The 8th International Conference

Charged & Neutral Particles Channeling Phenomena

CHANNELING 2018

STRONG REDUCTION OF THE EFFECTIVE RADIATION LENGTH IN AN AXIALLY ORIENTED SCINTILLATOR CRYSTAL

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Outlook

- State of the Art and motivation of this work;
- Introduction on electromagnetic processes in crystals;
- Experiment at CERN on an extracted line of SPS with 120 GeV/c electrons;
- Comparison with simulation;
- Possible applications;
- Conclusions.

State of the art: crystal scintillators

- Inorganic scintillator crystals found many application in medical, nuclear and high-energy physics.

- The invention of cheap and **high-Z inorganic crystalline scintillators** with **small radiation length** and high-density permitted to realize quite compact calorimeters for ultra-high energies.

- **The crystalline structure of inorganic scintillators is usually not considered in the** study of physical **processes at the base of e.m. calorimeter** operation.

State of the art: orientational e.m. effects

- In the last decades, many experiments demonstrated **the radiated energy and pair production increase in aligned crystals**;

- Starting from the theoretical idea of A.I. Atkiezer and N.F. Shulga [1] and Baier et al., experimental studies of **the enhancement of electromagnetic showers initiated by high-energy electrons or gamma-quanta** incident along major crystalline directions have been carried on with single-element crystals [2];

[1] A.I. Atkiezer and N.F. Shulga, Sov. Phys. JETP 58 (1983)
[2] R. Medenwalt et al., Phys. Lett. B 227 (1989) 3

Scientific motivation

- **Can these orientational effects be important also for inorganic scintillators used in HEP electromagnetic calorimeters?**
- A first study was performed with 26 GeV electrons [3];
- The modern electromagnetic calorimeters are designed for experiments at energies of hundreds of GeV/TeV and these enhancement effects are expected to be more important in this energy range [4].

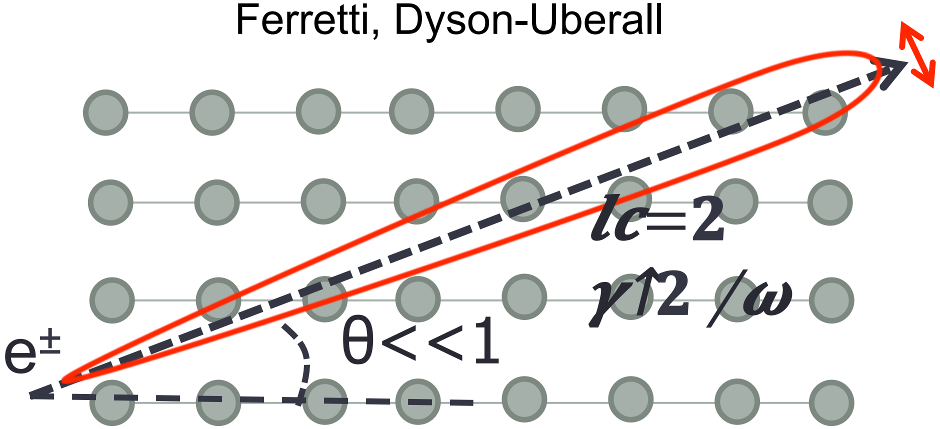
We performed a campaign of measurement to study the energy loss of hundreds GeV electrons in a lead tungstate at CERN for the first time.

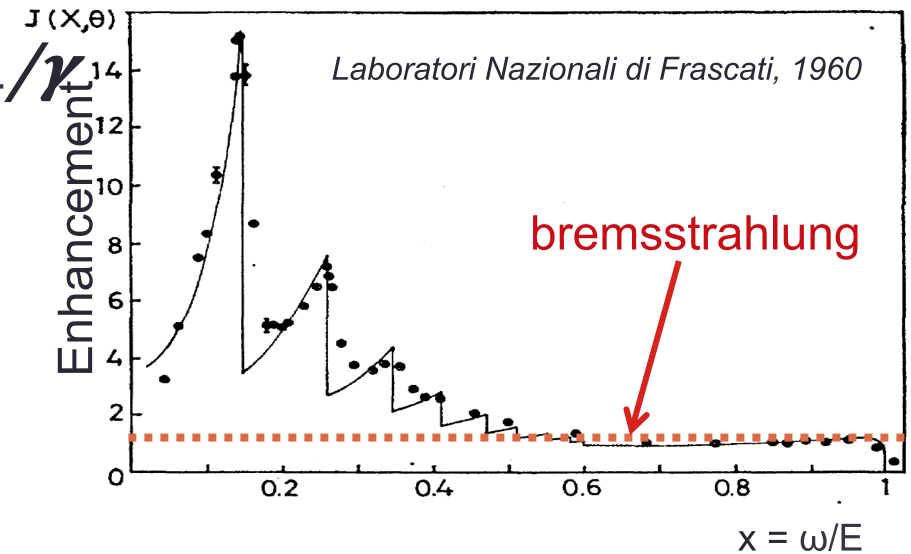
[3] Baskov et al. Nuclear Instruments and Methods in Physics Research B 145 (1998) 92
[4] V.G. Baryshevsky et al. Nuclear Instruments and Methods in Physics Research B 402 (2017) 35

ELECTROMAGNETIC PROCESSES IN ORIENTED CRYSTALS

Enhancement of bremsstrahlung radiation in aligned crystals

Coherent Bremsstrahlung (1950s) Ter-Mikaelian, Ferretti, Dyson-Uberall





Enhancement of bremsstrahlung radiation in aligned crystals

Coherent Bremsstrahlung
(1950s) Ter-Mikaelian,
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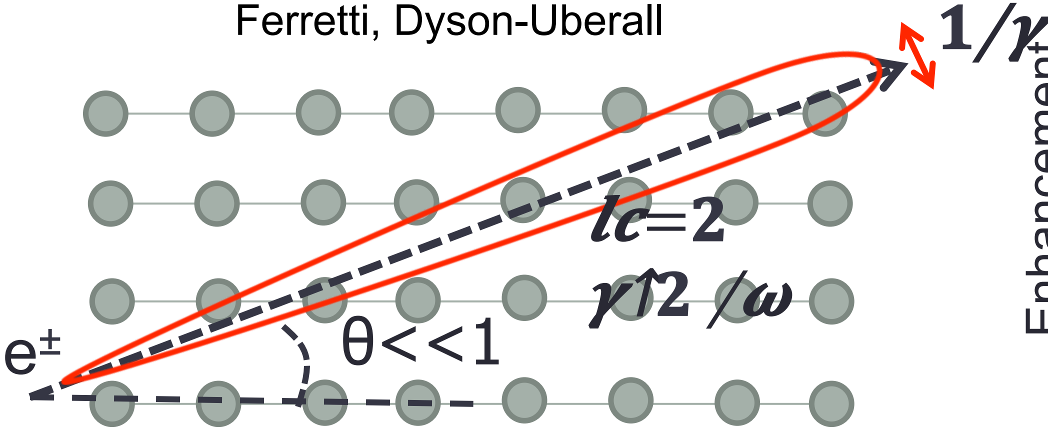
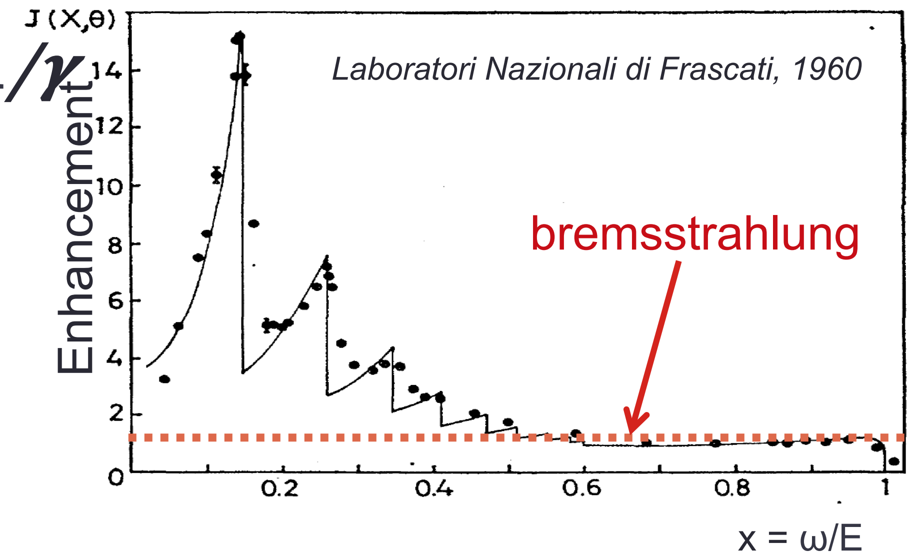
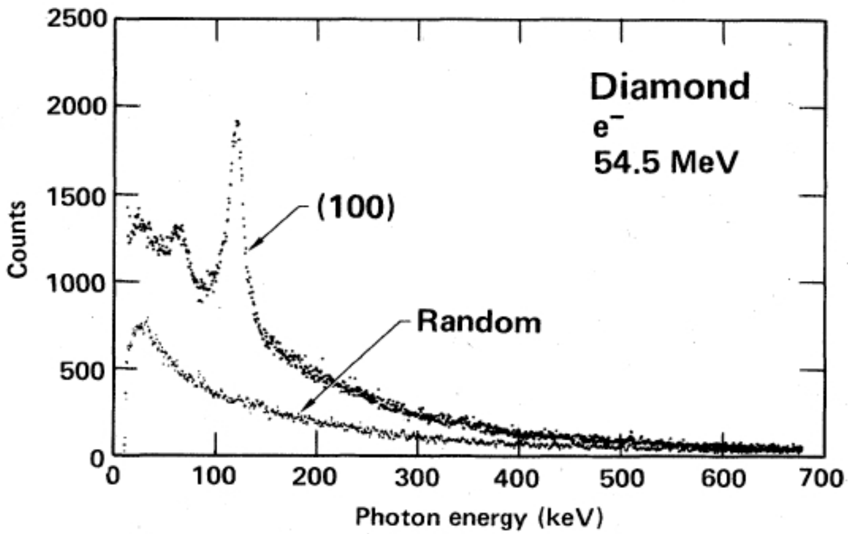
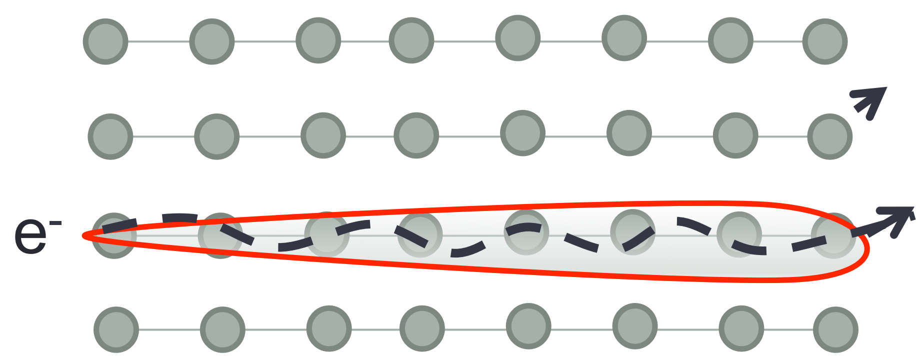




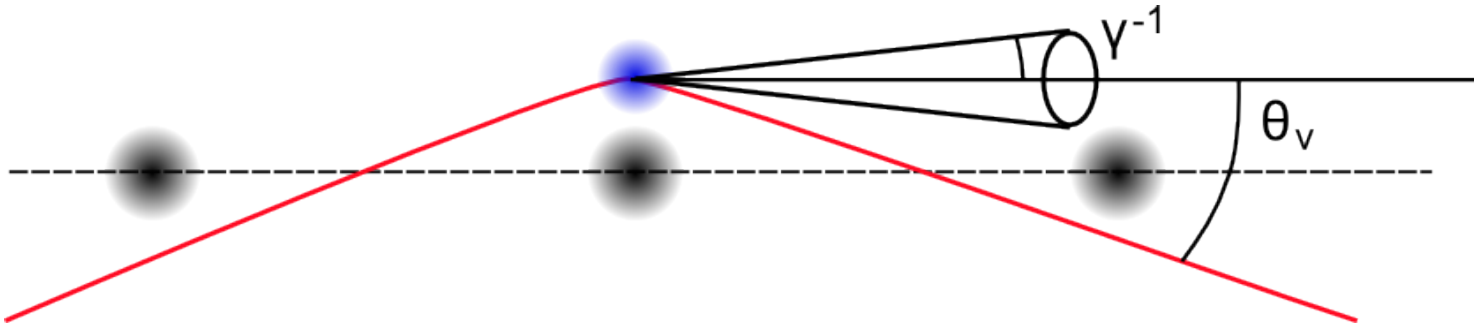




Channeling Radiation
(1976) Kumakhov

Synchrotron-like radiation in crystals

At energies > few GeV



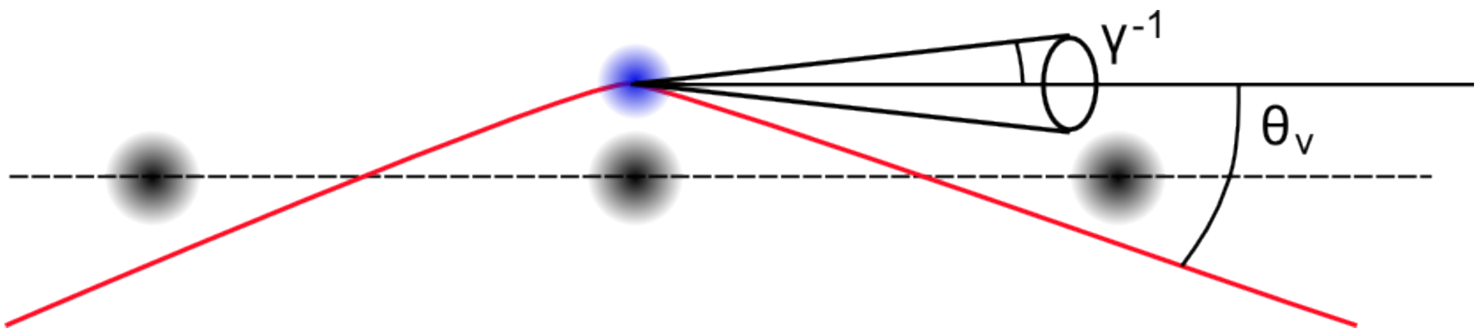
Radiation emission angle: $\theta_\gamma = 1/\gamma$

Threshold angle: $\theta_v = V_0/m$

$\theta_\gamma \ll \theta_v$ *Criterium for synchrotron radiation*

Strong field regime of Synchrotron Radiation

At energies >10 GeV (100 GeV) depending on atomic number Z



Relevant for linear colliders, astrophysical objects like magnetars, heavy ion collisions and more. When the magnetic/electric field reaches the

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

In the rest frame of the particle, the Lorentz contracted field can be computed as:

$\gamma E = E_0$

Being the Planar/Axial field $E = 10^9/10^{11}$ V/cm

"Quantum" synchrotron-like radiation is observable in crystals

TABLE I. Certain parameters of the averaged potentials of the principal axes and planes of a number of crystals.

Element	Z	(Plane) ⟨Axis⟩	d_{pl} (d_{ax}), Å	T, K	u_1, Å	V_{max}, eV	$\mathscr{E}_{max}$, GV/cm	$\varepsilon_{\chi=1}$
Diamond	6	(110)	1.26	293	0.04	20.8	7.7	890
		⟨110⟩	2.52	293	0.04	137	68	100
Si	14	(110)	1.92	293	0.075	21.5	5.7	1193
		⟨110⟩	3.84	293	0.075	133	46	145
Ge	32	(110)	2.00	293	0.085	37.7	9.9	684
		(110)	2.00	0	0.036	44.0	14.9	454
		⟨110⟩	4.00	293	0.085	229	78	87
		⟨110⟩	4.00	100	0.054	309	144	47 GeV
W	74	(110)	2.24	293	0.05	127	43	158
		(110)	2.24	0	0.025	142	57	119
		⟨111⟩	2.74	293	0.05	931	500	13.6
		⟨111⟩	2.74	0	0.025	1367	1160	5.8

At $\chi = \gamma E / E_0 \geq 1$ – quantum strong field limit

Emission of hard photons with energy comparable to the primary electron/positron – cannot be treated classically -> Strong increase in the energy lost by the primary particle.

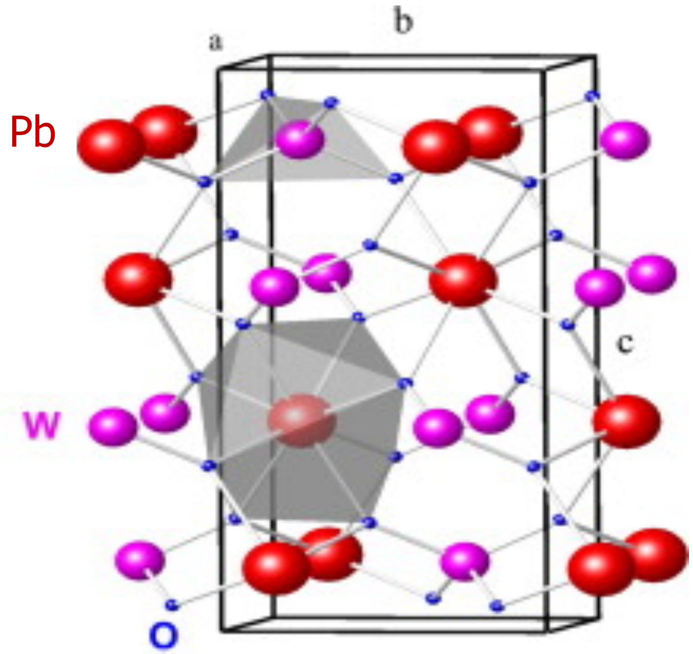
EXPERIMENT AT CERN

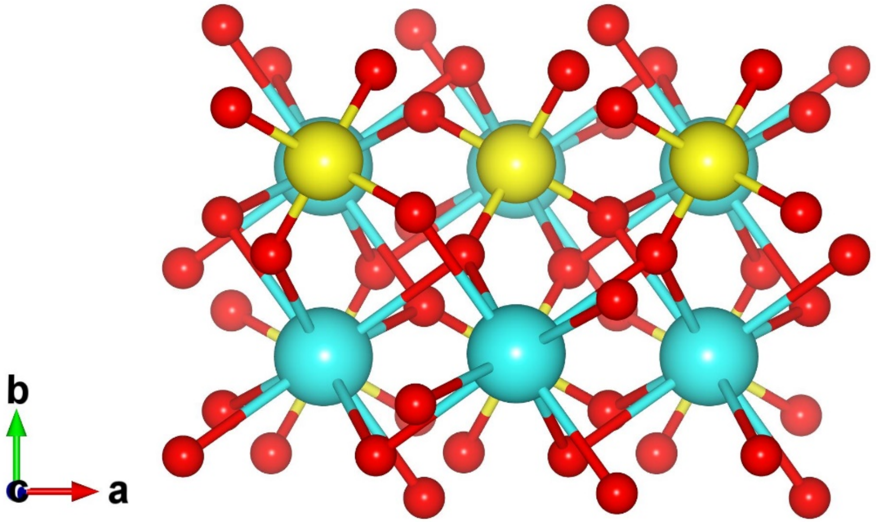
L. Bandiera et al., Phys. Rev. Lett. 121 (2018) 021603.

PWO crystal

PbWO4 (PWO) scintillation crystals introduced by INP team in 1994 are currently used by CMS, ALICE, PANDA collaborations in EM calorimeters.

- **Structure: scheelite type (tetragonal, a=5.456, c=12.020 Å);**
- **Radiation length: 8.9 mm.**

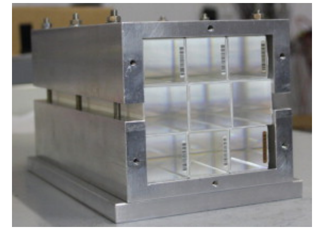




Experiment @ CERN with 120 GeV e$^-$

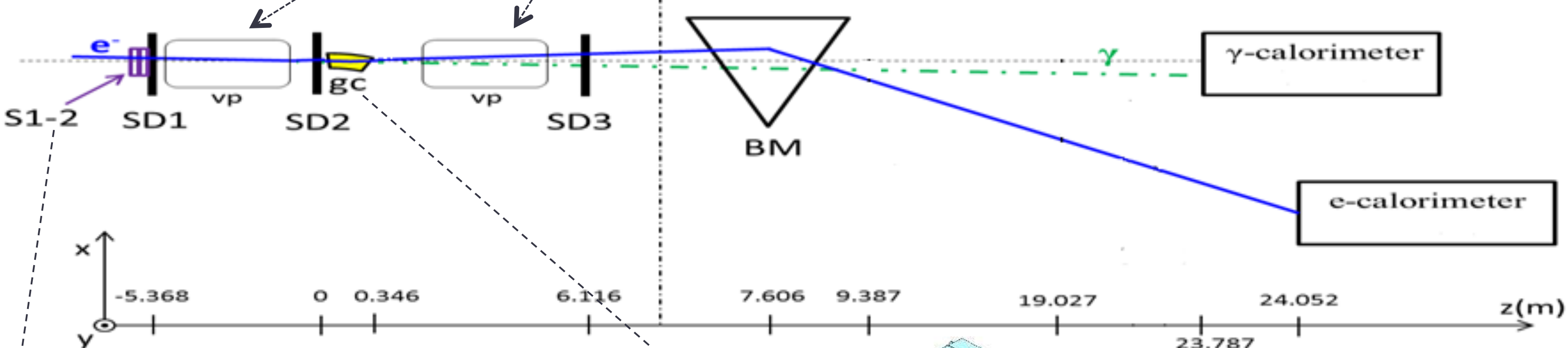
Double sided silicon detectors
1.92x1.92 cm^2 SDi
(300μm thick)
[6-11 μm spatial resolution]

vp = vacuum pipe

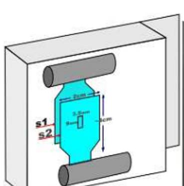


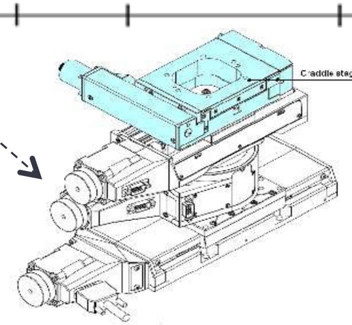
γ-beam (photo) and e-beam calorimeters to measure the emitted photons and to discriminate e$^{\pm}$ from impurities ($\mu^{\pm}$,$\pi^{\pm}$)

A bending magnet (BM) to separate the charged and the neutral beam



Scintillator Trigger: S2 has an hole (3x9mm^2)
Ainticoincidence

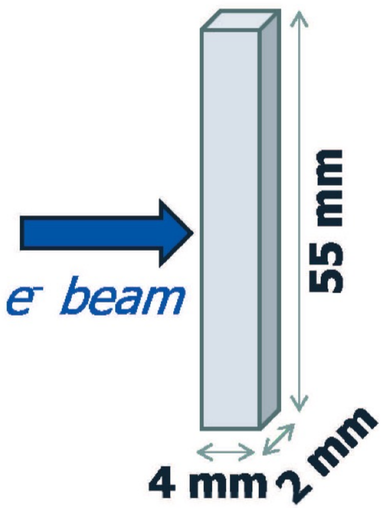


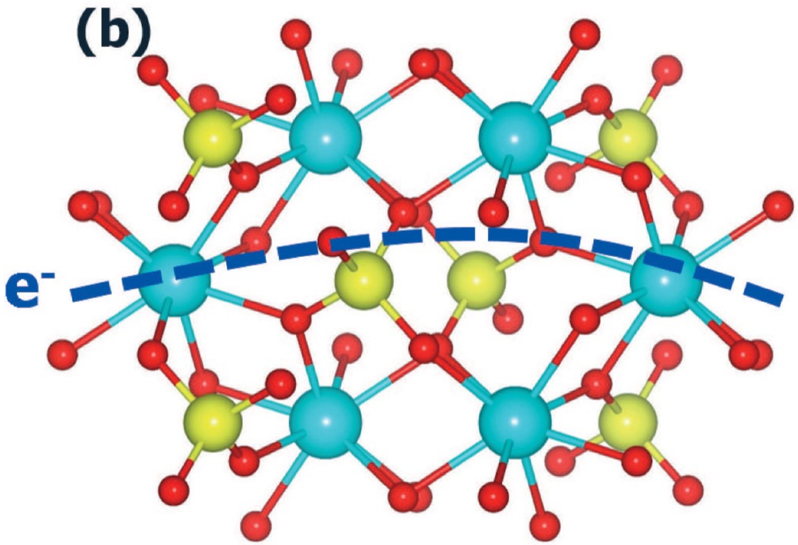


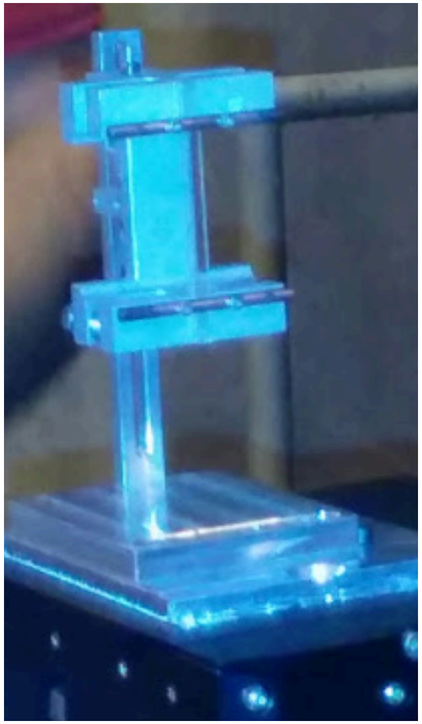
High precision goniometer to align the crystals on the beam.
[Few μrad of resolution]

See V. Mascagna poster today - PS3-06

Experiment with 120 GeV/c electrons

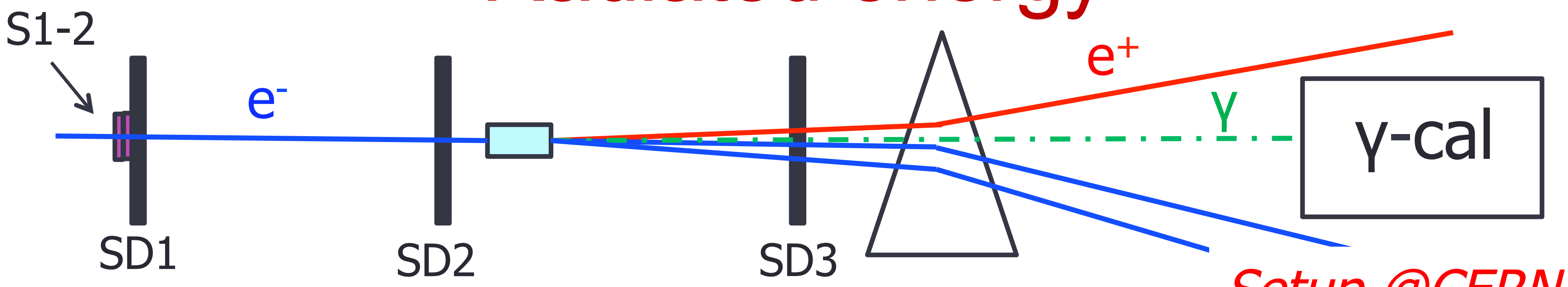






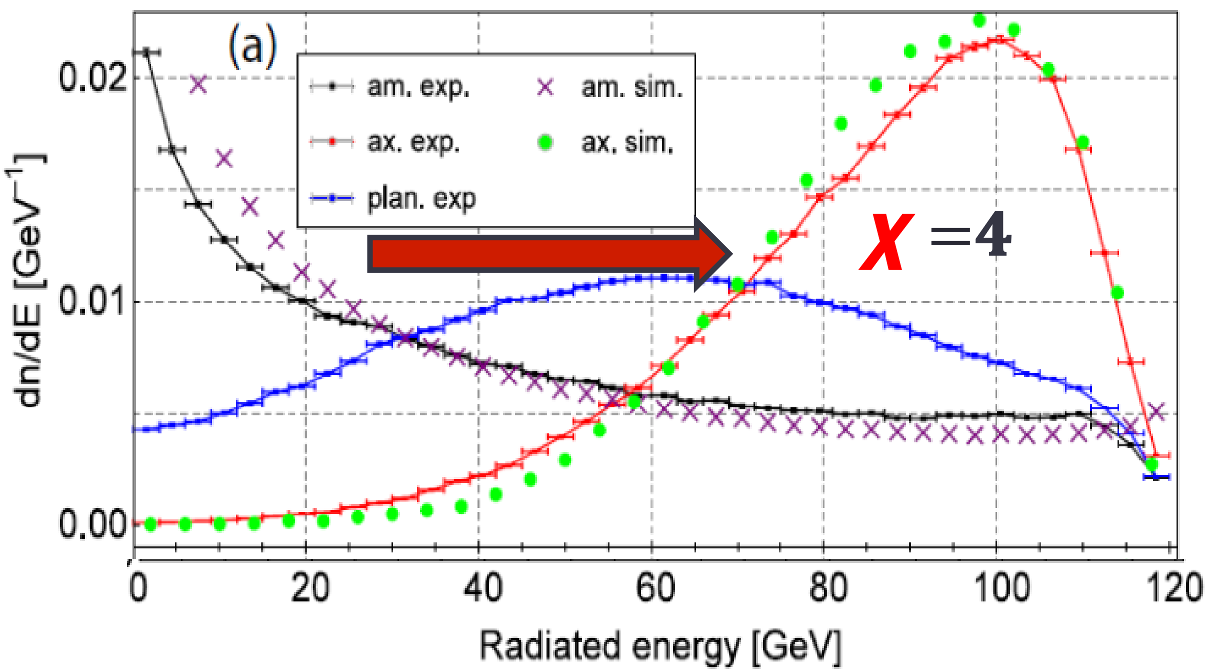
A 2x55x4 mm^3 strip-like PWO crystal with the largest faces oriented parallel to the (100) planes was selected for the experiment. **4 mm length** along the beam direction corresponds to about **$0.45\ X_0$**.

Radiated energy



Setup @CERN

We selected single events on SD1-2 and collected the emitted photons at the gamma-calorimeter.

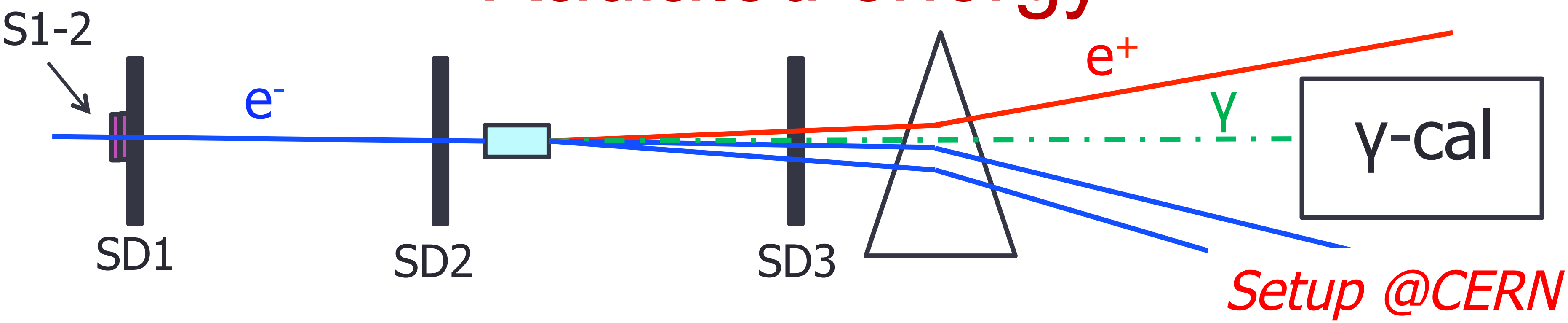


Peak at 100 GeV!

Strong reduction of X_0 in the oriented cases.

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

Radiated energy



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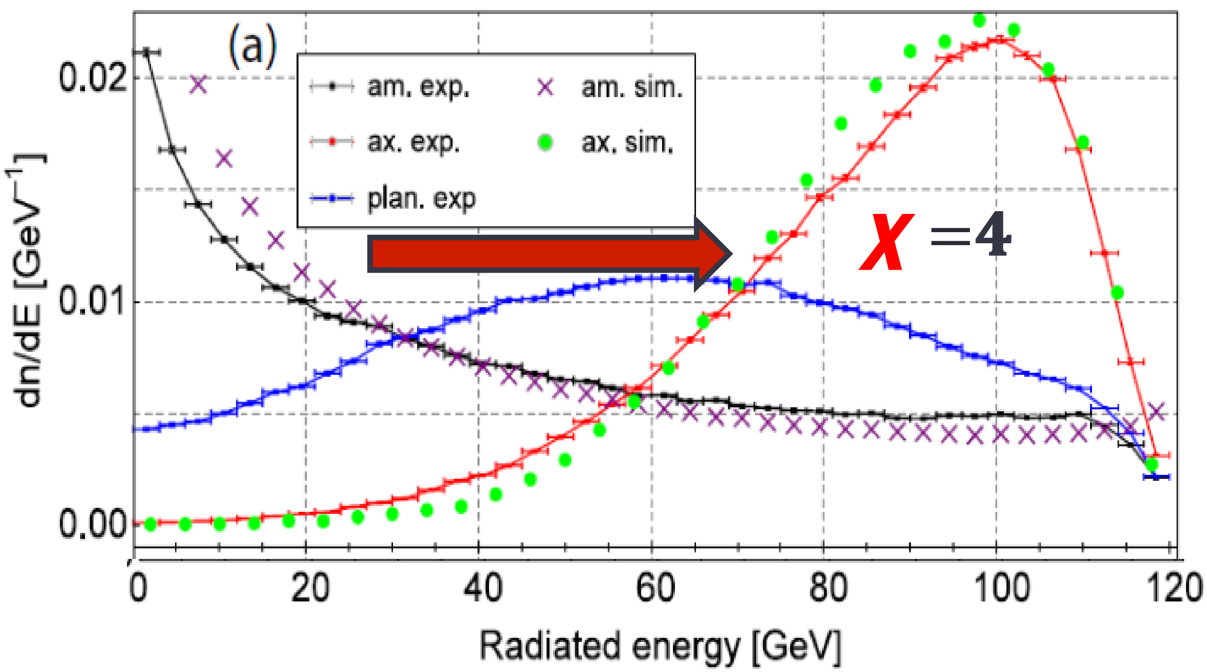
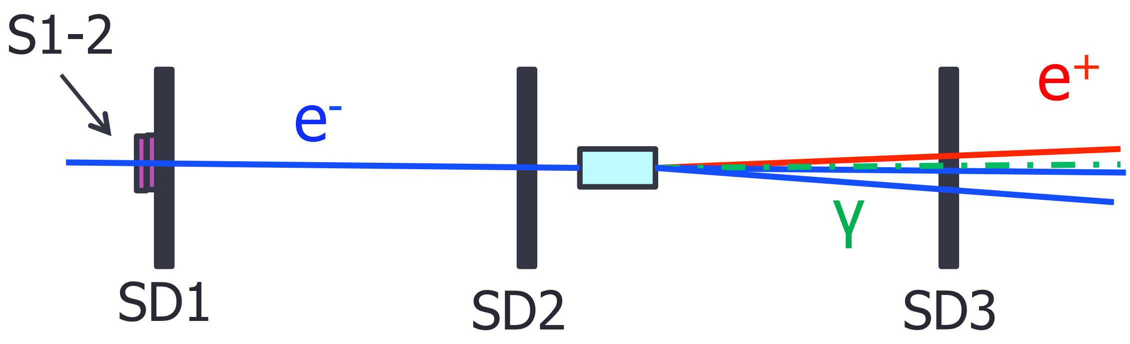
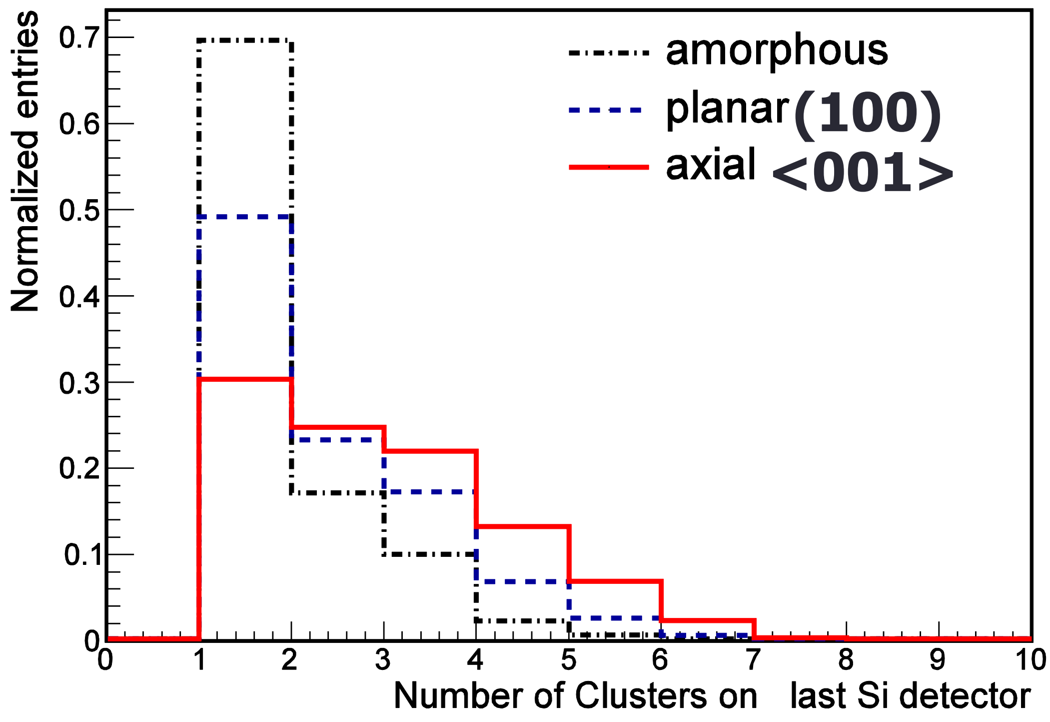


The energy lost into pairs cannot be measured, since the magnet swiped away not only the primary particles but also the secondary electrons and positrons.

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

Increase of secondaries in oriented crystal



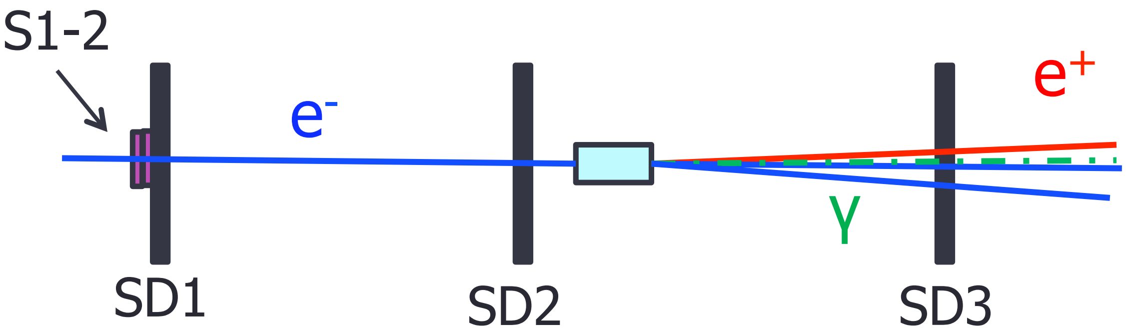


Multiple Tracks

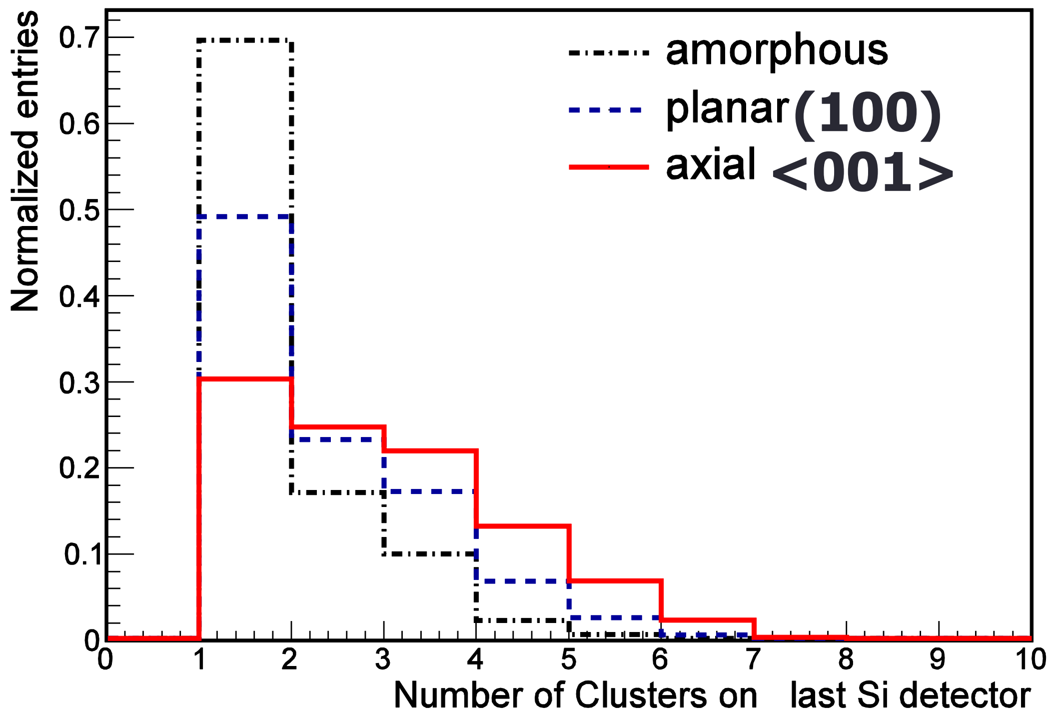
Scintillators S1-S2 are used for the trigger.
We selected single events on SD1-2 and measured the hits at the SD3 detector.

We measured a strong increment of multi-hits at the third detector, depending on crystal-to-beam orientation

Increase of secondaries in oriented crystal



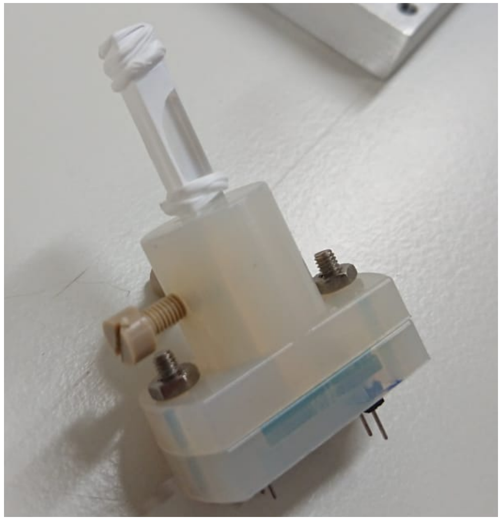
Multiple Tracks



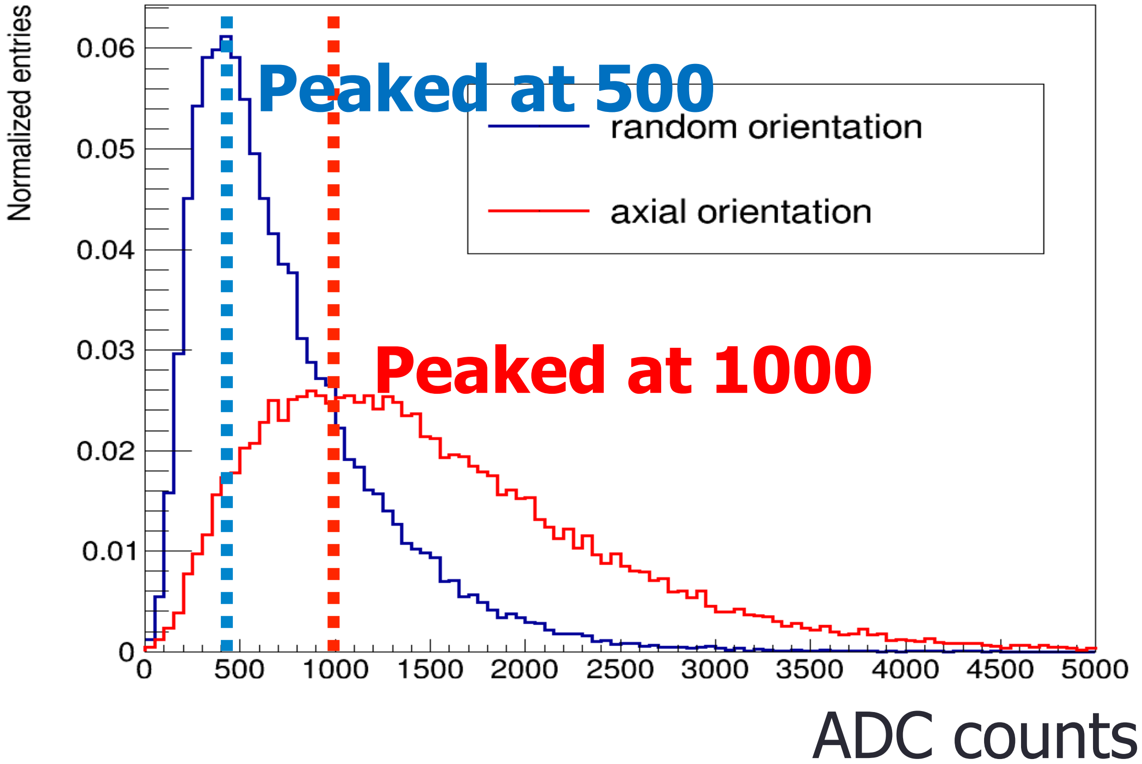
An electromagnetic shower has been initiated

Effective reduction of the radiation length in the oriented cases.

E.m. shower acceleration in an oriented PWO crystal – test with SiPM*



PWO crystal coupled with a SiPM
@Insulab - UniInsubria

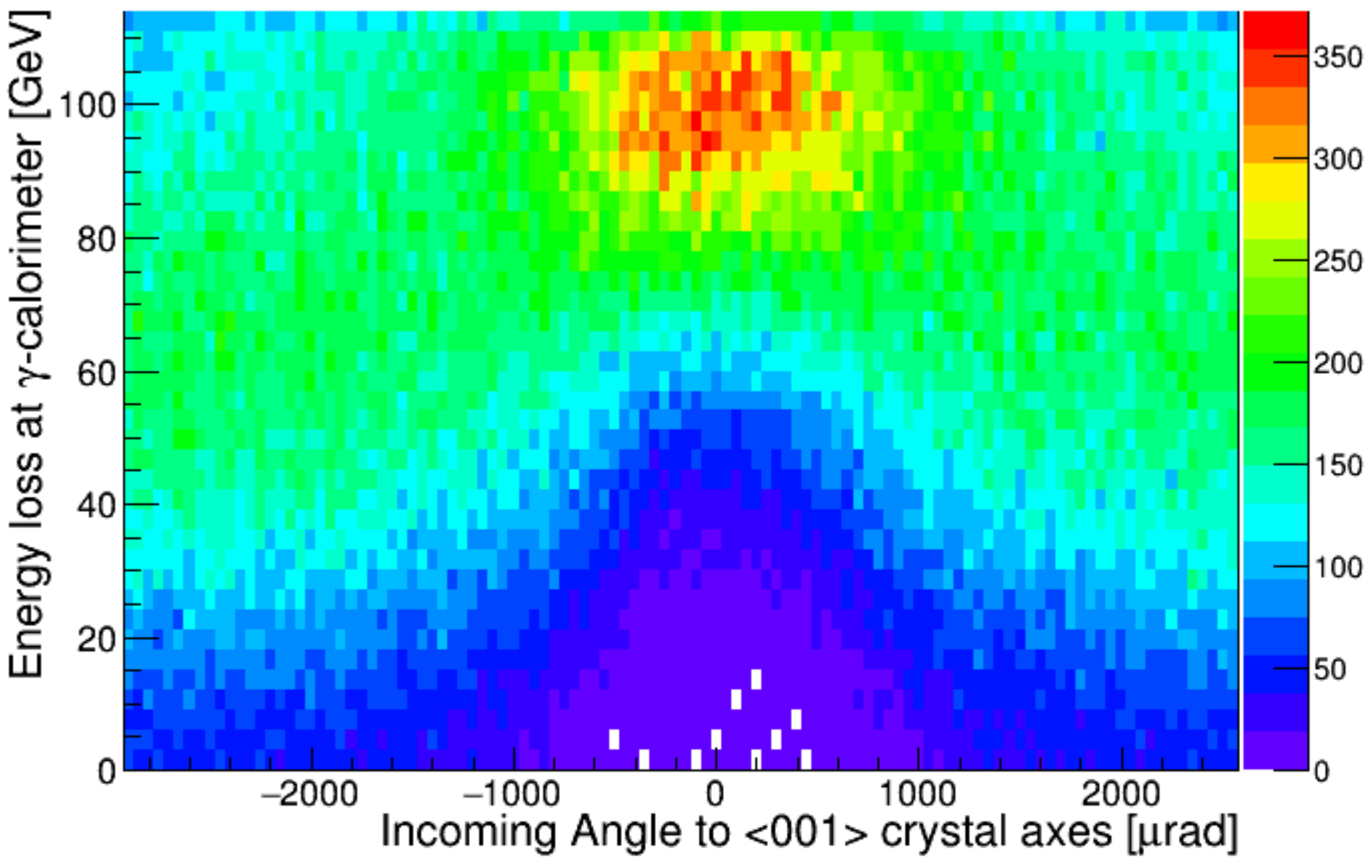


Scintillation signal @ SiPM

Strong enhancement of scintillation light (peaked at a double value) for the case of axial orientation if compared to random case. **The e.m. shower have been strongly accelerated by the X0 reduction, with the increase of secondaries emission.**

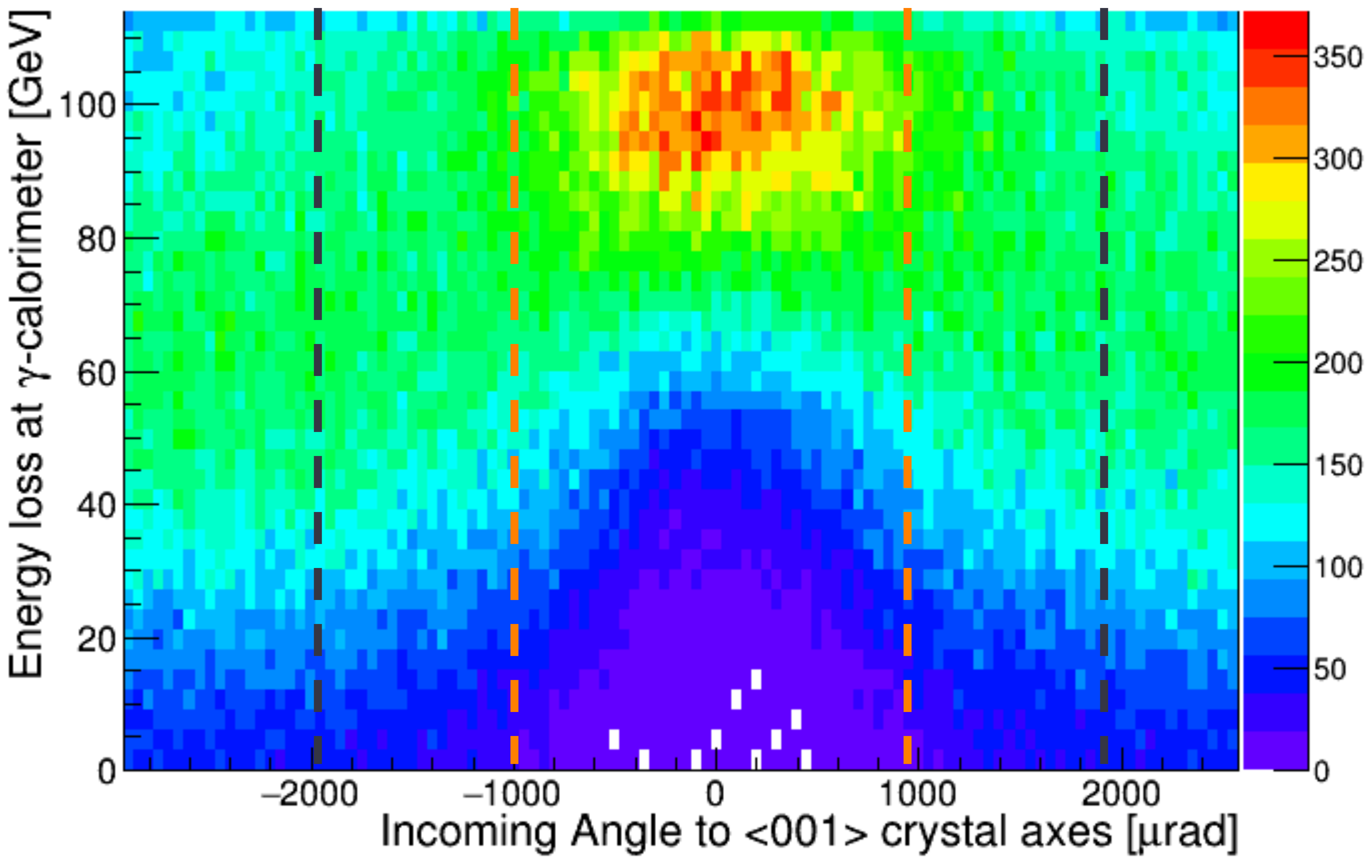
*** Preliminary results**

Angular acceptance of radiation enhancement



Rotational scan around the <001> axes – along the (100) planes

Angular acceptance of radiation enhancement



The axial influence is strong in **±1 mrad** angular range and it is maintained up to almost **±2 mrad** (±0.1 deg)

COMPARISON WITH SIMULATION

Baier-Katkov quasiclassical operator method (1967-1968)

General method for calculation of radiation generated by $e^{\pm}$ in an external field

The electromagnetic radiated energy is evaluated with the BK formula:

$$\frac{dE}{d^3k} = \omega \frac{dN}{d^3k} = \frac{\alpha}{4\pi^2} \iint dt_1\, dt_2 \frac{\left[(E^2+E'^2)(v_1 v_2 - 1) + \omega^2/\gamma^2\right]}{2E'^2} e^{-ik'(x_1 - x_2)} \qquad (1)$$

where the integration is made over the classical trajectory.

Why classical trajectory?

2 types of quantum effects :

- the quantization of particle motion $\sim \hbar\omega_0/E$
  In crystals: negligible for electron/positron energy >10-100 MeV
- **the quantum recoil of the particle when it radiates a photon with energy $\hbar\omega \sim E$** **NOT negligible for electron/positron energy >50 GeV**

An algorithm for radiation in crystals

Integration of the quasi-classical Baier-Katkov formula

General method for calculation of radiation generated by e± in an external field

The electromagnetic radiated energy is evaluated with the BK formula:

$$\frac{dE}{d^3k} = \omega \frac{dN}{d^3k} = \frac{\alpha}{4\pi^2} \iint dt_1\, dt_2\, \frac{(E^2+E'^2)(v_1 v_2 - 1)+\omega^2/\gamma^2}{2E'^2}\, e^{-ik'(x_1-x_2)} \qquad (1)$$

where the integration is made over the classical trajectory.

SMALL ANGLE APPROXIMATION:

$$\frac{dE}{d^3k} \sim \frac{\alpha}{8\pi^2}\frac{\varepsilon^2+\varepsilon'^2}{\varepsilon'^2}\omega^2 C, \qquad (2)$$

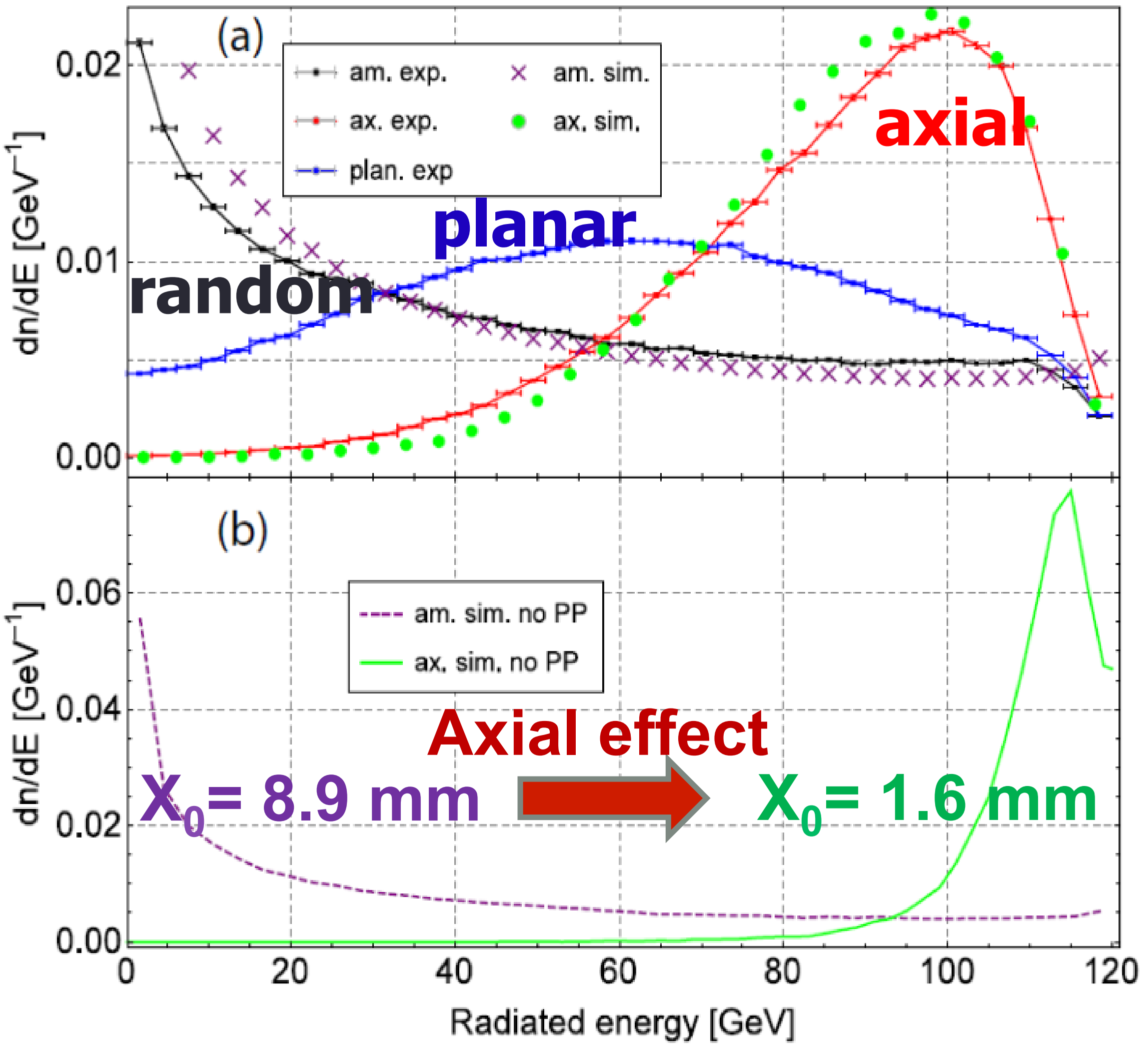
where

$$C = |\, \boldsymbol{I}_\perp \,|^2 + \gamma^{-2}\frac{\omega^2}{\varepsilon^2+\varepsilon'^2}\,|\, J \,|^2 \qquad 3)$$

V. Guidi, L. Bandiera, V. Tikhomirov, Phys. Rev. A 86 (2012) 042903

L. Bandiera et al., Phys. Rev. Lett. 111(2013) 255502 – past experiment with Si crystal

Simulation results for PWO



Simulation for **bremsstrahlung + pair production** in agreement with experimental results for:

Random orientation

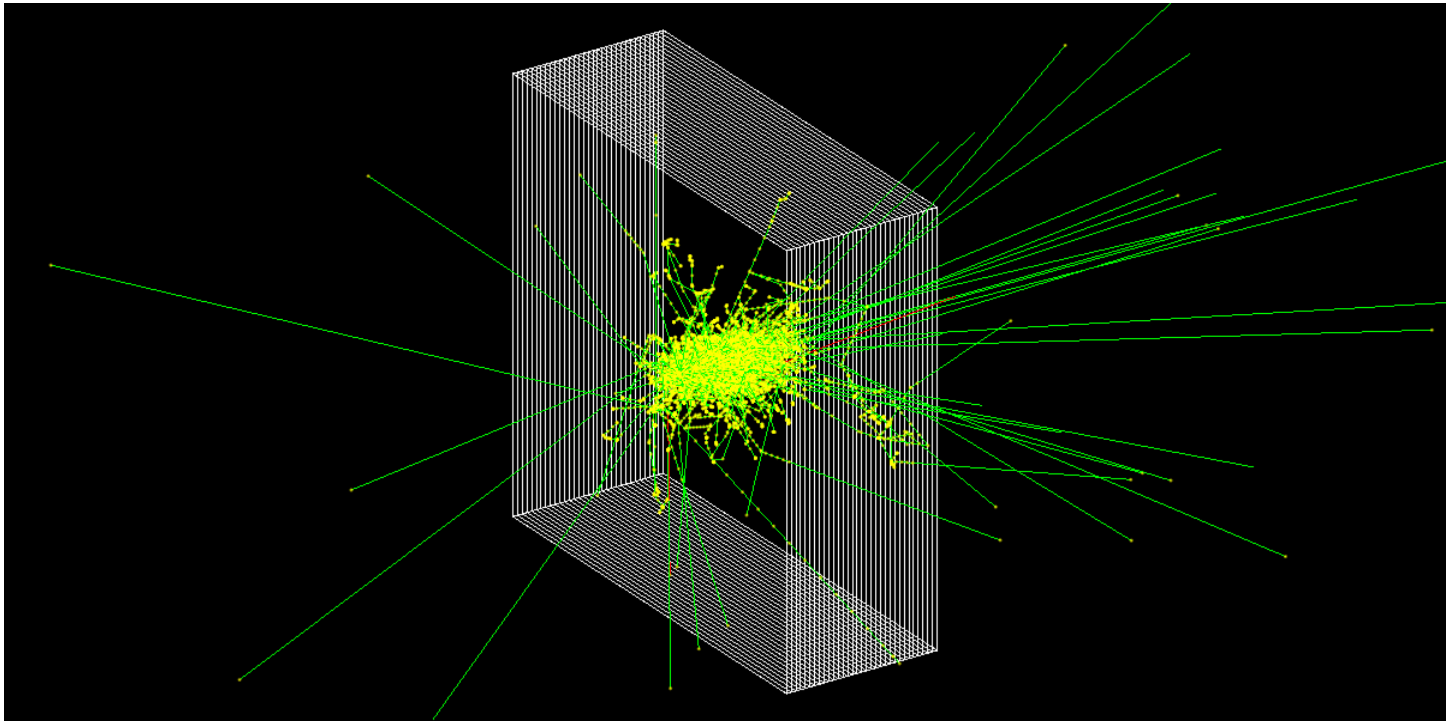
Axial orientation

Simulation for **pure bremsstrahlung .**

In axial case, X_0 is decreased from 8.9 to 1.6 mm

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

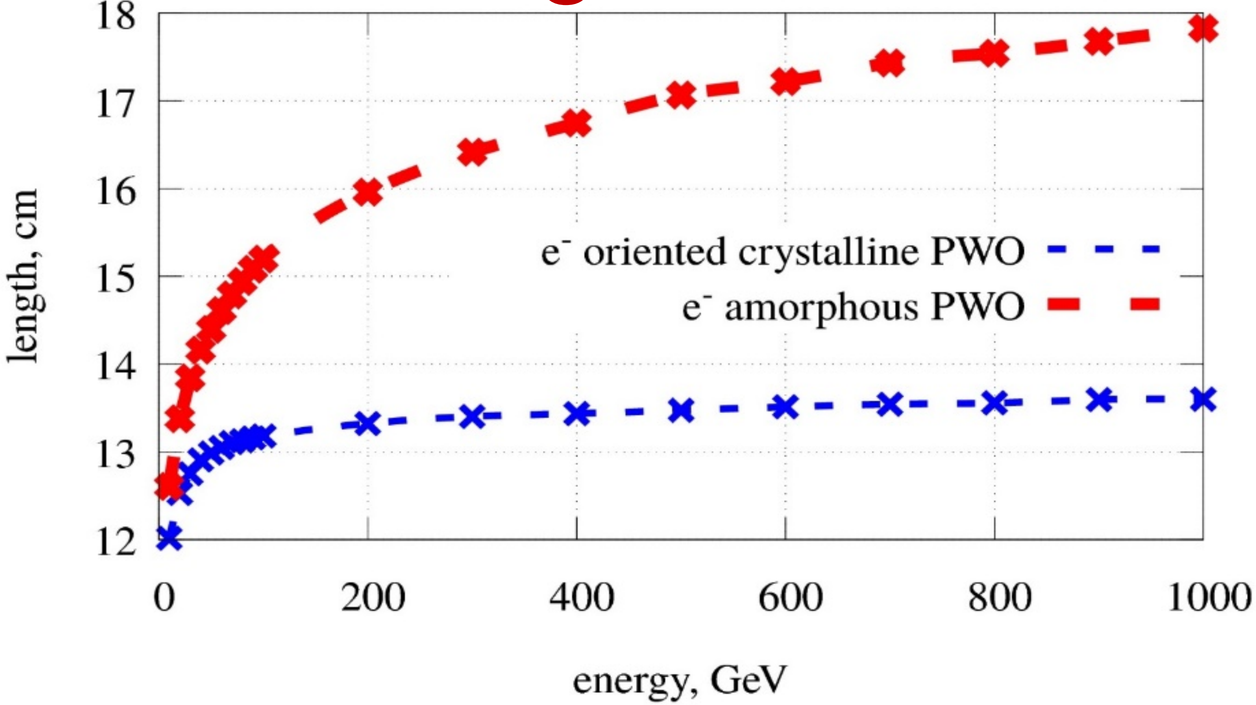
GEANT4 modified simulation for a PWO crystal with X_0 reduced



The electromagnetic shower is simulated using the **Geant4** toolkit in which the cross sections for **bremsstrahlung and pair production are rescaled** in agreement with full BK Monte Carlo.

V.G.Baryshevsky, **V.V.Haurylavets**, et al., Nucl. Instrum. Methods Phys. Res. B, 402 (2017) 35.

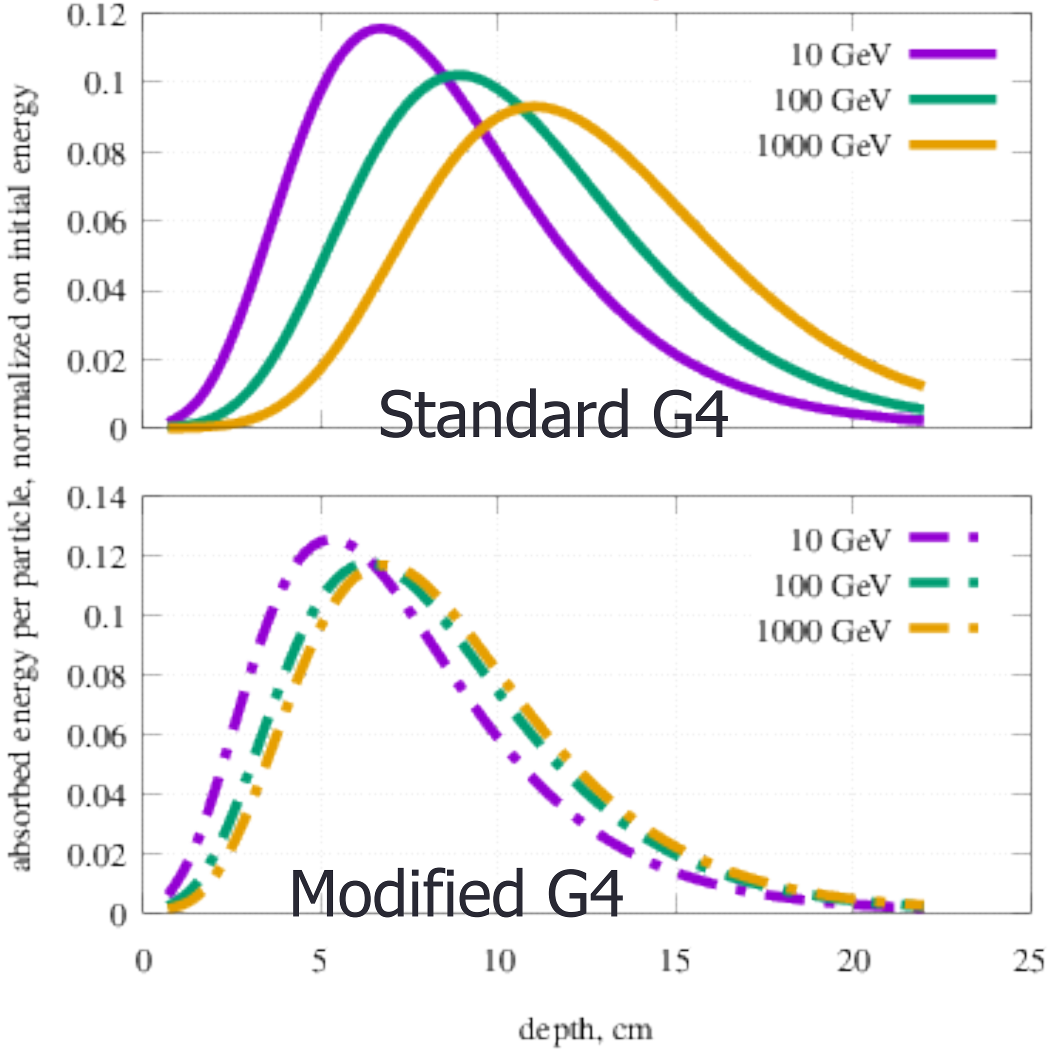
E.m. shower length vs. beam energy



Electromagnetic shower length (defined as 90% of energy deposited inside the crystal) vs. beam energy, for primary electrons. Since the crystalline strong field effect increases with beam energy with a consequent X_0 decreasing, the shower length is almost constant with energy.

L. Bandiera et al. Nucl. Instrum. Methods Phys. Res. A, in press.
https://doi.org/10.1016/j.nima.2018.07.085

Shower longitudinal development



Electromagnetic shower longitudinal development vs. e- beam energy.

In case of oriented PWO, the maximum is shifted to the entry surface of the crystal.

L. Bandiera et al.,Nucl. Instrum. Methods Phys. Res. A, in press.
https://doi.org/10.1016/j.nima.2018.07.085

Possible applications

- Realization of **forward calorimeters and preshowers with a reduced volume;**
- **Smart gamma-converters** for **fixed-target experiments** with reduced ratio X_0/λ_{int} (KLEVER proposal);
- **Light dark matter search** with fixed-target/beam dump experiments (*Idea of M. Raggi, UniSapienza*). If a dark photon is created during the shower generated by a primary electron, it can be detected only if survives after the remaining dump length. Shorter is such length, higher is the sensitivity.

Possible applications

In Astroparticle Physics: Production of **compact calorimeters** that contain the gamma e.m. showers at energies > 100 GeV **without increasing the weight** (and so the cost). With the birth of multimessenger astrophysics one can think of **pointing a telescope towards the source** (0.5°-1° acceptance) and exploit the X_0 reduction in oriented crystals.

Possible applications

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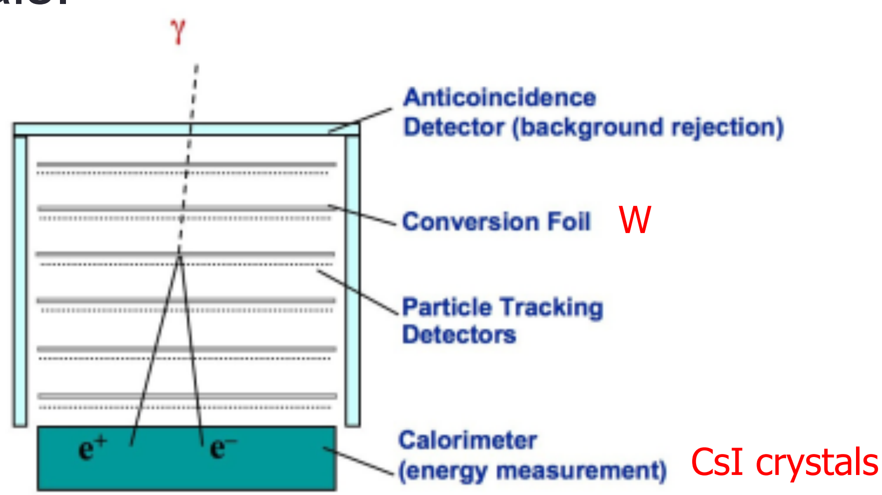
FERMI LAT-like telescope:

- reduce the thickness of the calorimeter (and so the weigth)
- **reduce the thickness of the photon converters in the tracker**, thus increasing the resolution.



Conclusions

- The electromagnetic showers developing along axial directions in a lead tungstate single crystal has been investigated, showing a strong reduction of radiation length depending on the crystal-to-beam orientation;

- A Monte Carlo code capable to reproduce well the experimental results has been developed and currently a first implementation in Geant4 has been carried out, thus being useful to design future experiments ;

- These effect can be exploited to decrease the shower length in calorimeters for high-energy physics and astrophysics.

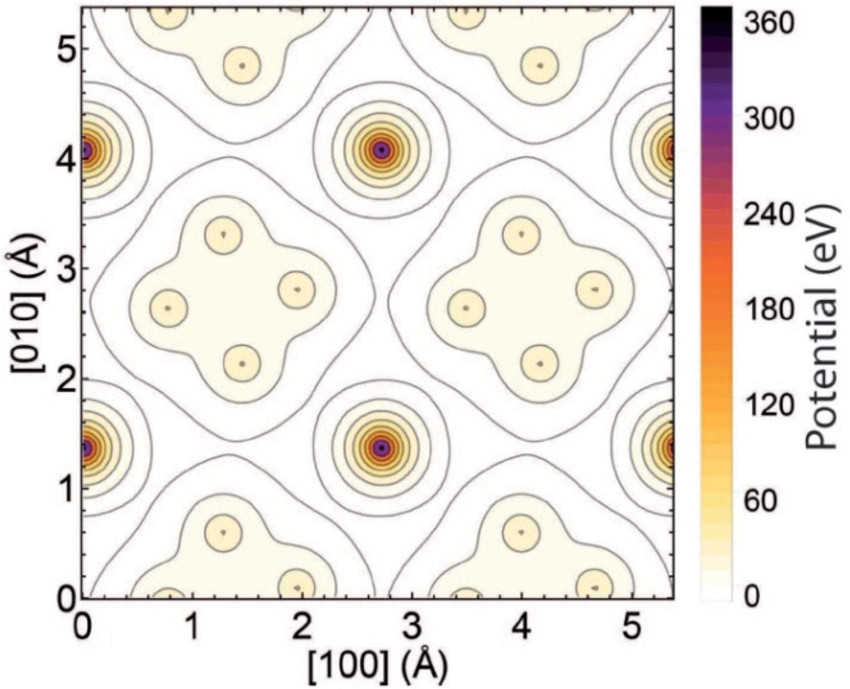
THANK YOU FOR THE ATTENTION!

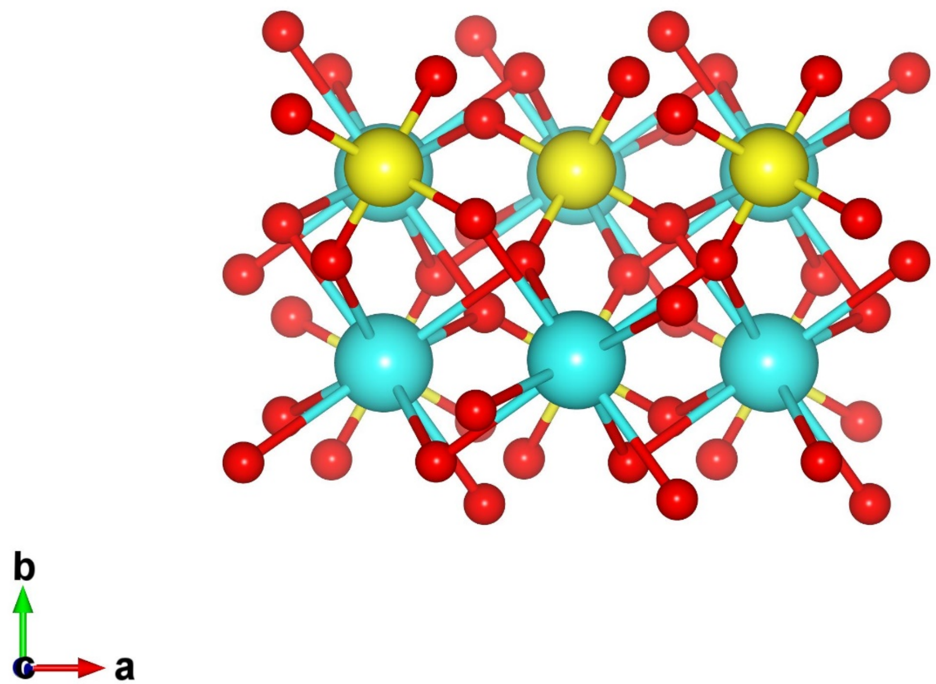
BACK UP SLIDES

PWO crystralline structure

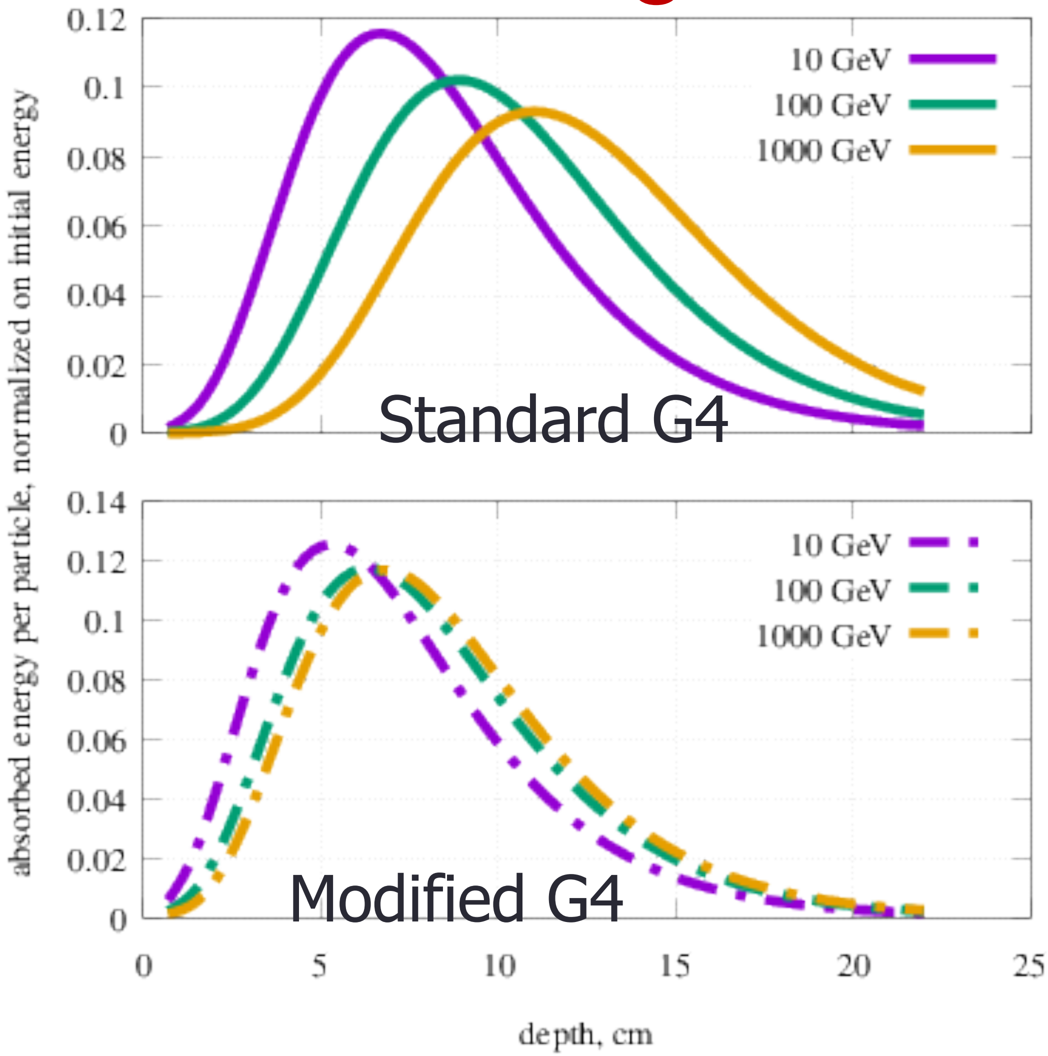
Structural characterization of PWO single crystal by x-ray diffraction showed scheelite type structure

(tetragonal, a=5.456, c=12.020 Å).





Shower longitudinal development



Electromagnetic shower longitudinal development vs. e- beam energy.

In case of oriented PWO, the maximum is shifted to the entry surface of the crystal.

L. Bandiera et al., Nucl. Instrum. Methods Phys. Res. A, in press. https://doi.org/10.1016/j.nima.2018.07.085

PWO as high-Z scintillator

- $PbWO_4$ (PWO) scintillation crystals introduced by INP team in 1994 are currently used by CMS, ALICE, PANDA collaborations in EM calorimeters, about 100000 crystals in total is produced.
- **PWO propreties:**
  - **Short radiation lenght (8.9 mm);**
  - **small Moliere Radius;**
  - **emission in visible;**
  - **cheap;**
  - **low light yield;**
  - **temperature dependent.**

The small Moliere radius of PWO crystals make them ideal for use in a compact detector and their light yield outperforms that of other heavy crystals.

Baier-Katkov quasiclassical operator method (1967-1968)

General method for calculation of radiation pair production by a HE photon in an external field

$$\frac{d^2N}{d\varepsilon_- d\Omega} = \frac{\alpha\varepsilon_-^2}{8\pi^2\omega\varepsilon_+^2}\left[\omega^2|A|^2/\gamma_-^2 + \left(\varepsilon_-^2+\varepsilon_+^2\right)|\vec{B}|^2\right],$$

$$A = \int_{-\infty}^{\infty}\exp\{i\varphi(t)\}dt, \qquad \vec{B} = \int_{-\infty}^{\infty}\left(\vec{v}_\perp(t)-\vec{\theta}_\perp\right)\exp\{i\varphi(t)\}dt,$$

$$\varphi(t) = \frac{\varepsilon_-}{\varepsilon_+}\left(\omega t - \vec{k}\vec{r}\right) = \frac{\varepsilon_-}{\varepsilon_+}\int_0^t \dot{\varphi}(t')\,dt' = \frac{\omega'}{2}\int_0^t\left[\gamma_-^{-2} + (\vec{v}_\perp(t')-\vec{\theta})^2\right]dt', \quad \omega' = \frac{\omega\varepsilon_-}{\varepsilon_+}.$$

The Constant Field Approximation (CFA) is applied to evaluate the pair production process when high-energy photons enters a crystal along the major crystal axis. However, CFA does not explain the angular dependence of the pair production rate.

The BK method has the advantage to be applicable in the whole angular region.

Possible applications

In Astroparticle Physics: Production of **compact calorimeters** that contain the gamma e.m. showers at energies > 100 GeV **without increasing the weight** (and so the cost). With the birth of multimessenger astrophysics one can think of **pointing a telescope towards the source** (0.5°-1° acceptance) and exploit the X_0 reduction in oriented crystals.

Possible applications

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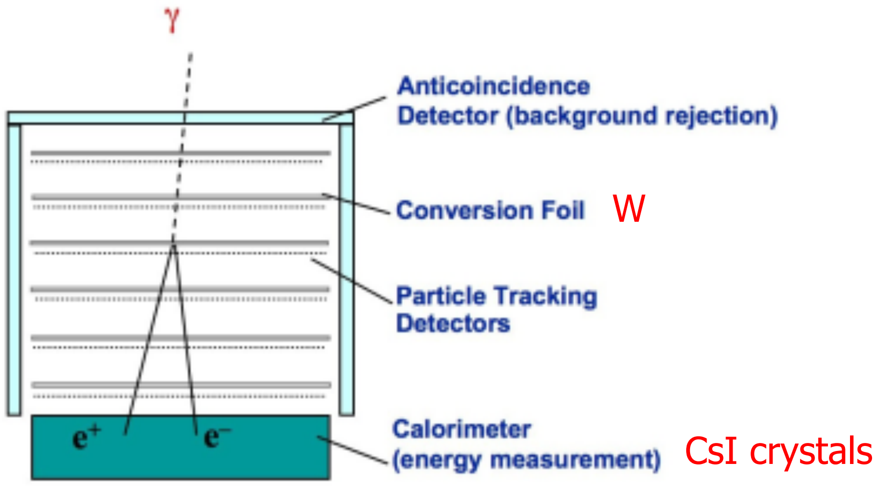
FERMI LAT-like telescope:

- reduce the thickness of the calorimeter (and so the weigth)
- **reduce the thickness of the photon converters in the tracker**, thus increasing the resolution.



The main point: total radiated energy can strongly increase!

VOLUME 54, NUMBER 25   PHYSICAL REVIEW LETTERS   24 JUNE 1985

Measurement of the Total Energy Radiated by 150-GeV Electrons in a Ge Crystal

A. Belkacem, M. Chevallier, A. Clouvas, M. J. Gaillard, R. Genre, R. Kirsch, J. C. Poizat, and J. Remillieux,
Institut de Physique Nucléaire and Institut National de Physique Nucléaire et de Physique des Particules, Université Claude Bernard Lyon I, 69622 Villeurbanne Cedex, France

and

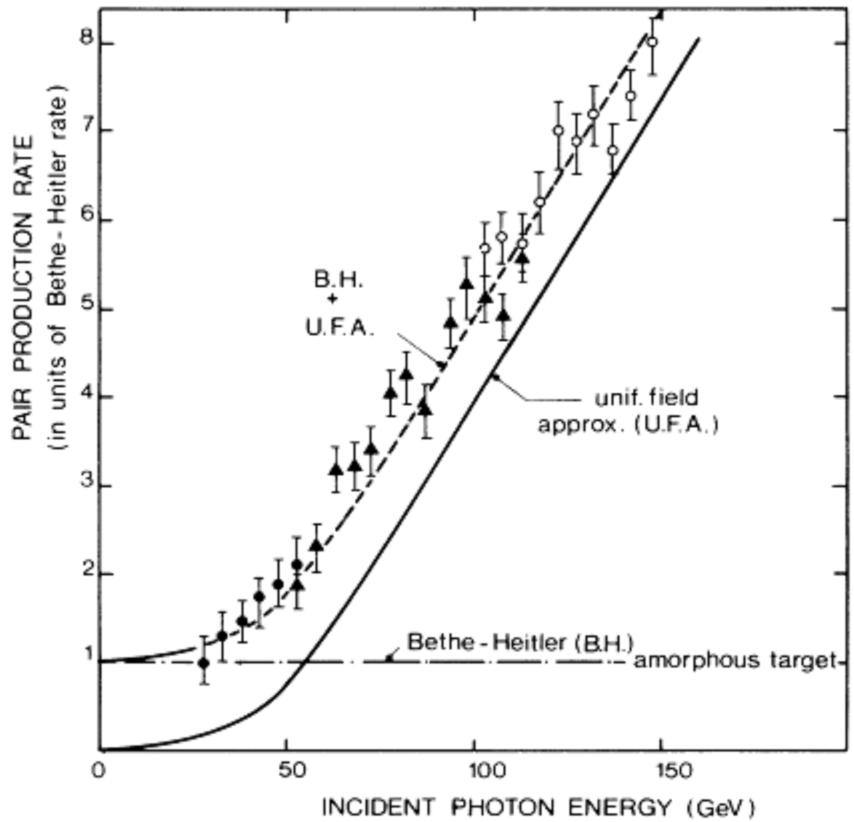
G. Bologna,[a] J. P. Peigneux, D. Sillou, and M. Spighel
Laboratoire d'Annecy-le-Vieux de Physique des Particules, Laboratoire de Physique des Particules and Institut National de Physique Nucléaire et de Physique des Particules, 74019 Annecy-le-Vieux Cedex, France

and

N. Cue, J. C. Kimball, B. Marsh, and C. R. Sun
Physics Department, State University of New York at Albany, Albany, New York 12222
(Received 11 February 1985)

We have measured the radiation emitted by 150-GeV e^- incident along the ⟨110⟩ axis of Ge crystals. The on-axis total radiated energy is 25 times larger than for nonaligned directions for 0.4-mm-thick Ge. The distribution of the radiated energy versus the angle of the electron beam yields a half-width much larger than the channeling critical angle. The on-axis results confirm the predictions of the crystal-assisted radiation theory. The Born approximation to the coherent bremsstrahlung fits the data at large angles.

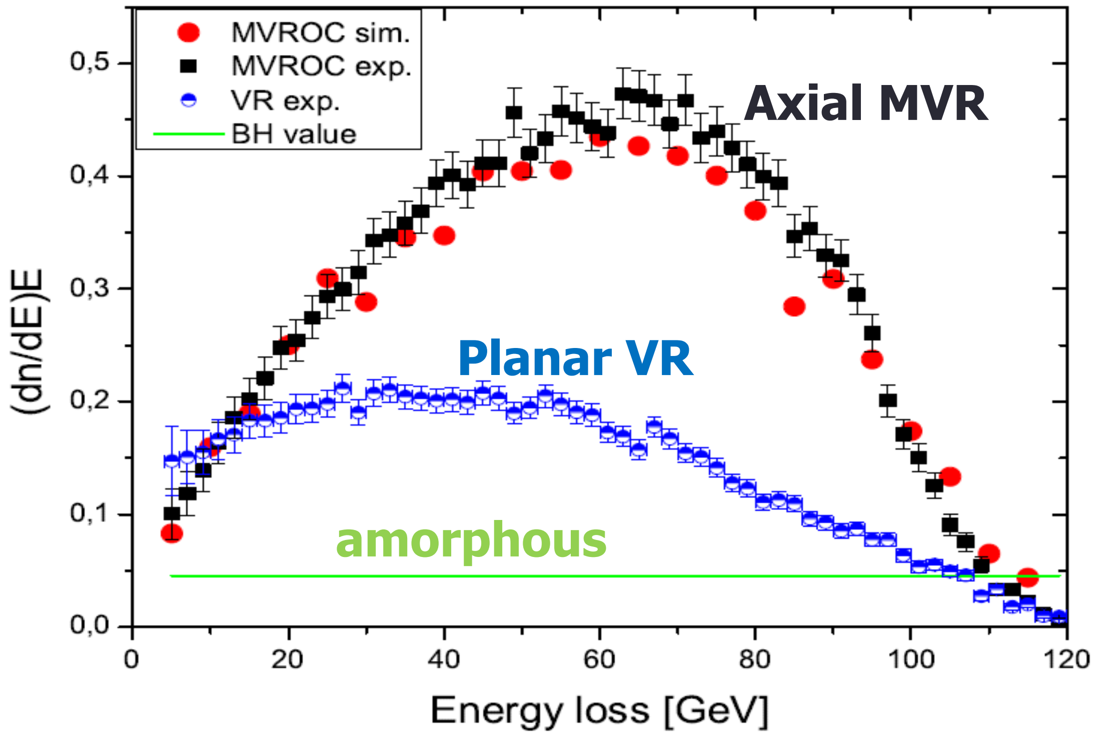
… also for Pair Production



Study of e+/e- Pair Creation by 20 — 150-Gev Photons Incident on a Germanium Crystal in Alignment Conditions

A. Belkacem et al., Phys. Rev. Lett. 58 (1987) 1196

Simulation vs previous experimental results of axial multi-volume reflection in a 2 mm Si bent crystal

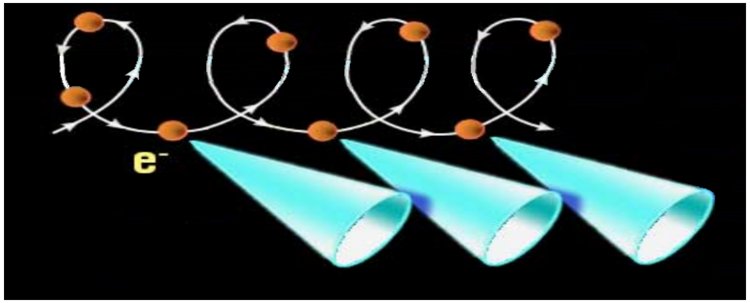


Energy loss spectral intensities: (dn/dE)*E of 120 GeV/c single and multi-reflected electrons

L. Bandiera et al., Phys. Rev. Lett. 111(2013) 255502

When channeling radiation becomes synchrotron-like radiation

$$\vartheta \approx \sqrt{\frac{2V_0}{\varepsilon}} > \frac{m}{\varepsilon} \Rightarrow \varepsilon \gg \frac{m^2}{2V_0} \sim 1 \div 10\,GeV$$



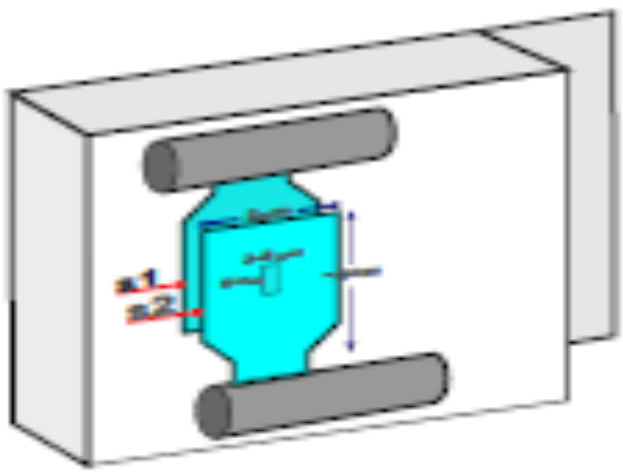
and quantum?

if $E\gamma = E\downarrow 0$

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

The trigger system

A schematic drawing of the s1-2 scintillators mounted on the Ds1 detector



(a)

(b)

The s2 scintillator has a hole (3.5x9 mm^2) and it can act as an anticoincidence ($s1 \wedge \overline{s2}$) to acquire a beam portion that matches the crystal shape thus increasing the number of events impinging on the crystal itself.

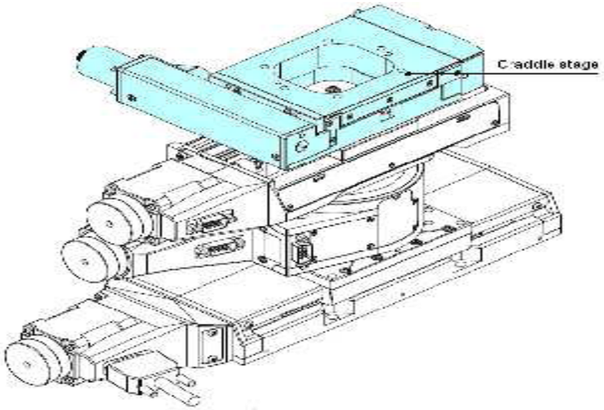
Telescope system: Silicon microstrip detectors and high precision goniometer

Double sided silicon detectors **DsX** (300μm thick)

Spatial resolution
~5-10 μm

Angular Resolution
~10 μrad

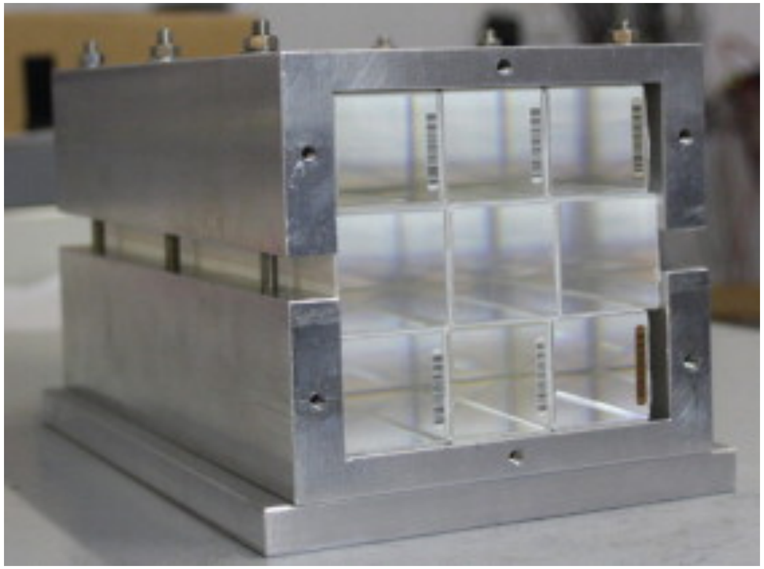
High-precision goniometer

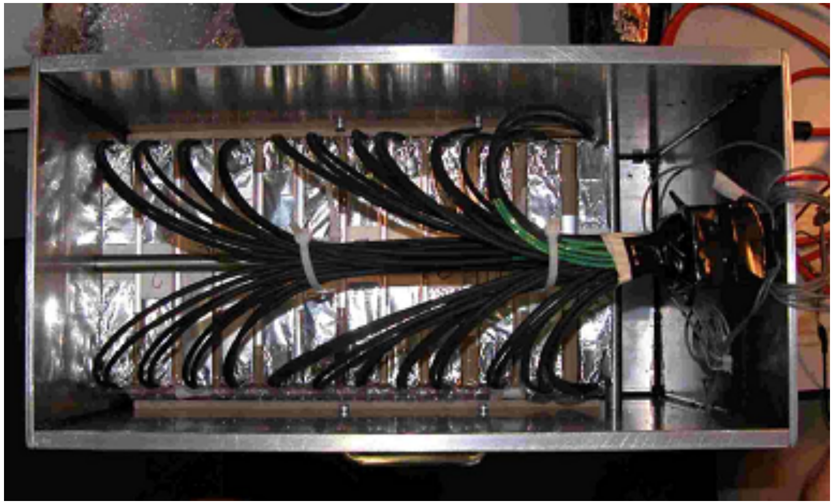


Goniometer resolution
~few μrad

E.M. CALORIMETERS

Gamma-cal: Lead tungstate crystals as CMS endcap crystals: 22 cm long, with a front section of 2.86×2.86 cm^2 and a rear one of 2.96×2.96 cm^2, for a total of ~24.7 radiation lengths.





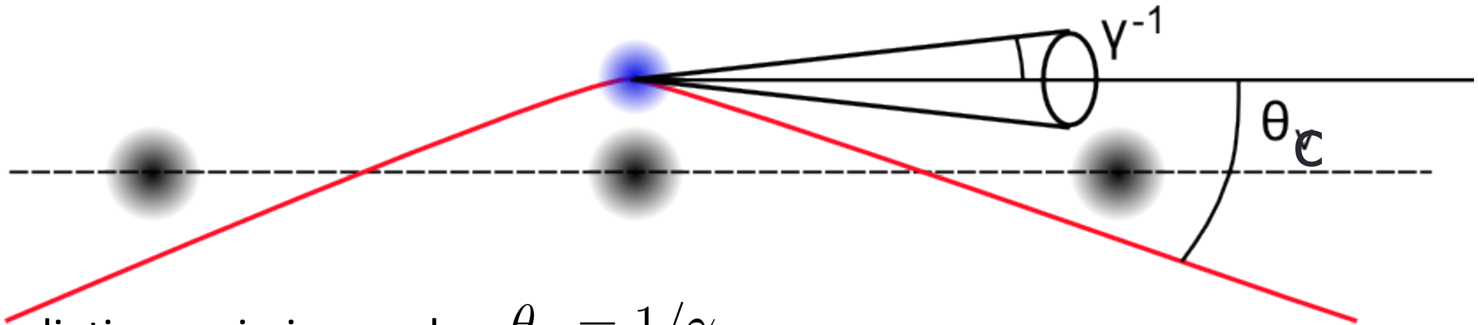
The e-calorimeter is formed by 12 plastic scintillator tiles and 11 lead tiles for a total of 13.07 X_0. The light produced in the scintillators is brought out by WLS fibers to a 16-channel PMT.

Experimental test at CERN SPS

On the extracted beamline H4 from the Super Proton Synchrotron, tertiary “clean” beams of electrons and positrons are available up to 200 GeV/c.

Synchrotron-like radiation in crystals

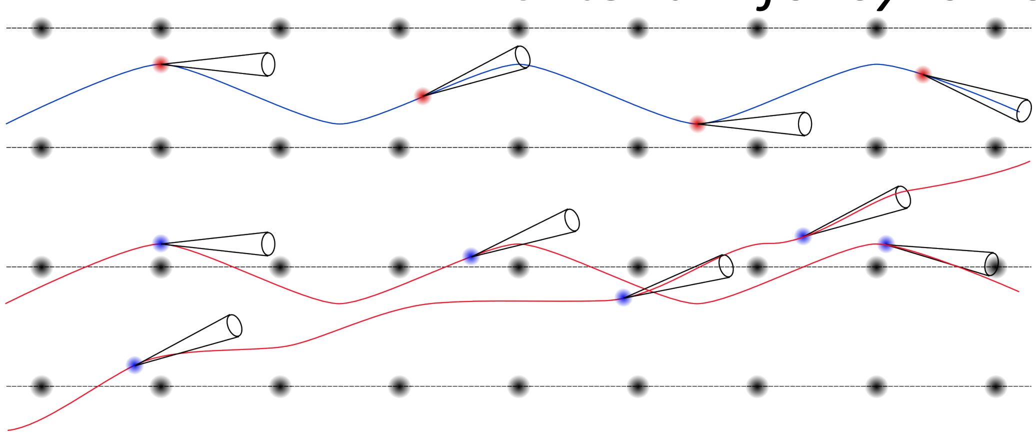
At energies > few GeV



Radiation emission angle: $\theta_\gamma = 1/\gamma$

Threshold angle: $\theta_v = V_0/m$

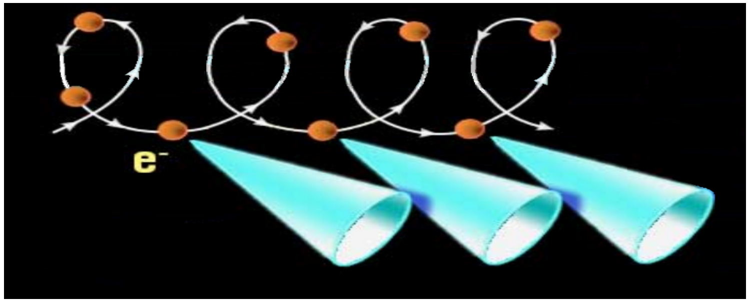
$\theta_\gamma \ll \theta_v$ *Criterium for synchrotron radiation*



Strong field regime of Synchrotron Radiation

At energies >10 GeV (100 GeV) depending on atomic number Z

$$\vartheta \approx \sqrt{\frac{2V_0}{\varepsilon}} > \frac{m}{\varepsilon} \Rightarrow \varepsilon \gg \frac{m^2}{2V_0}$$



Relevant for linear colliders, astrophysical objects like magnetars, heavy ion collisions and more. When the magnetic/electric field reaches the

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

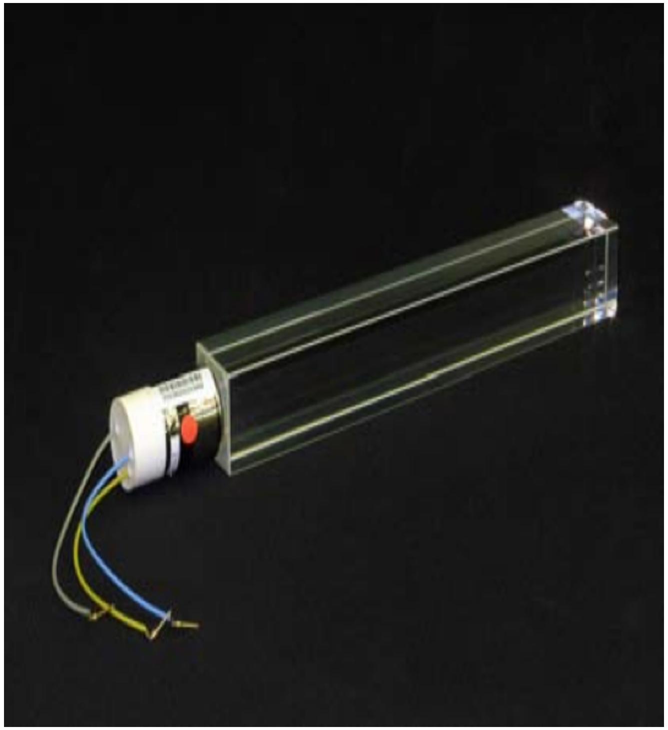
In the rest frame of the particle, the Lorentz contracted field can be computed as:

$$\gamma E = E_0$$

Being the Planar/Axial field *E* = $10^9/10^{11}$ V/cm

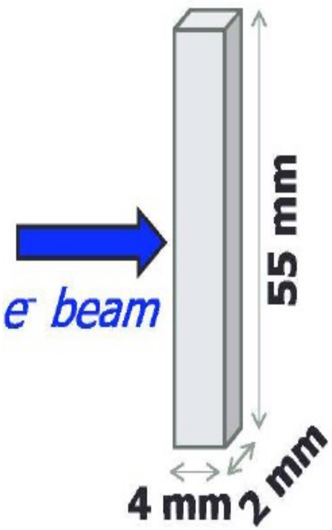
CMS ECAL PWO crystals

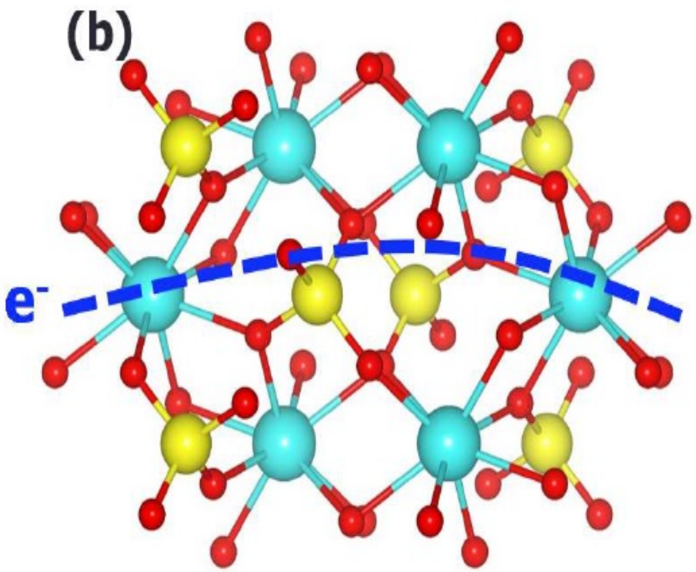
Picture of a $PbWO_4$ 23 cm-long crystal (left) used in the CMS ECAL with its photomultiplier, and of the endcap ECAL (right) showing the crates in which the crystals are placed.

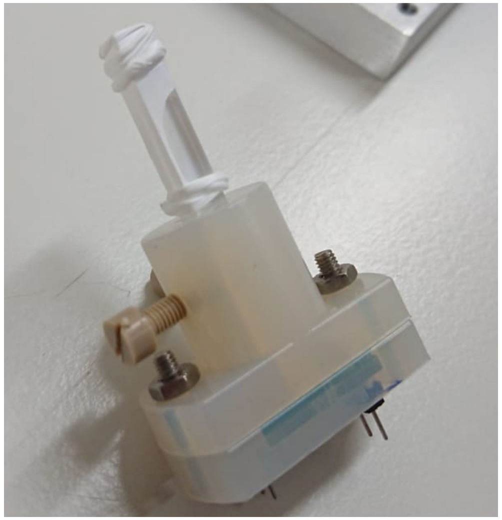


E.m. shower acceleration in an oriented PWO crystal – test with SiPM on 2018

A strip-like PWO crystal **4 mm length** along the beam direction corresponds to about **0.45 X_0**. **Axis <001>.**







PWO crystal coupled with a SiPM

Possible applications

In HEP:

- Realization of **forward calorimeters and preshowers with a reduced volume;**
- **Smart gamma-converters** for **fixed-target experiments** with reduced ratio X_0/λ_{int} (KLEVER proposal);
- **Light dark matter search** with fixed-target/beam dump experiments (*Idea of M. Raggi, UniSapienza*). If a dark photon is created during the shower generated by a primary electron, it can be detected only if survives after the remaining dump length. Shorter is such length, higher is the sensitivity.

Further advantages of scintillators:

- Possibility to measure the cascade characteristics inside the crystal (e.g. NA64 active beam dump);
- Scintillators have better crystallographic quality than metals and the possibility to be produced in virtually any size.