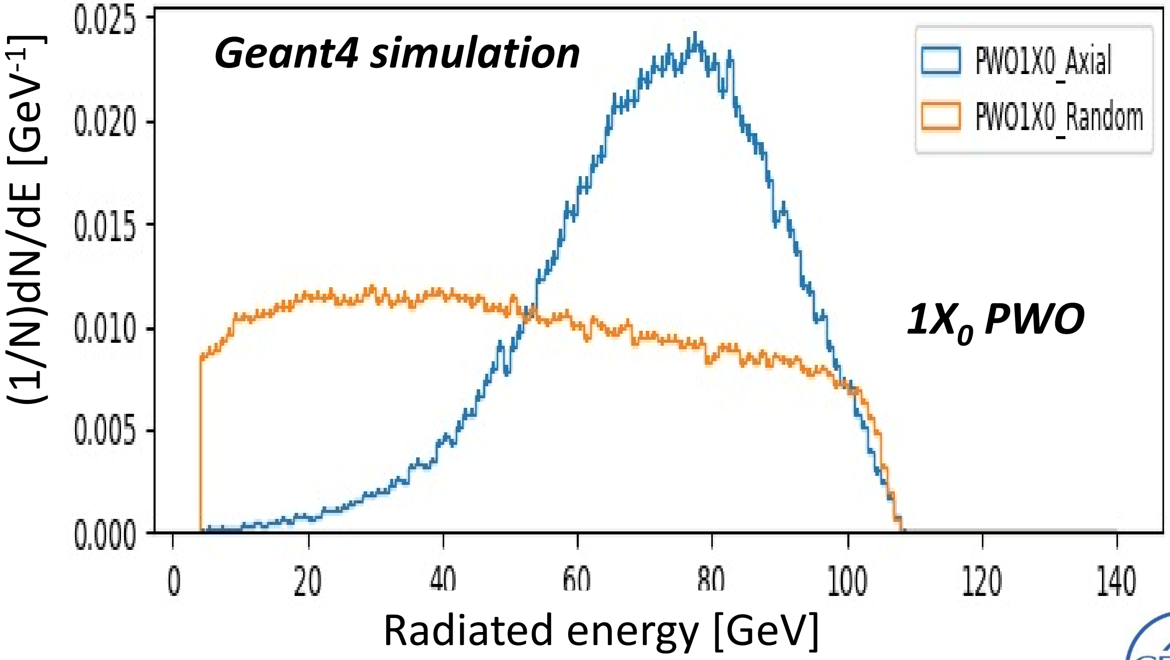


CERN SPS NA H2 beamline

Beam: e⁻ @120 GeV

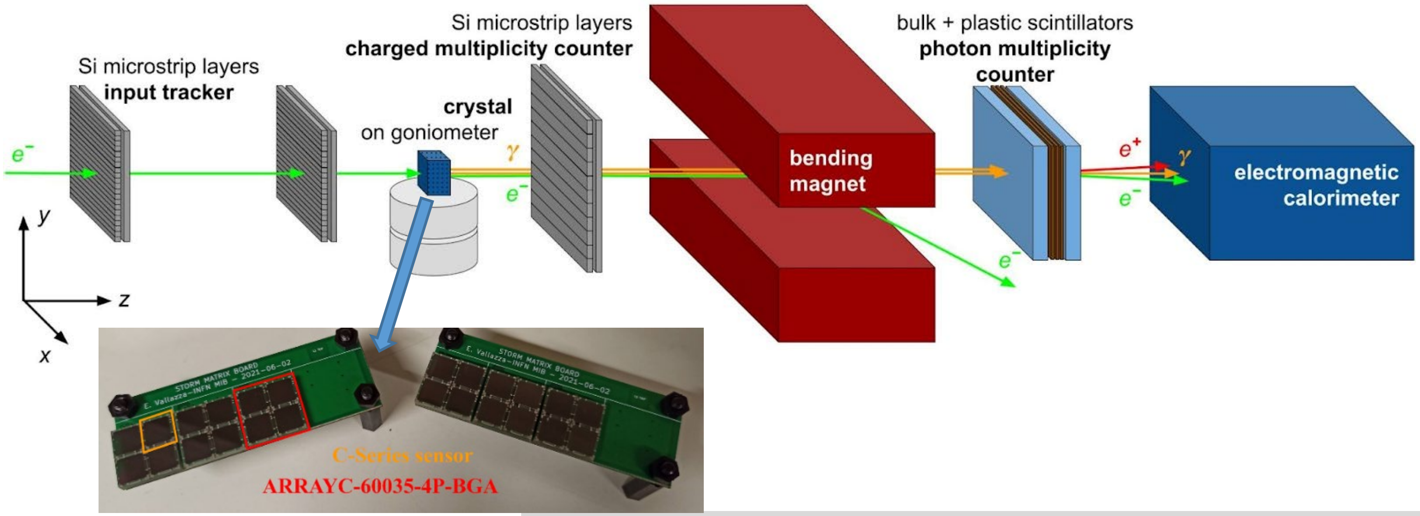
Crystal: 1 X_0 PWO

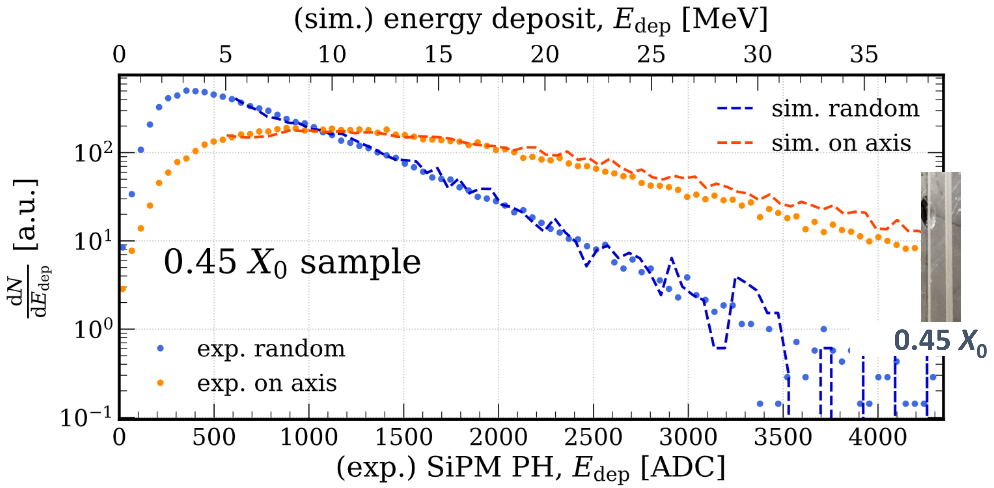




North Area H2 line

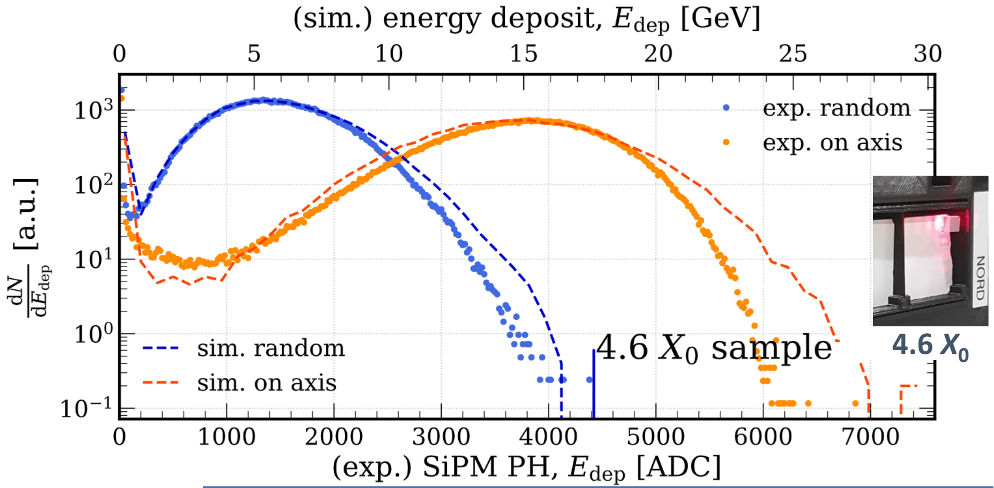
Experiment & Monte Carlo – Scintillation light





Effective thickness that a randomly oriented crystal should have to make the electrons lose the same amount of energy deposited on axis.

Thickness [X_0]	effective thickness [X_0]
0.45	**0.745**
1	**1.5**
2	**3**
4.6	**6.2**



M. Soldani et al., arXiv:2404.12016v1

CERN SPS NA H2 beamline

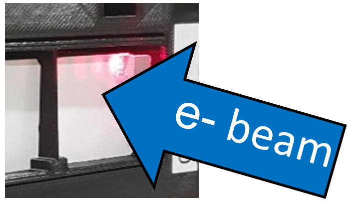
Beam: e⁻ @120 GeV

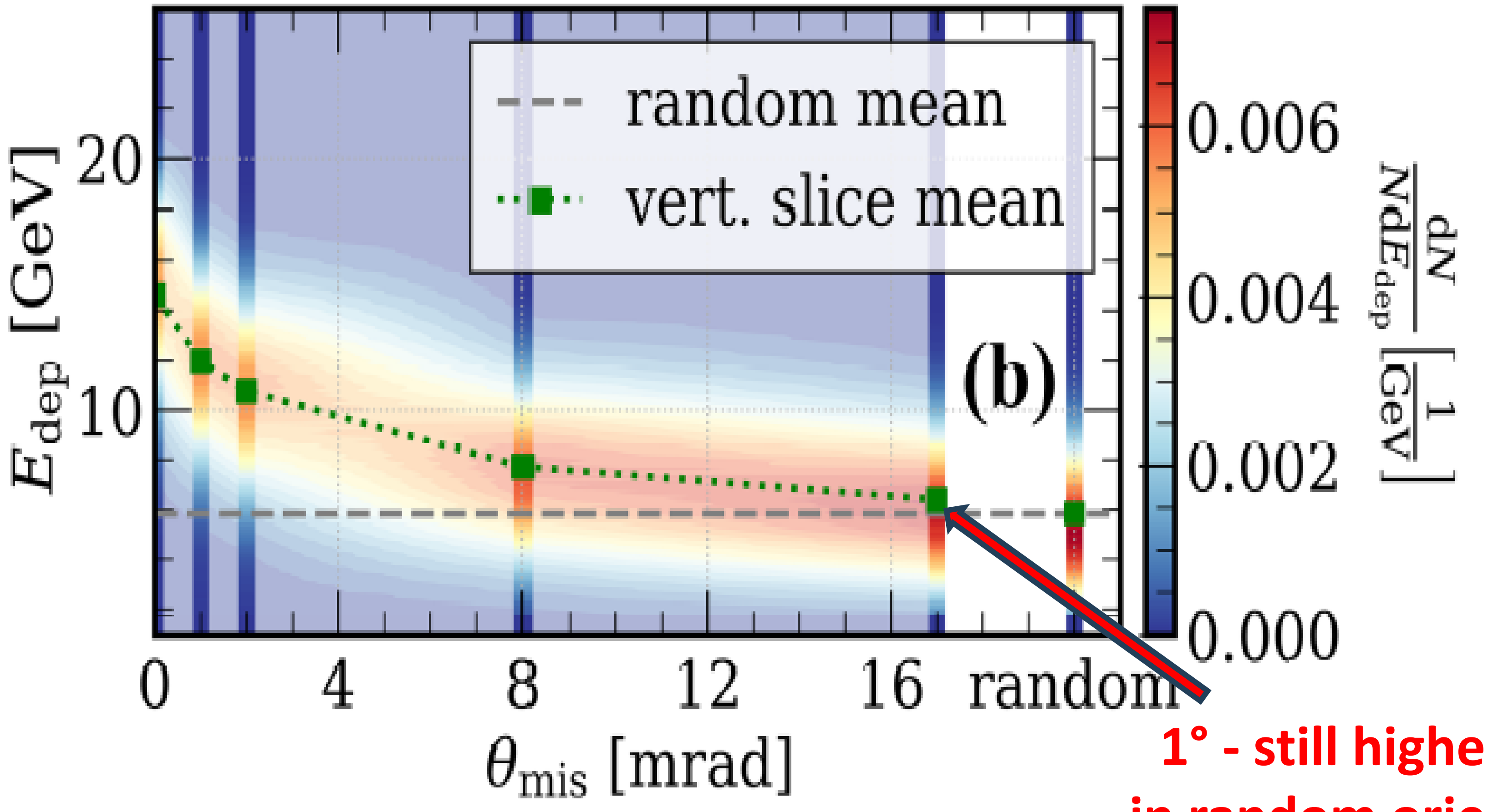
Angular range of the effect

CERN SPS NA H2 beamline

Beam: e⁻ @120 GeV

4.6X_0 PWO



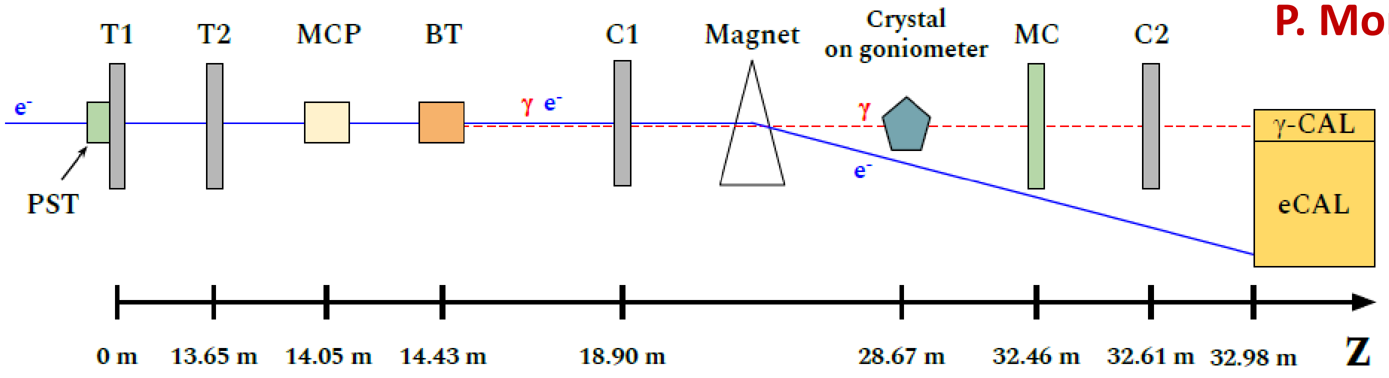


1° - still higher than in random orientation

N.B. Sample from CMS ECAL prototype of 15 X_0 It was measured with XRD to be already axially oriented within 1 °

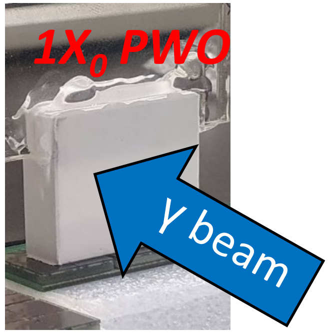
M. Soldani et al., arXiv:2404.12016v1

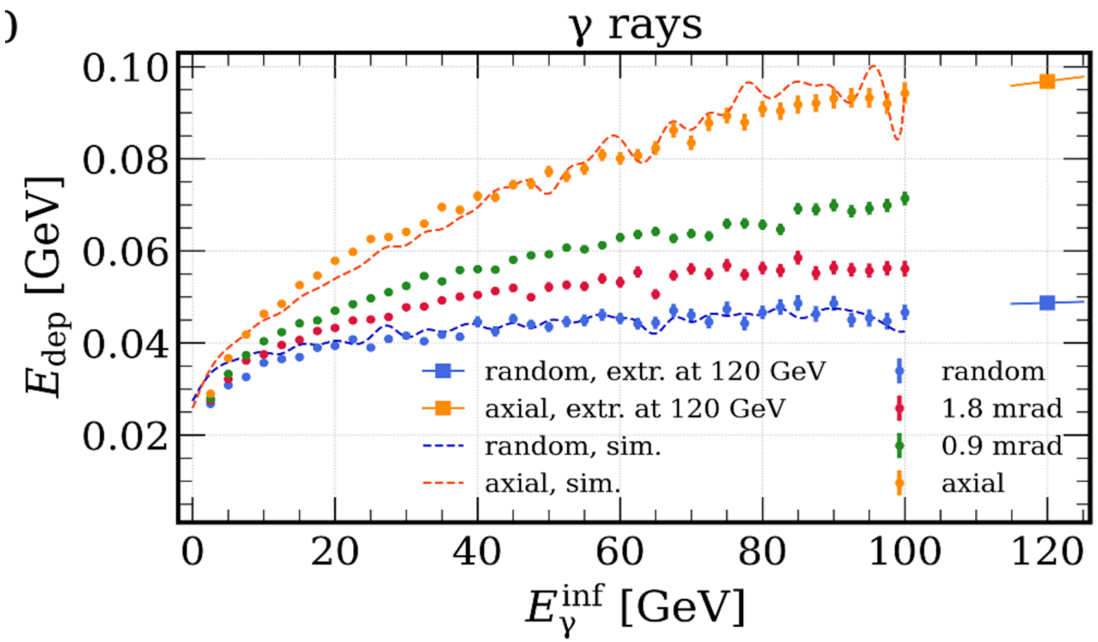
Measurement with a VHE gamma beam



P. Monti-Guarnieri et al., PoS ICHEP2022 (342) 414 (2022)

CERN SPS NA H2 beamline
Beam: γ @5-100 GeV
Crystal: 1 X_0 PWO





Energy deposited inside the crystal by the photon beam in axial orientation as measured by SiPM vs. the photon energy

M. Soldani et al., arXiv:2404.12016v1

North Area H2 line

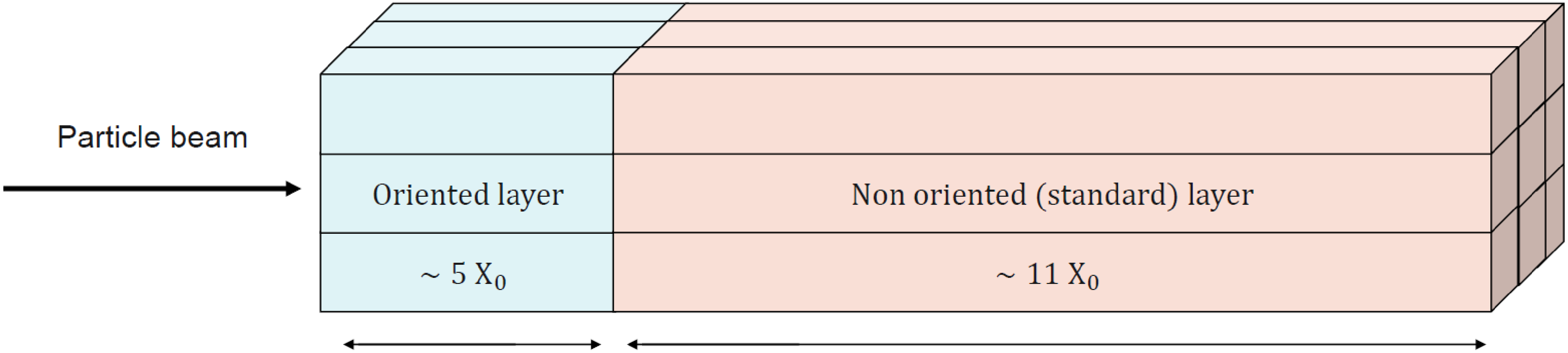
CERN

Work done in collaboration with the HIKE/KLEVER&CRILIN team

The ***ORiEnted calOrimeter*** project

Challenge:
- Construction of an oriented layer of many crystals

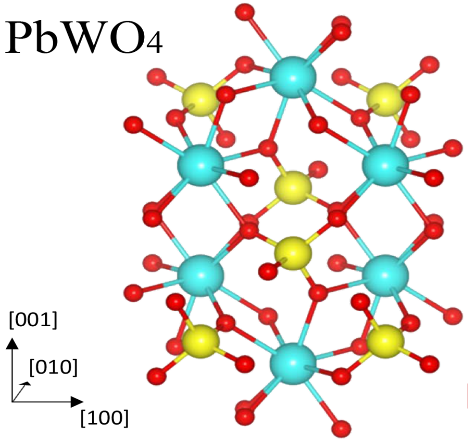
OREO - ORiEnted calOrimeter
2023-2025 project financed by INFN



Construction of the OREO prototype

3x3 matrix of ultrafast PWO (PWO-UF)

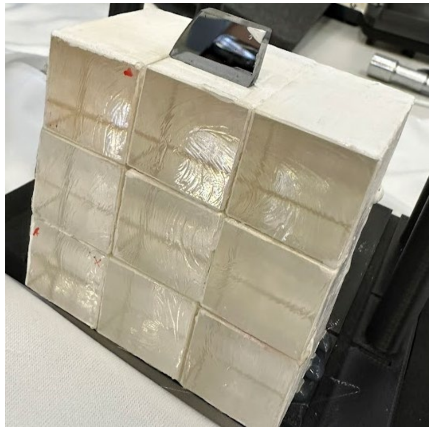
$PbWO_4$

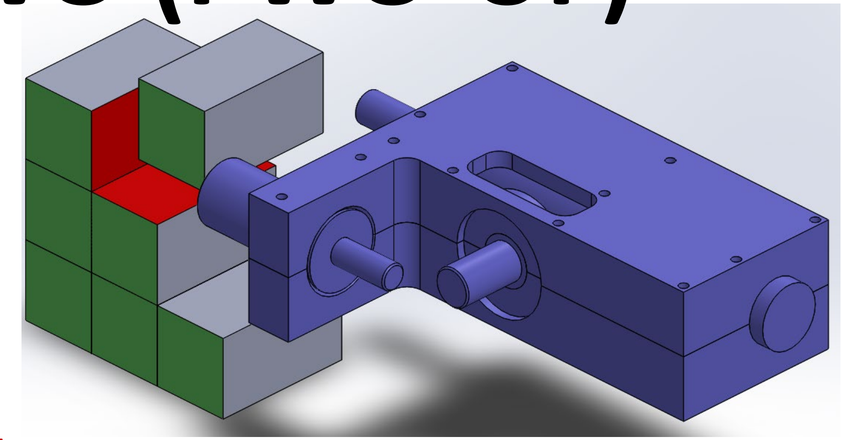


A newly developed PWO-Ultrafast is a candidate future detectors

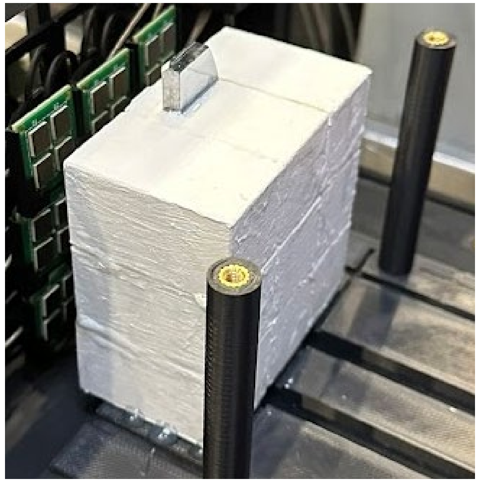
Scintillation decay decreased down to the subnanosecond (0.7 ns)

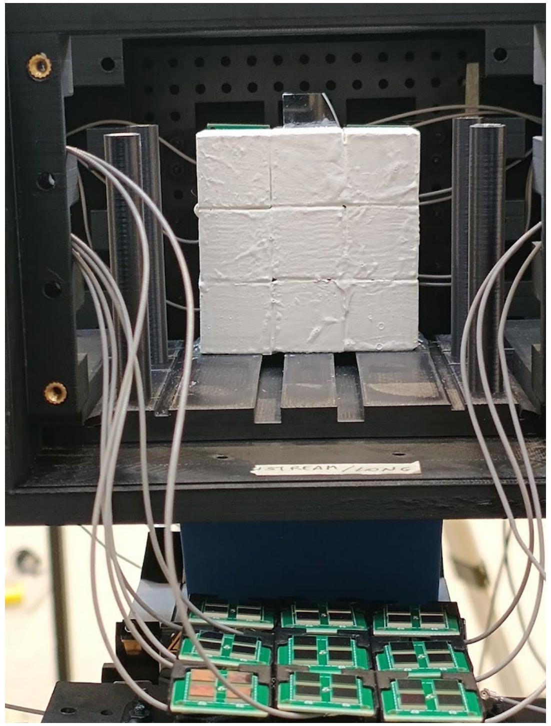
M. Korjik et al., NIM A,1034(2022)166781





Orientation control: handling system based on motorized optomechanical components (Thorlabs) and autocollimator laser





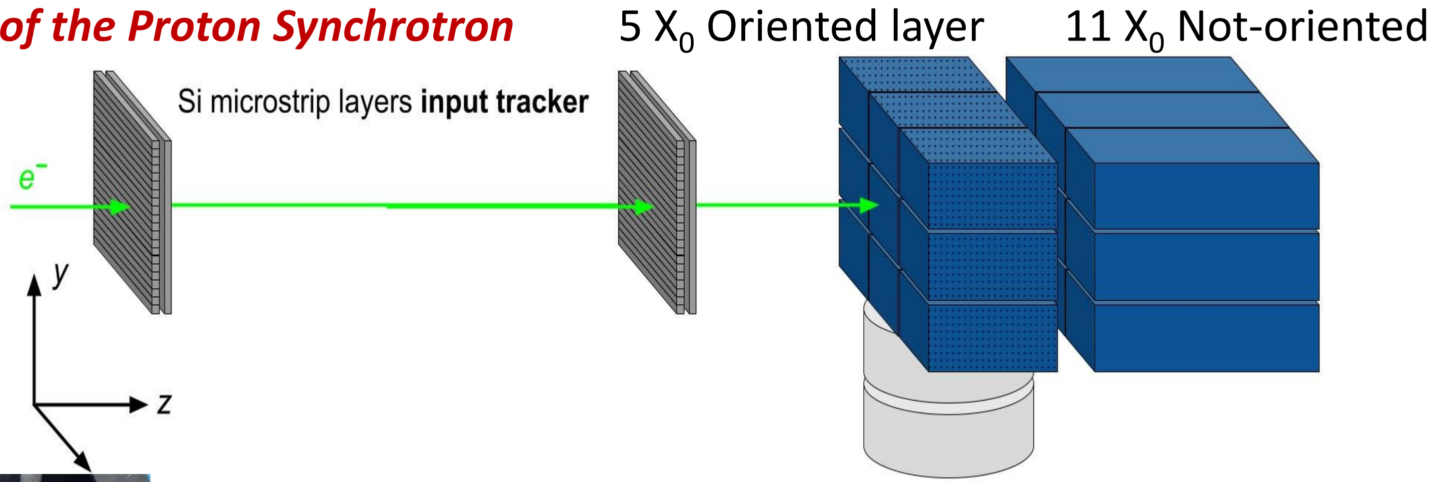
Crystals were coated with a reflective paint and the glued together.

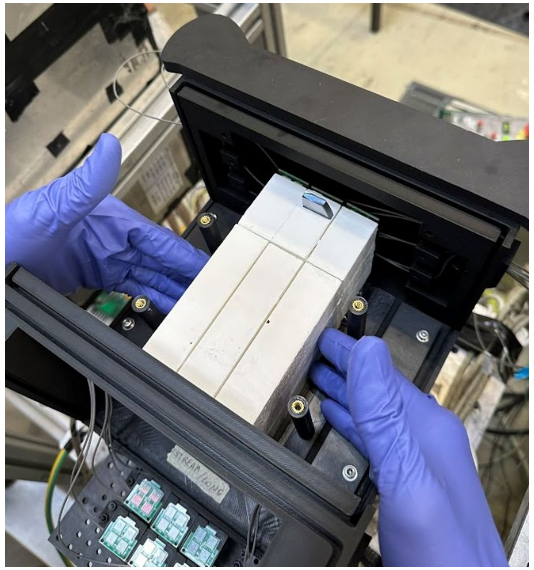
Misalignment < 0.3 mrad (< Θ_{max})

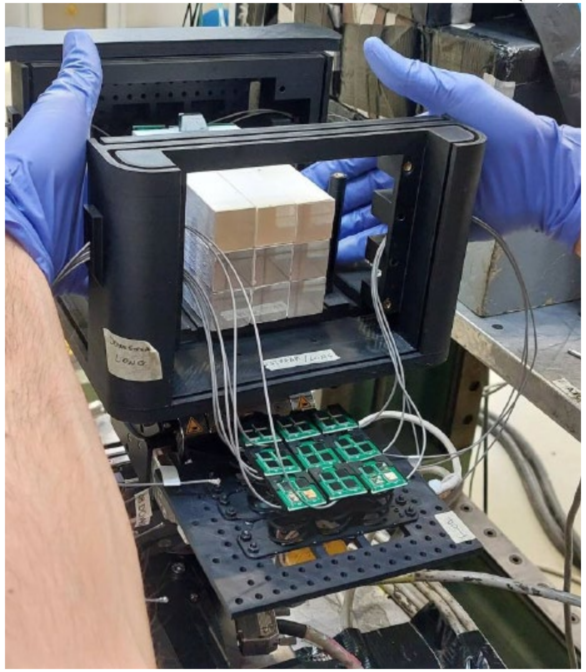
Readout: SiPM matrix, each coupled to one of the three crystals

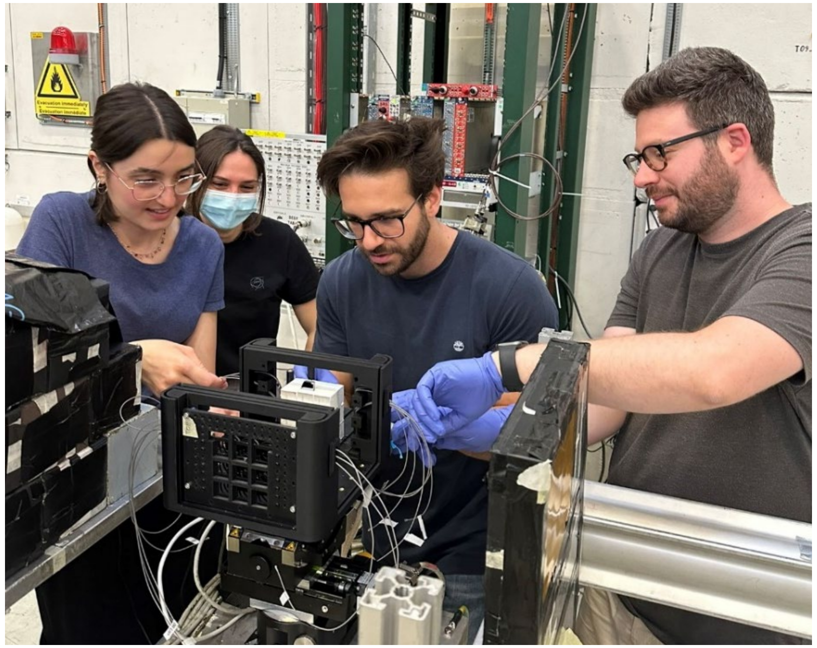
First test of the OREO prototype
3x3 matrix of ultrafast PWO (PWO-UF)

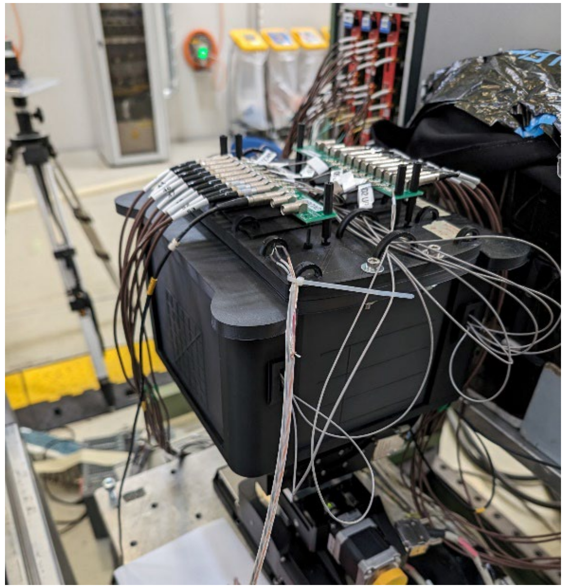
Setup on T9 line of the Proton Synchrotron









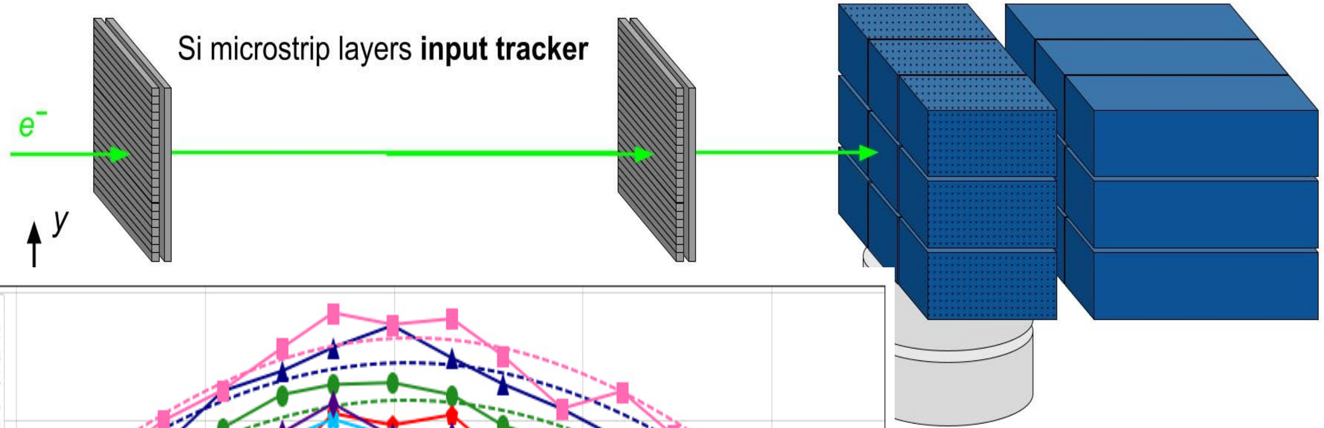


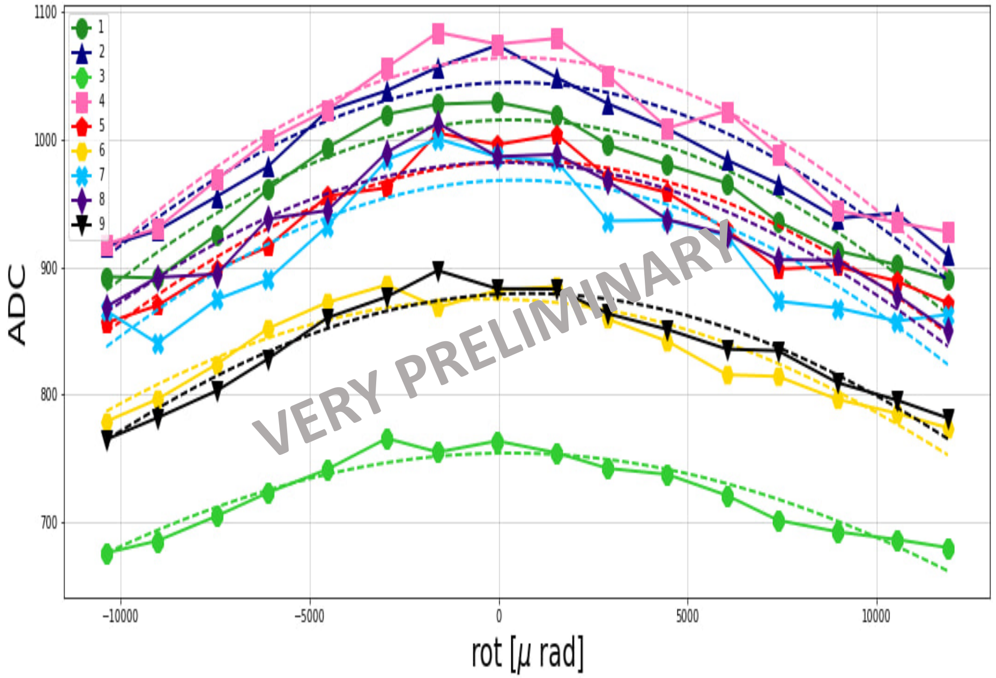
First test of the OREO prototype

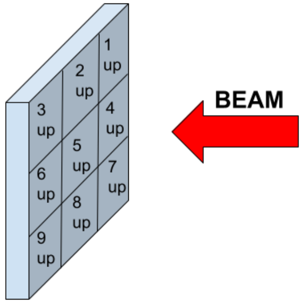
3x3 matrix of ultrafast PWO (PWO-UF)

Setup on T9 line of the Proton Synchrotron

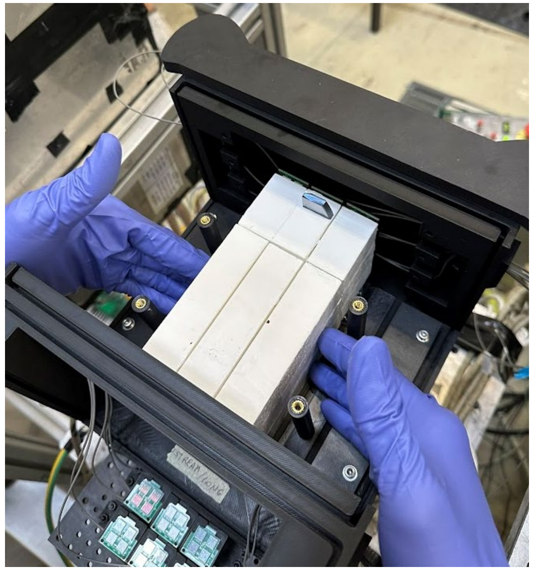
5 X_0 Oriented layer   11 X_0 Not-oriented







Energy deposited in the 9 OREO oriented crystals (ADC) vs. crystal orientation (zero is for PWO axis)

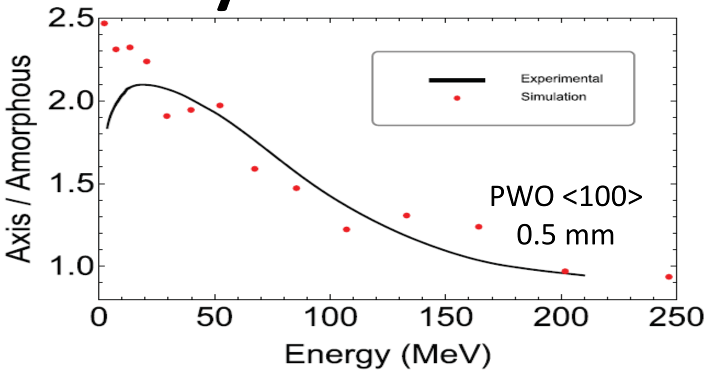


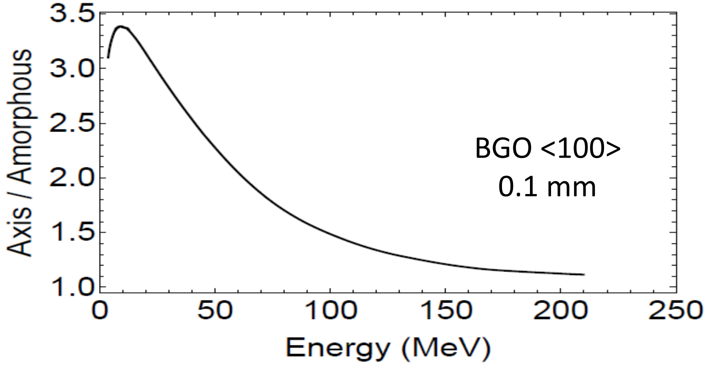
Tested @CERN PS/SPS in June 2024 with 6 GeV electrons

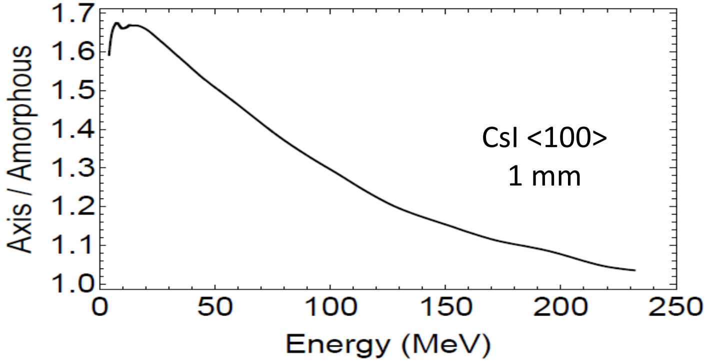
SUCCESS: All the crystals aligned with each other!!

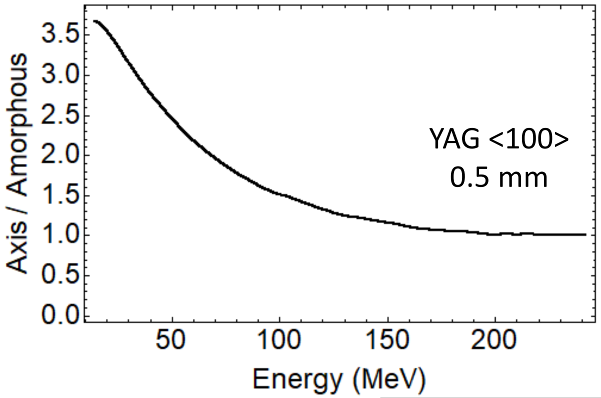
Also tested @CERN SPS with 120 GeV electrons at the end of July 2024

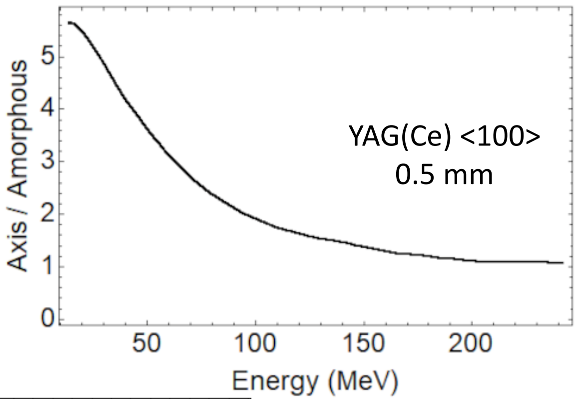
Just to mention electromagnetic processes are modified not only in PWO…

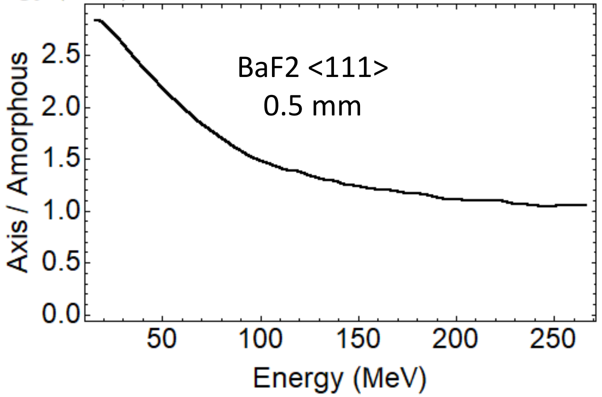










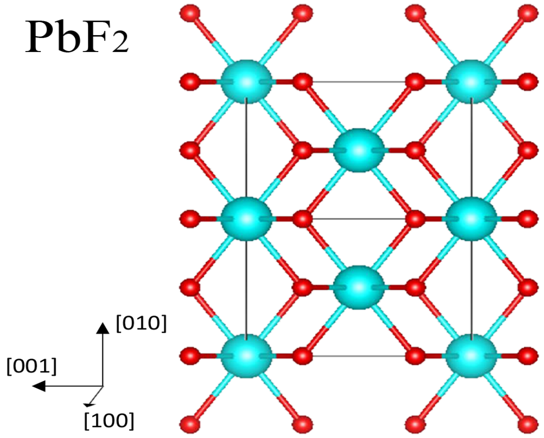


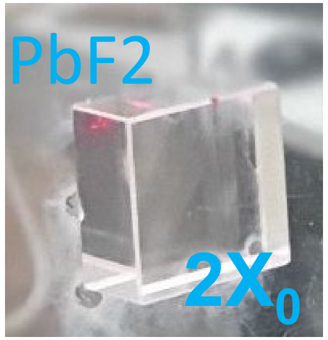
MAINZER MIKROTRON

- Bremsstrahlung radiation enhancement in axial orientation in the [0, 150] MeV range (e- beam @855 MeV – below Strong Field threshold), which **indicates an enhancement of the electromagnetic processes inside the axially oriented crystals.**
- **First measurements ever of radiation enhancement** due to coherent orientational effects for all these **scintillator crystals (PWO, BGO, CsI, YAG(Ce), BaF2)**.

L. Bandiera et al., NIM A 1060 (2024) 169022

…also in Cherenkov crystals



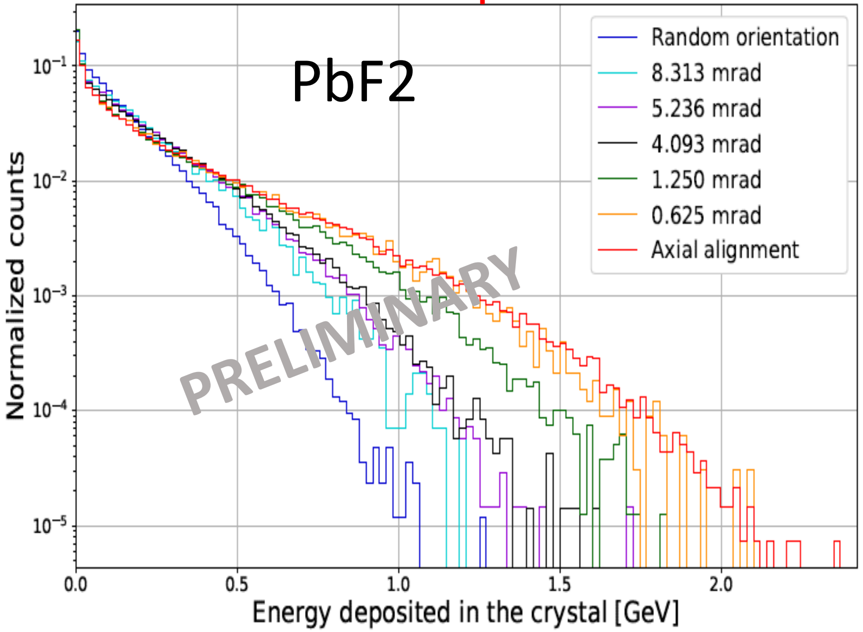


PbF2 (Ceren.) X_0 = 9.3 mm

P. Monti-Guarnieri et al., PoS ICHEP2022 (342) 414 (2022)

CERN SPS NA H2 beamline
Beam: γ @5-100 GeV
Crystal: 2 X_0 PbF2*, 1 X_0 PWO

1st measurement with a pure Cerenkov radiator



Energy deposited inside the crystal by the photon beam (of mixed energy) as measured by SiPM for different crystal-to-beam orientations.

Pietro Monti-Guarnieri (UniInsubria&INFN MiB) Ms. Thesis

Work done in collaboration with the CRILIN&HIKE team

North Area H2 line

CERN

Exciting times ahead!

several progress in the years in

- probing crystalline SF effects
- developing sound simulation tools + integration with Geant4
- designing and building an operational longitudinally segmented, oriented-calorimeter prototype

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

Exciting times ahead!

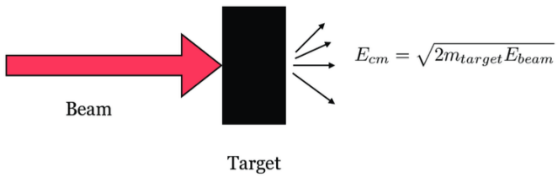
several progress in the years in
- probing crystalline SF effects
- developing sound simulation tools + integration with Geant4
- designing and building
  segmented, oriented-c

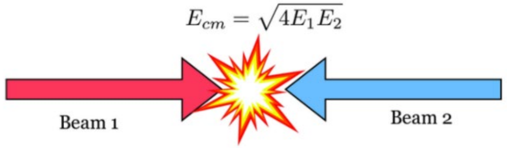
getting ready for integration in

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

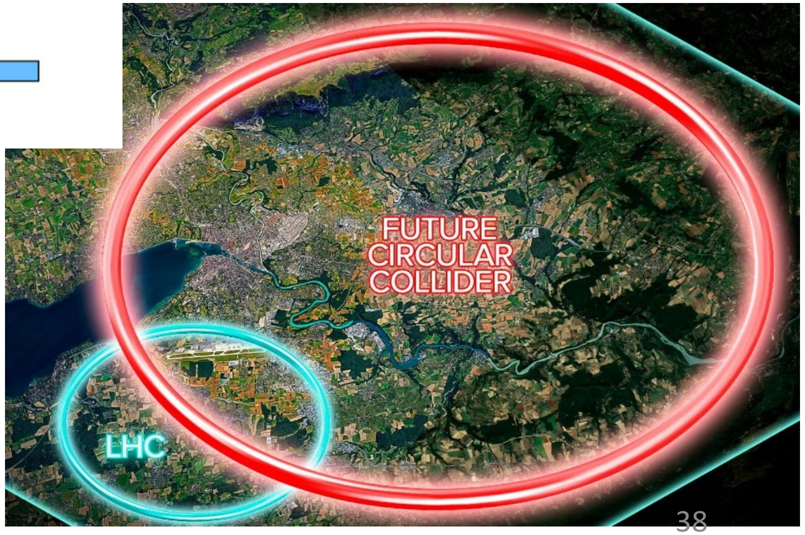
Forward-geometry accelerator-based experiments

fixed-target **collider forward region**





- Improved shower containment
  ⇒ Energy resolution
- Higher γ efficiency ⇒ Ideal for γ vetoes
- Better γ/hadron discrimination



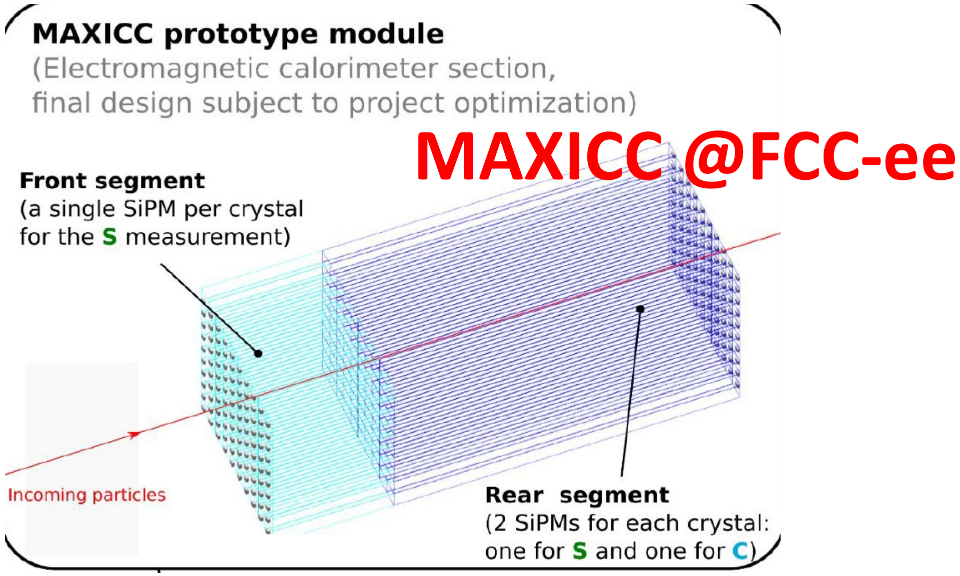
L. Bandiera et al., Frontiers In Physics 10.3389/fphy.2023.1254020
P. Monti Guarnieri et al., arXiv preprint arXiv:2405.11302

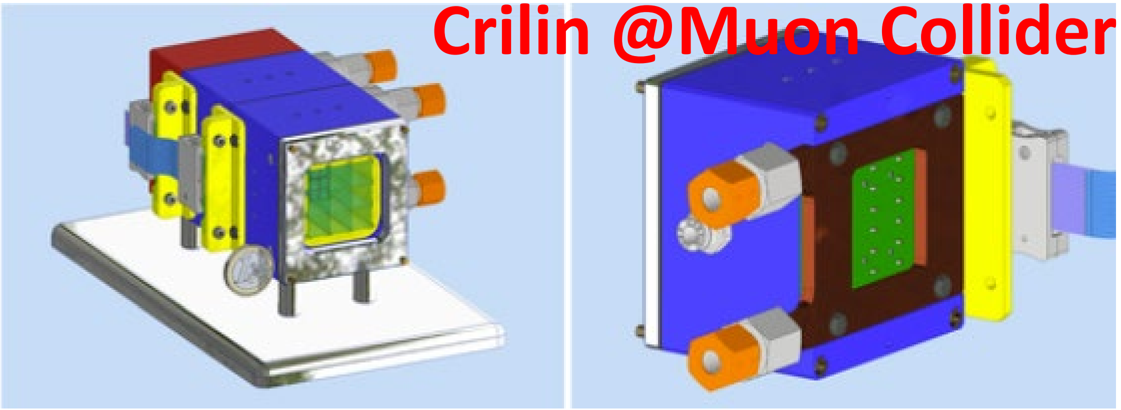
….in High-Energy Physics

- in **dark matter search**, to realize **compact active beam dump or target** with an **increased sensitivity to light dark matter**. If a dark photon is created in a shower initiated by an $e^{\pm}$, it can be detected only if it survives for the remaining dump or target length. The shorter the length, the higher the sensitivity. – Interest by the **POKER collaboration with NA64 @SPS**, where the PWO calorimeter will be either the target and the missing energy detector

- **Longitudinally segmented e.m. calorimeters*:***
  - To realize **compact high-resolution em calorimeter** in forward geometry (e.g. HIKE SAC)
  - In isotropic calorimeter -> **need to control the orientation to avoid unexpected effects.**

Longitudinally Segmented Crystal Calorimeter for future Colliders





Exciting times ahead!

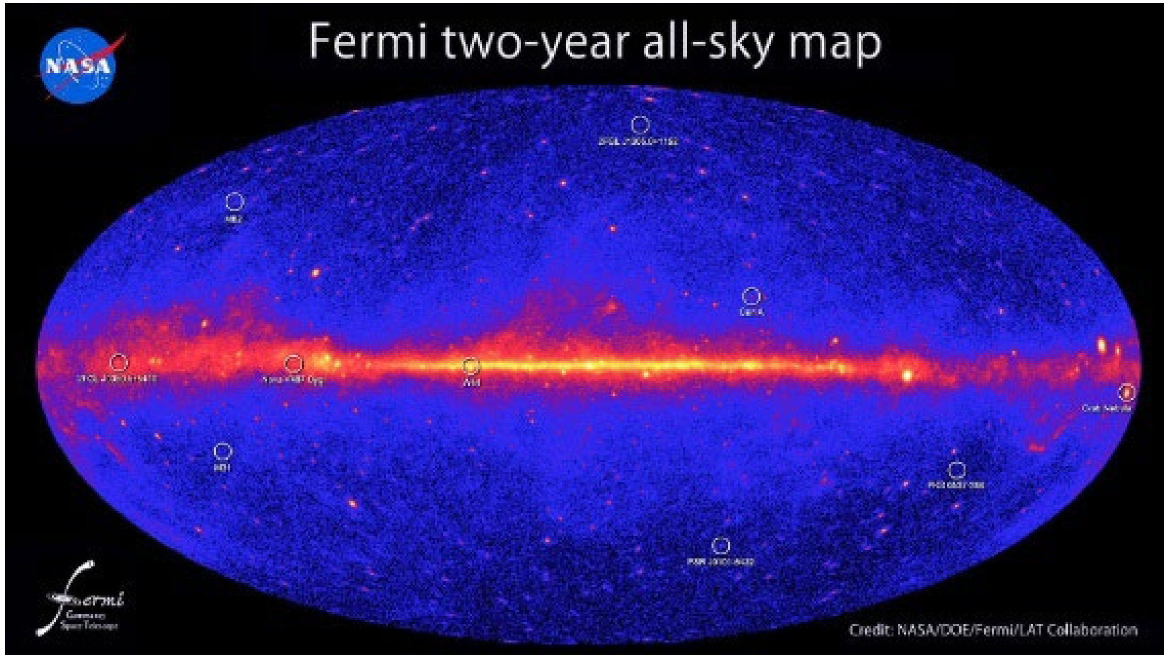
several progress in the years in

- probing crystalline SF effects
- developing sound simulation tools + integration with Geant4
- designing and building
  segmented, oriented-c

getting ready for integration in

space-borne γ-ray (VHE/UHE) detectors
with pointing systems
à la Fermi LAT

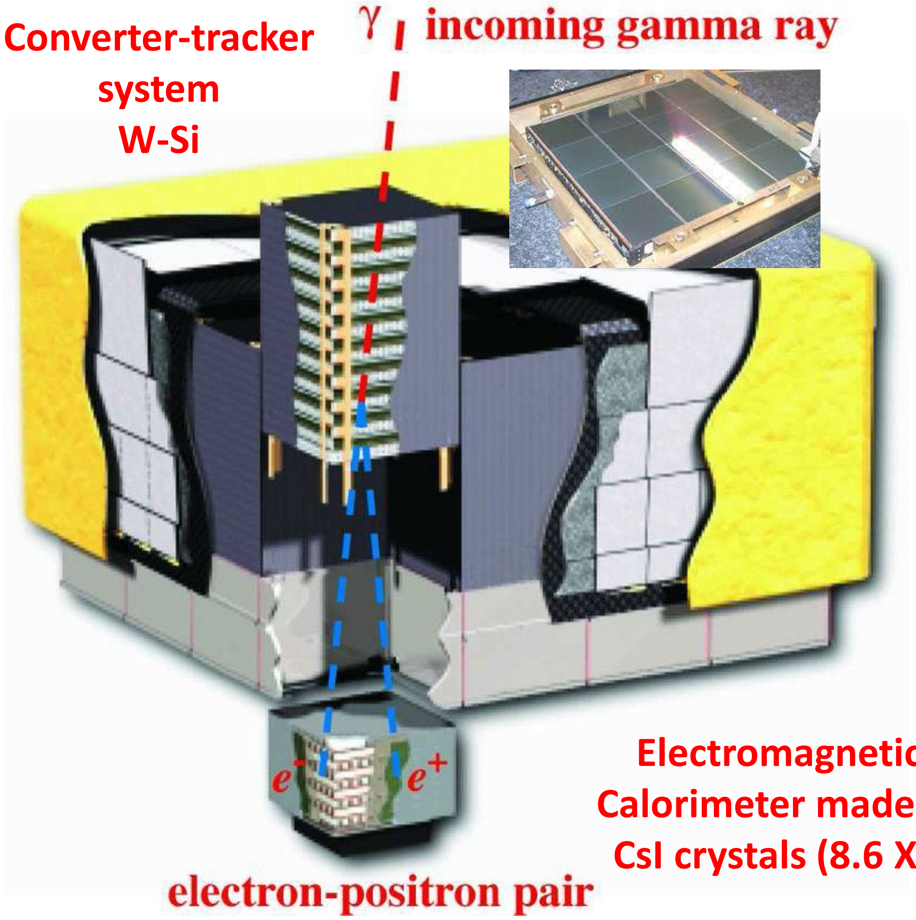
- reduced thickness ⇒ more payload available for transverse size increase ⇒ acceptance
- improved shower containment ⇒ less longitudinal leakage
- higher γ efficiency
- better γ/hadron discrimination



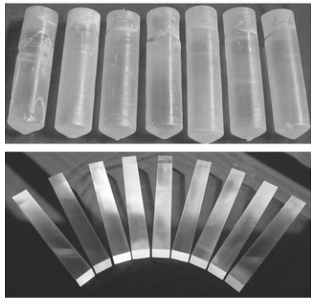
L. Bandiera et al., Frontiers In Physics 10.3389/fphy.2023.1254020
P. Monti Guarnieri et al., arXiv preprint arXiv:2405.11302

.... astroparticle physics...

take FERMI-LAT as an example

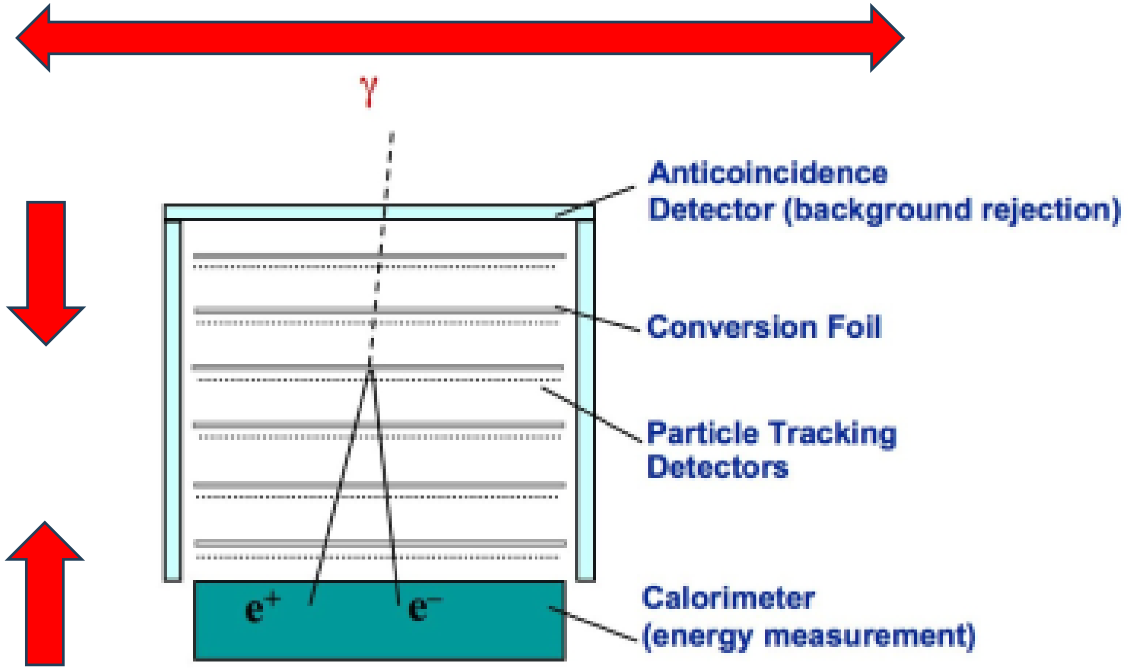


Electromagnetic Calorimeter made of CsI crystals (8.6 X_0)



All of these materials have a crystalline structure and can be oriented along some preferred lattice direction

Ultra-compact space-borne satellite to detect VHE gamma-rays



- **Above 1 GeV**, the primary challenge is the **very limited photon flux**. Reducing the longitudinal dimension of the calorimeter would enable **the increase of the detector area** (to **see more photons**!) at no net cost in weight
- Improved energy and angular resolution to **investigate the GeV gamma-ray sky open questions**!

We started a collaboration with **Fermi-LAT, Italian Space Agency** and **Brown University** researchers

L. Bandiera et al., Frontiers In Physics 10.3389/fphy.2023.1254020
P. Monti Guarnieri et al., arXiv preprint arXiv:2405.11302

The INFN OREO team

- ✓ **INFN Ferrara and University of Ferrara**

L. Bandiera, N. Canale, V. Guidi, L. Malagutti, A. Mazzolari, R. Negrello, M. Romagnoni, A. Sytov

- ✓ **INFN Legnaro Labs and University of Padua**

D. De Salvador, F. Sgarbossa, D. Valsani

- ✓ **INFN Milan Bicocca and Insubria University**

S. Carsi, G. Lezzani, P. Monti-Guarnieri, M. Prest, A. Selmi, E. Vallazza

External partners:

M. Moulson & M. Soldani (INFN LNF/NA62/HIKE), P. Monti Guarnieri (UniTrieste and INFN Trieste), F. Davì, D. Rinaldi & L. Montalto (UNIPVM)

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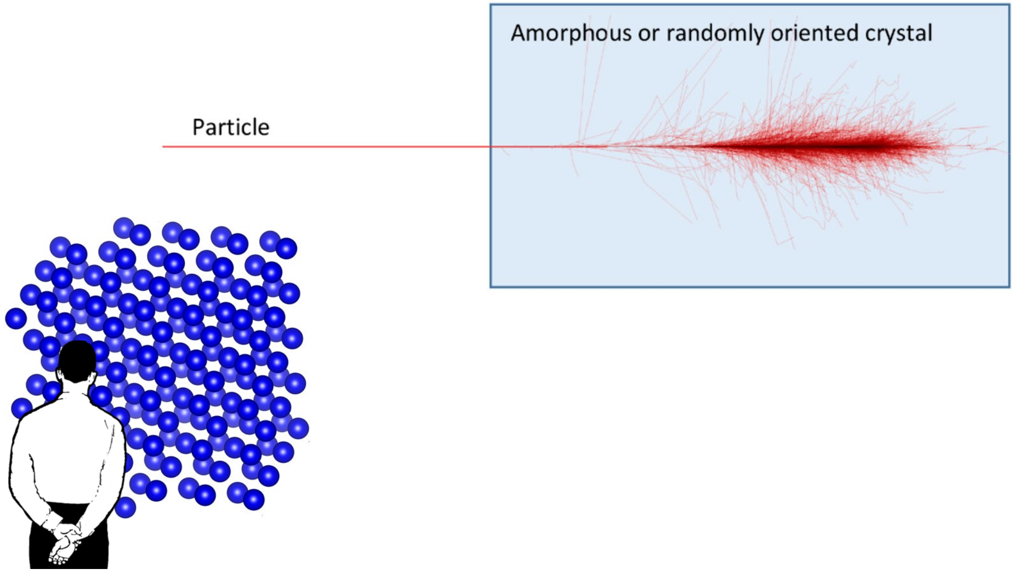

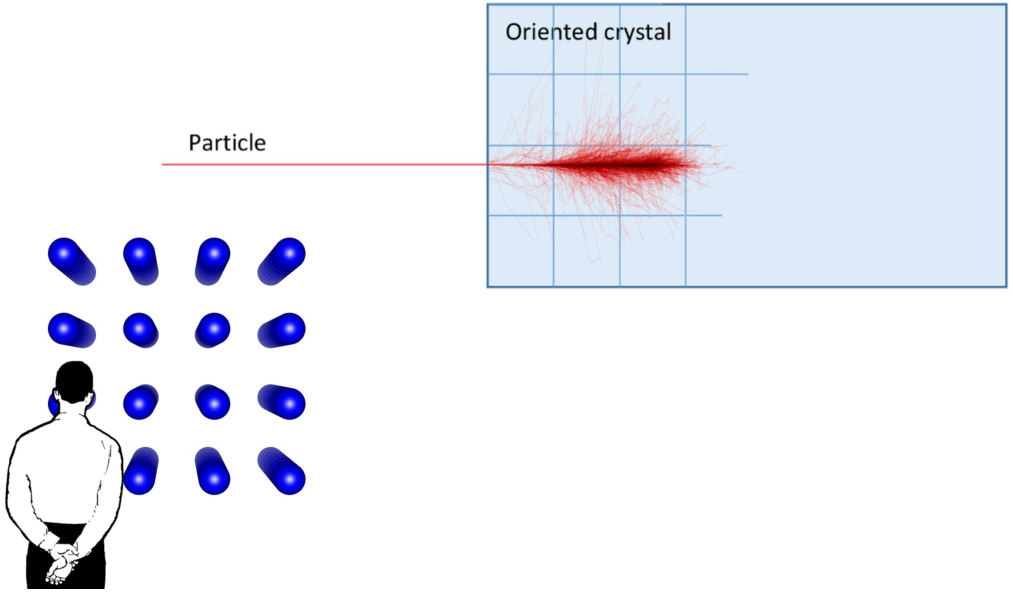

Thank you for the attention