PAIR PRODUCTION AND RADIATION ENHANCEMENT IN STRAIGHT CRYSTALS: KLEVER AND POSSIBLE NEW APPLICATIONS

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13/02/2018, INFN and UNIFE, Ferrara (Italy)
Meeting on beam manipulation through oriented crystals

Outlook

Possible studies of PP and radiation enhancement for HEP and Future accelerators:

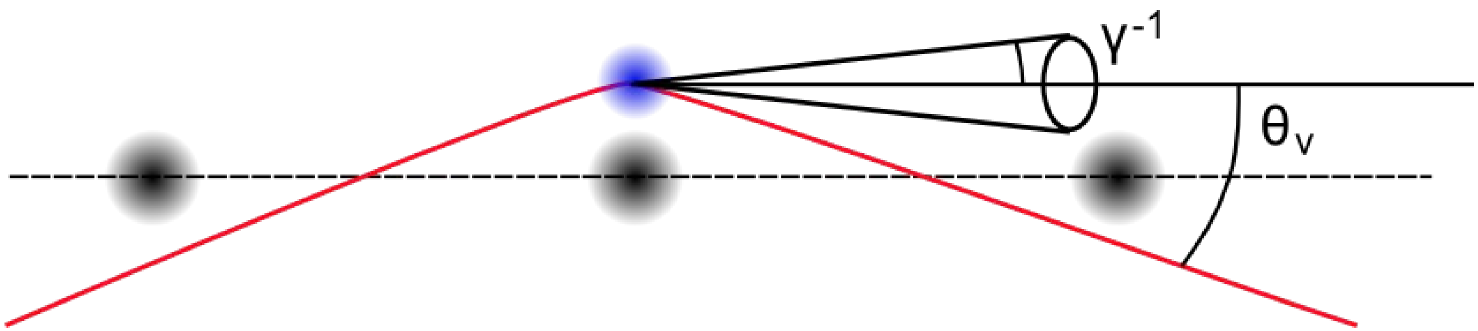
1. Smart gamma-converter for KLEVER @CERN SPS;

2. Possible PRIN project 2017 to investigate electromagnetic processes in standard and scintillator crystals for application in HEP and astrophysics;

3. Innovative positron source for future linear or muon colliders.

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:

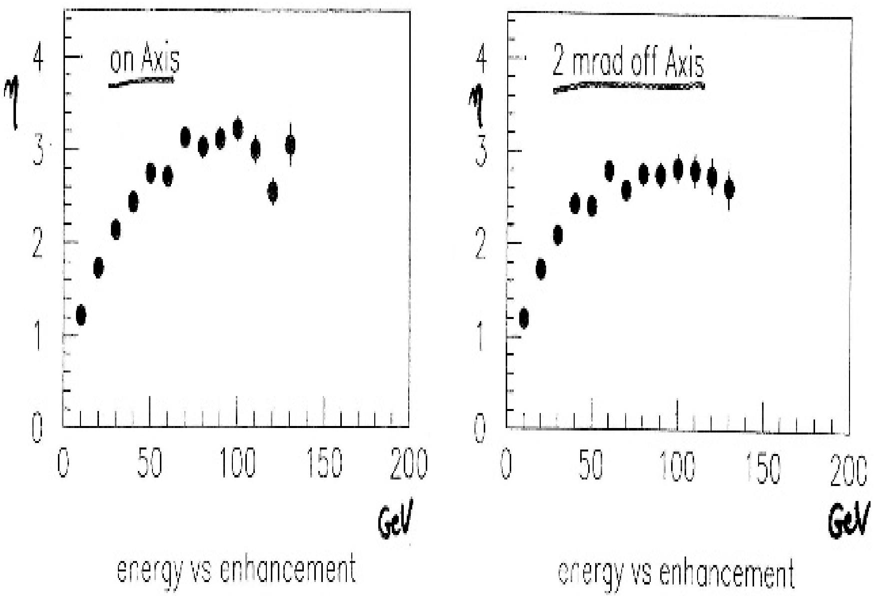
$$\gamma E = E_0$$

Parameter $X = \gamma E / E_0 \geq 1$

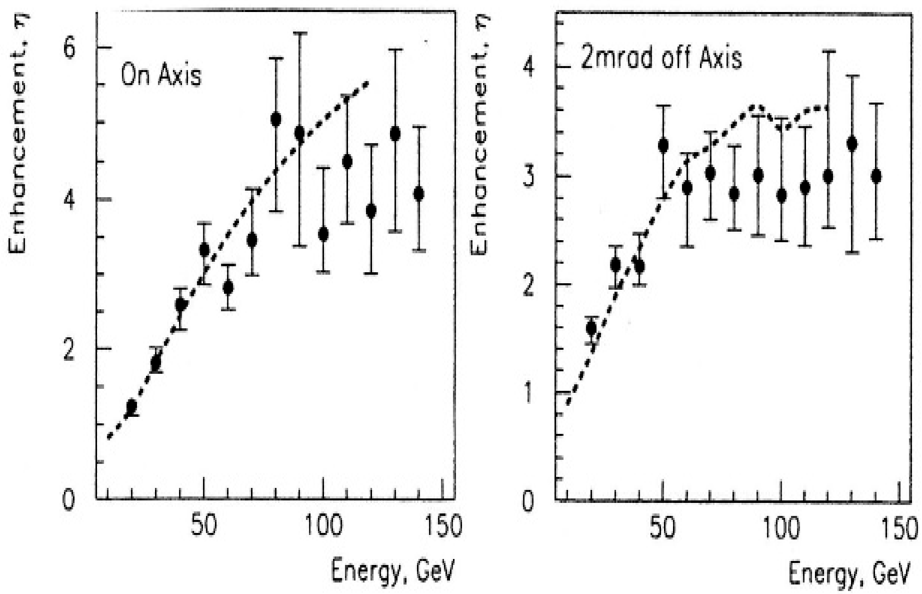
Being the Axial/Planar field E = $10^9/10^{11}$ V/cm

… and also for Pair Production

Iridium



Tungsten



The NA48 experiment at CERN used **Ir crystal of 3mm thickness, corresponding to 0.98 X0 which became 1.79 X0 for the aligned crystal**, as a high energy photon converter.

A **30% reduction of multiple scattering occurred**, when **compared to** a lead converter with a thickness of **1.33 X0**.

From C. Biino, MiniWorkshop on Crystal Collimation @CERN, 2005

KLEVER

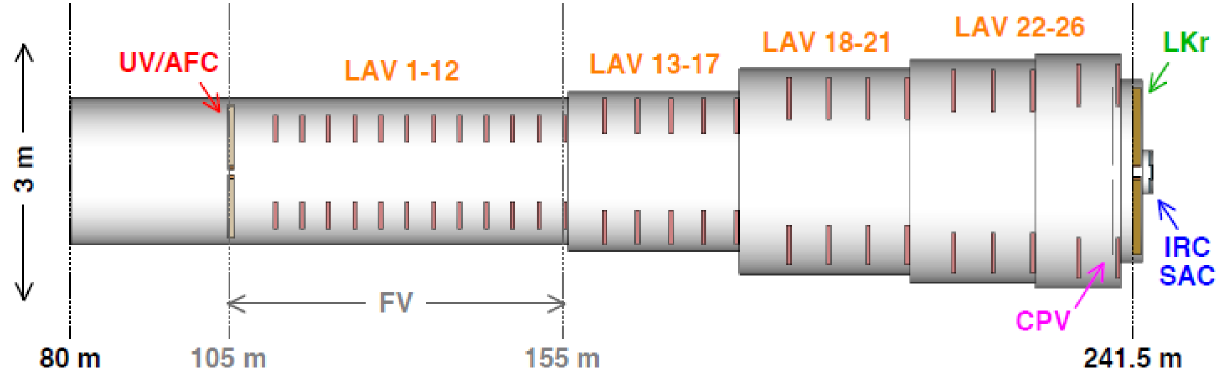
On behalf of KLEVER & AXIAL groups

KLEVER

PI: M. Moulson (LNF)

An experiment to measure $K_L \rightarrow \pi^0 \nu \bar{\nu}$ KLEVER

@SPS North Area – NA62 zone



New physics (NP) affects BRs differently for K+ and KL channels. Measurements of both can discriminate among NP scenarios.

Null NP results from direct searches at LHC so far - but NP may simply occur at a higher mass scale, indirect probes to explore high mass scales is even more interesting.

KLEVER Goal:
60 SM events with S/B ~ 1
(20% BR measurement)

Project timeline – target dates:

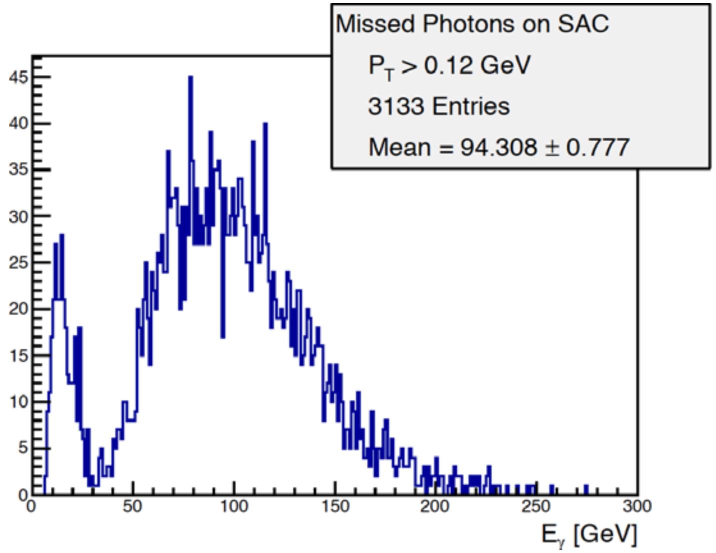
2017-2018	**Project consolidation and proposal** • Beam test of crystal pair enhancement • Consolidate the design
2019-2021	**Detector R&D**
2021-2025	**Detector construction** • Possible K12 beam test if compatible with NA62
2024-2026	**Installation during LS3**
2026-	**Data taking beginning Run 4**

Courtesy of Matthew Moulson

$K_L \rightarrow \pi^0\pi^0$ photons on Small Angle Calorimeter

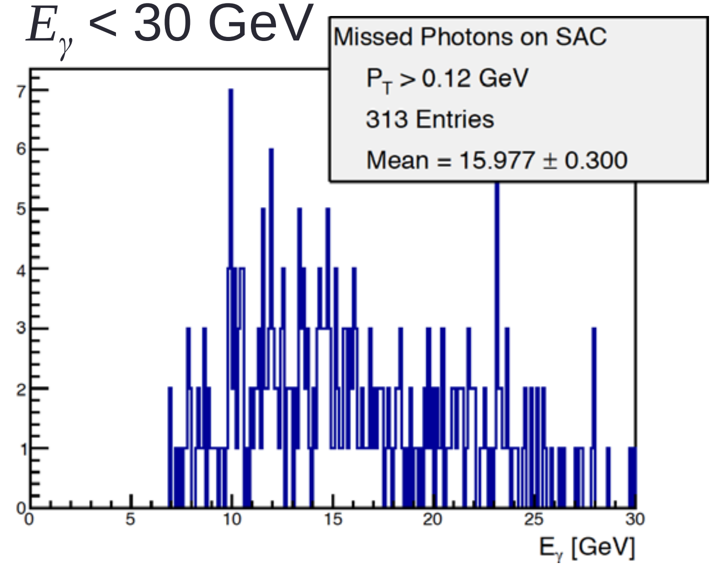
Energy of photons from $K_L \rightarrow \pi^0\pi^0$ on SAC after all cuts:

All photons



Detail:

E_γ < 30 GeV



90% of γs from K_L on SAC have 30 < E_γ < 250 GeV

- Need inefficiency < 10^{-4} for E_γ > 30 GeV
- Tolerate 1% inefficiency for E_γ < 30 GeV
- Can be blind for E_γ < 5 GeV

Baseline technology:

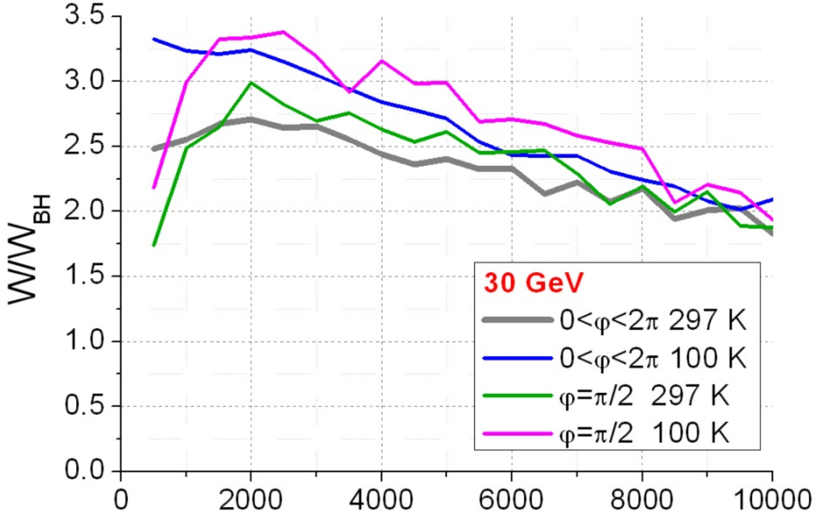
Compact W/Si sampling calorimeter

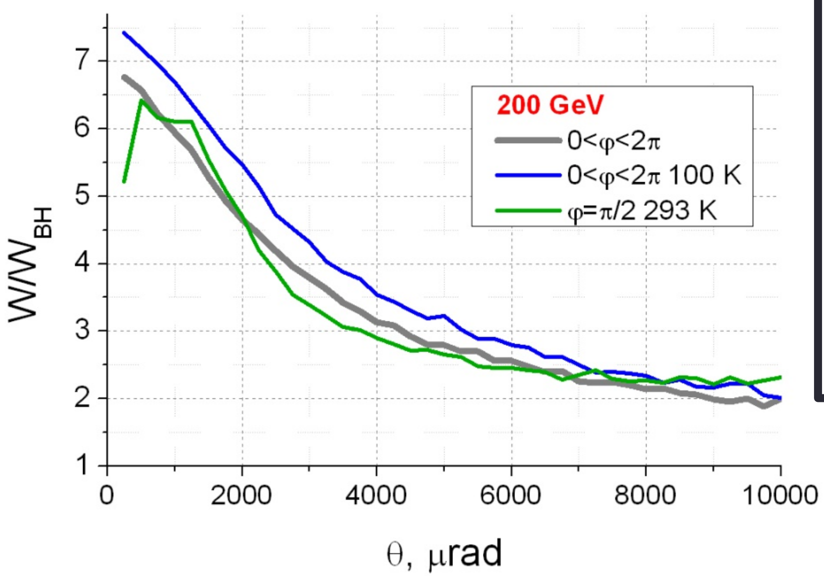
Courtesy of M. Moulson

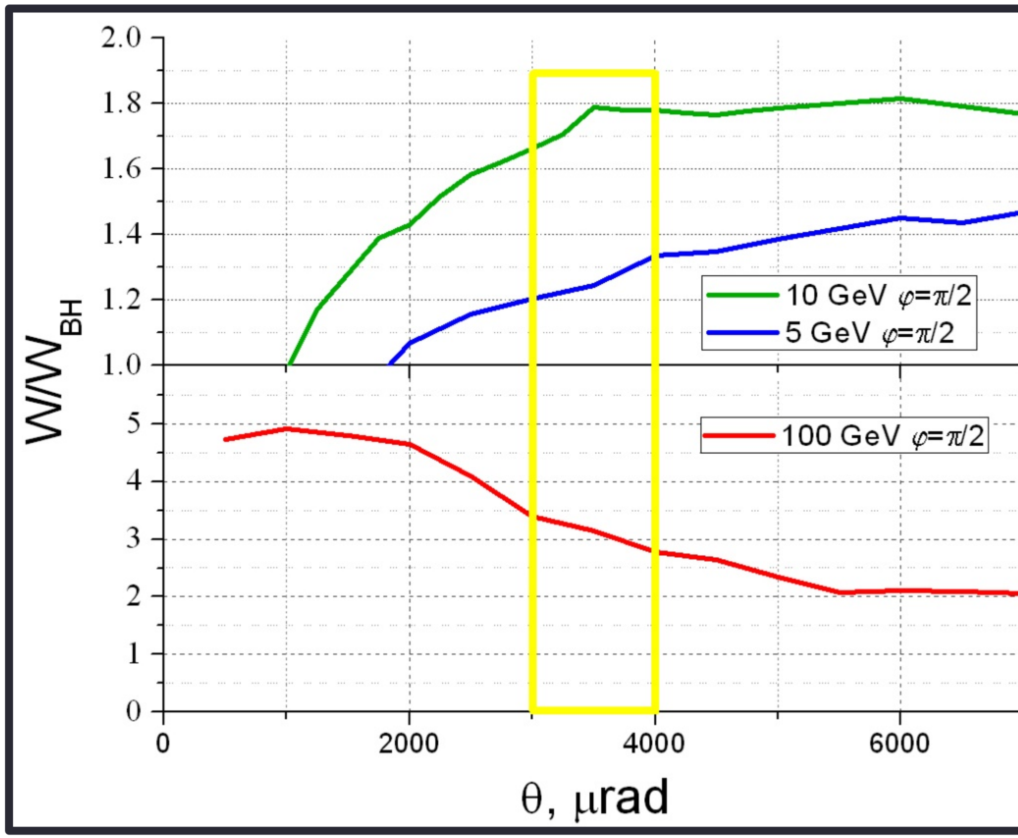
Crystal-based converter for Small Angle Calorimeter

- Reject high-energy γ_s from $K_L \rightarrow \pi^0\pi^0$
- The idea is to exploit coherent interactions in oriented crystals to obtain a converter with large effective λ_{int}/X_0 to convert γ_s while being relatively transparent to K_L
- This possibility follows the work of NA48 and the studies of NA43

PP in a W crystal vs. photon energy and incidence angle



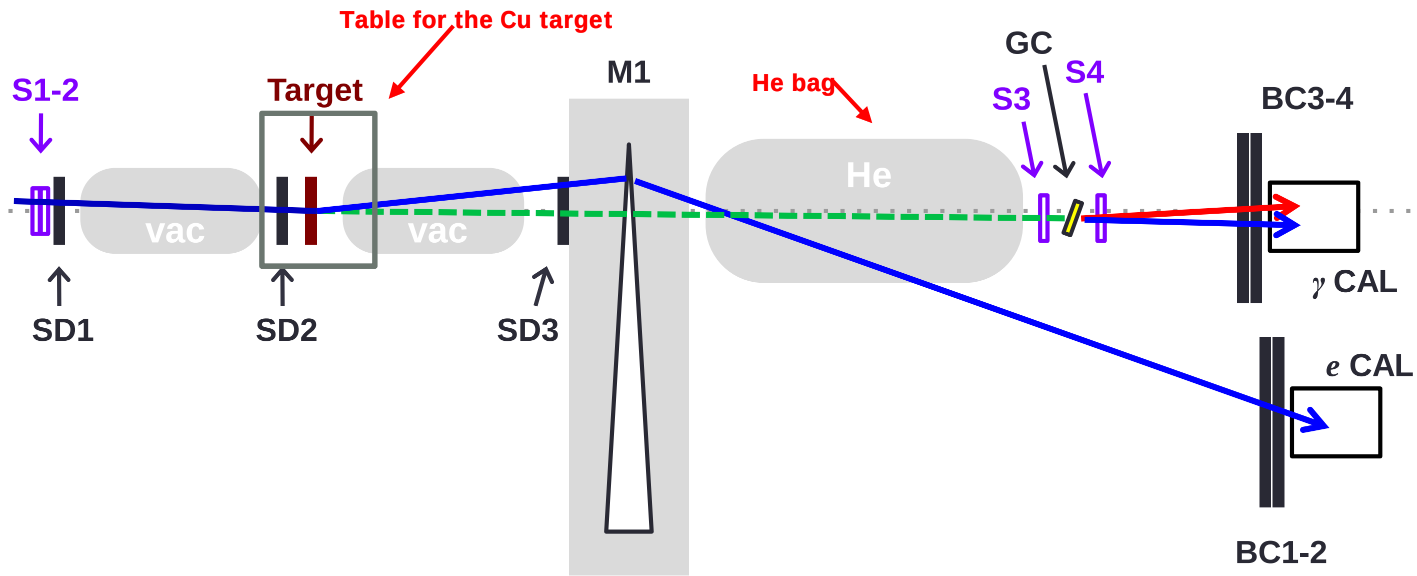


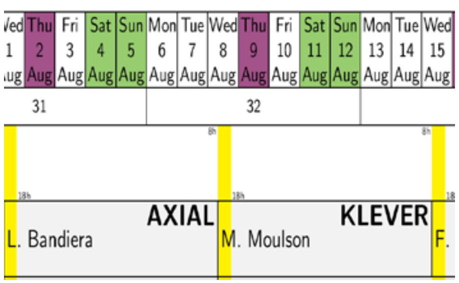


Courtesy of V.V. Tikhomirov

2018 Test Beam in NA@CERN SPS

Tagged photon beam setup for H2 test beam based on AXIAL:





Planned measurement in collaboration with AXIAL:

Using a high-energy tagged photon beam:

- Observe pair conversion enhancement with a tungsten crystal
- Measure pair conversion vs. Eγ, θ_{inc} for 5 < Eγ< 120 GeV
- Confirm theoretical predictions for tungsten

Supported by CSN1 & CSN5

PRIN 2017

Possible proposal for the type B call “under 40”

PI: L. Bandiera (INFN Fe)

Unit 1 INFN (From Ferrara L.Bandiera, A. Mazzolari…)

Unit 2 UniMarconi (M. Martini)

Premises for the project

- **Can these orientational effects be important also for inorganic scintillators used in HEP electromagnetic calorimeters?**

- The modern electromagnetic calorimeters are designed for experiments at energies of hundreds of GeV/TeV and these enhancement effects are expected to be quite important in this energy range.

We performed a new campaign of measurement to study the energy loss of hundreds GeV electrons in a lead tungstate at CERN [1,2].

[1] L. Bandiera e al., Contribution at EPS- HEP 2017 (5-12) July 2017, Venice (Italy).
[2] L. Bandiera et al., Contribution at IEEE Nuclear Science Symposium 2018 (21-28) October 2017, Atlanta (USA).

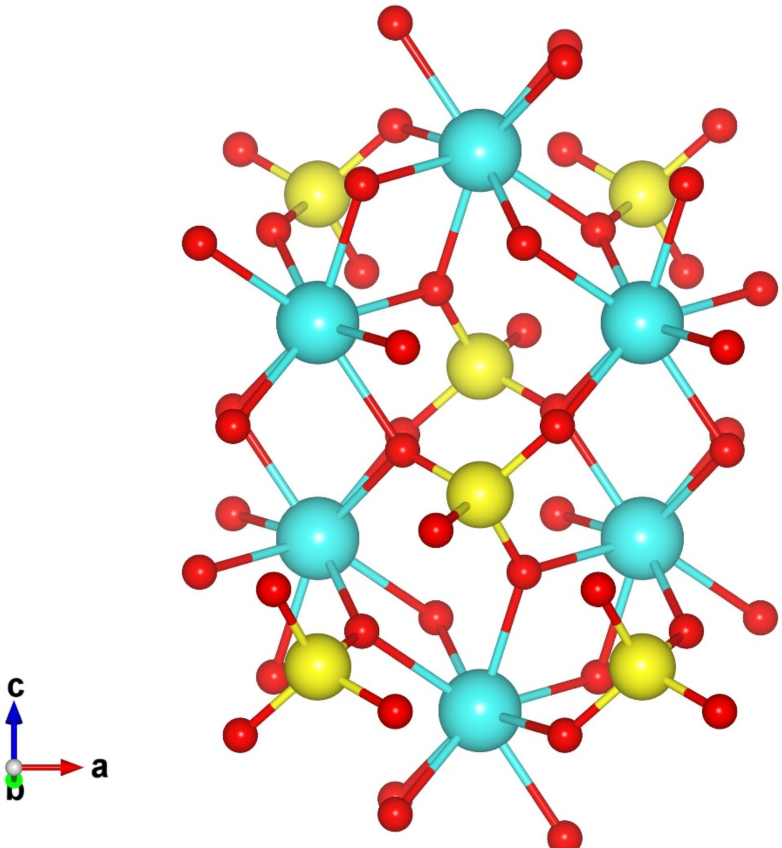
PWO as high-Z scintillator

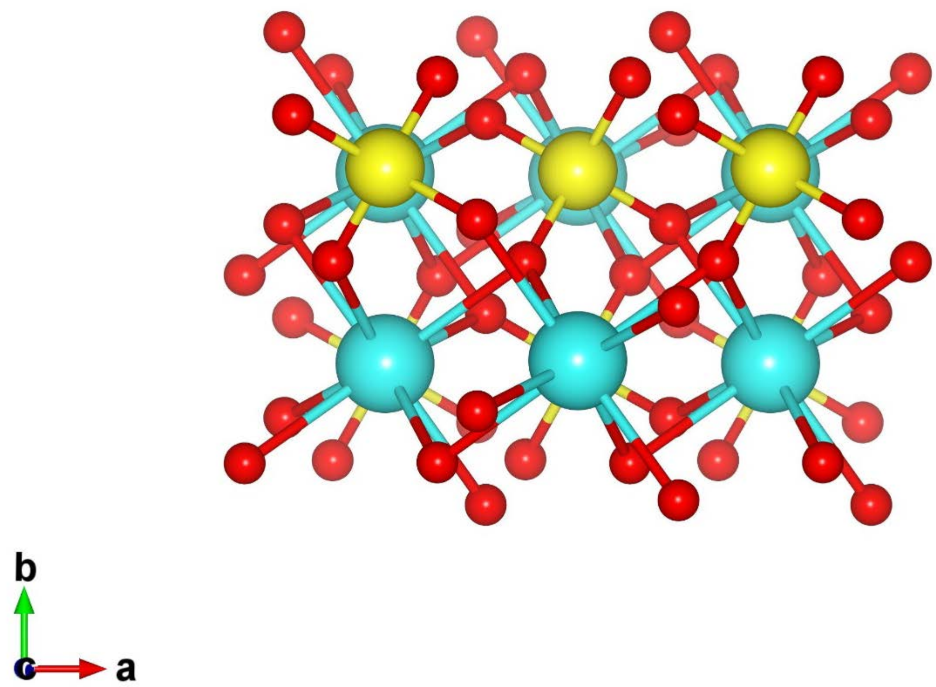
- $PbWO_4$ (PWO) scintillation crystals introduced by INP team in 1994 are currently used by CMS, ALICE, PANDA collaborations in EM calorimeters, about 100000 crystals in total has been produced.
- **PWO propreties:**
  - **Short radiation length (8.9 mm);**
  - **small Moliere Radius;**
  - **emission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

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).





PWO crystal

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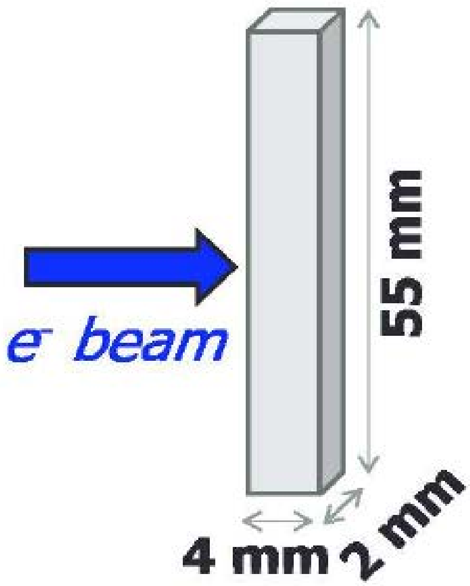

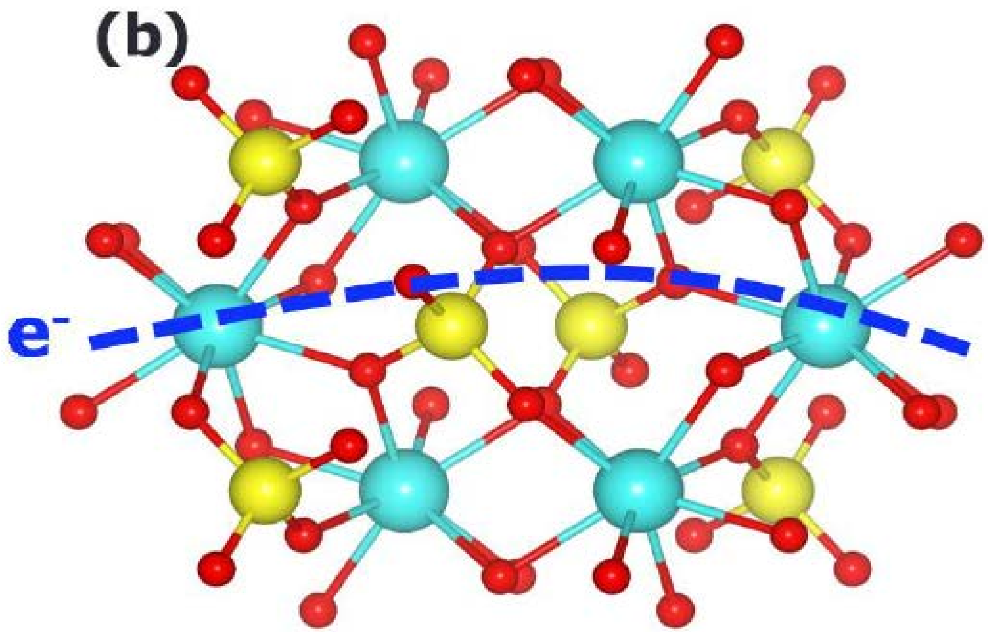

A 2x55x4 mm^3 strip-like PWO crystal with the largest faces oriented parallel to the (100) planes was selected for the experiment. **4 mm length** along the beam direction corresponds to about **0.45 X_0**.

An algorithm for radiation in crystals

Integration of the quasi-classical Baier-Katkov formula

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

The electromagnetic radiated energy is evaluated with the BK formula:

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

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

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SMALL ANGLE APPROXIMATION:

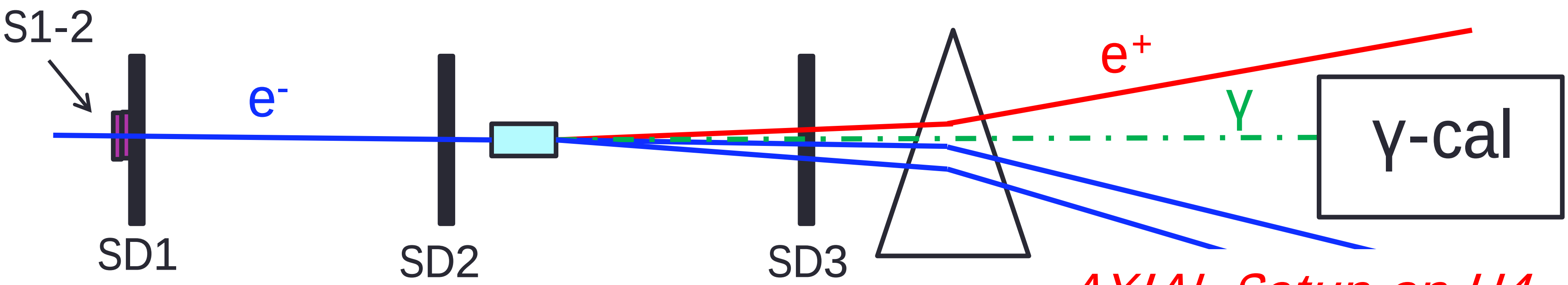
$$\frac{dE}{d^3k} \sim \frac{\alpha}{8\pi^2} \frac{\varepsilon^2 + \varepsilon'^2}{\varepsilon'^2} \omega^2 C, \qquad (2)$$

where

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

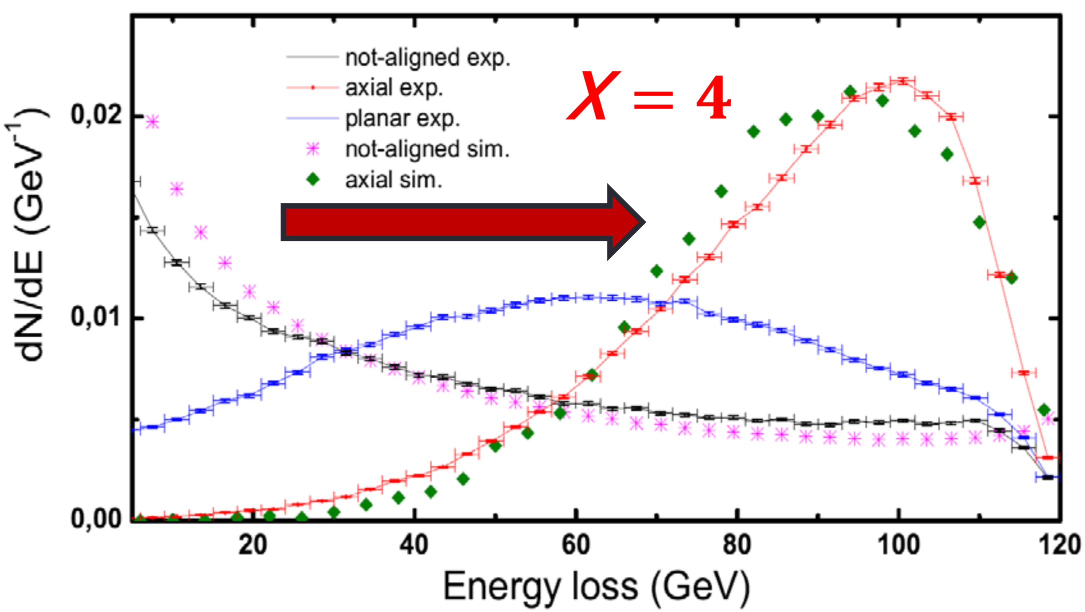
V. Guidi, L. Bandiera, V. Tikhomirov, Phys. Rev. A 86 (2012) 042903

ENERGY LOSS RADIATED



AXIAL Setup on H4

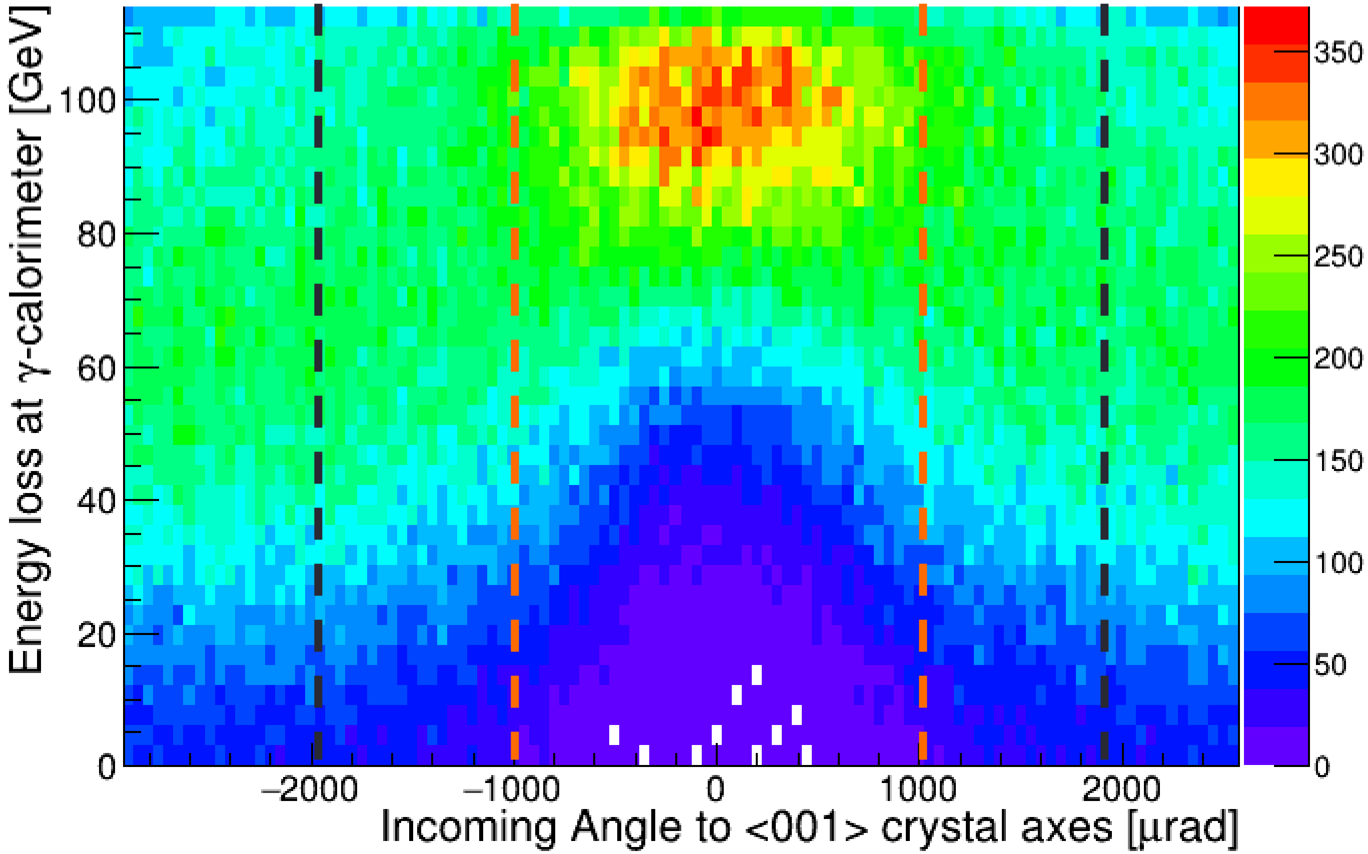
We selected single events on SD1-2 and collected the energy loss at the gamma-calorimeter.



Mean energy loss in photons:
~ 40 GeV not-aligned;
~ 85 GeV axial.

Strong reduction of X_0 in the oriented cases.

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)

Aims of the project

1. Study of the **modification of the electromagnetic shower in high-Z oriented crystals**: standard crystals (W for example) and scintillators (PWO, CsI, BGO, LYSO, ect ..). In the latter case, **studying in particular the emission of scintillation** light;

2. Creation of a **Monte Carlo that includes the reduction of X_0**. A code reproducing the bremsstrahlung increase has already been realized in collaboration with V. Tikhomirov (INP) and has well reproduced results of experiments made with Si crystals and electrons from 0.855 to 120 GeV;

3. Realization of a **prototype/module of calorimeter/preshower** based on oriented scintillator crystals and its test @CERN.

Study of possible applications

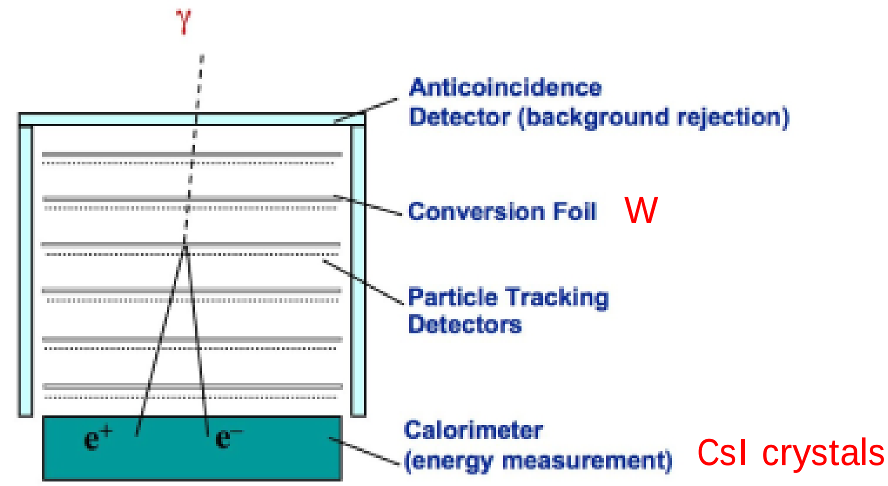
- **In HEP**: Realization of **forward calorimeters and preshowers**, as well as for **smart gamma-converters** for **fixed-target experiments** (interesting for KLEVER). Investigate possible applications of **X_0 reduction** in the research of light dark matter with fixed-target/beam dump experiments (*Collaboration with M. Raggi, UniSapienza –NA62 & PADME*).

- **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. *(Collaboration with S. Cutini, INFN Perugia - FERMI)*

Study of possible applications

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.



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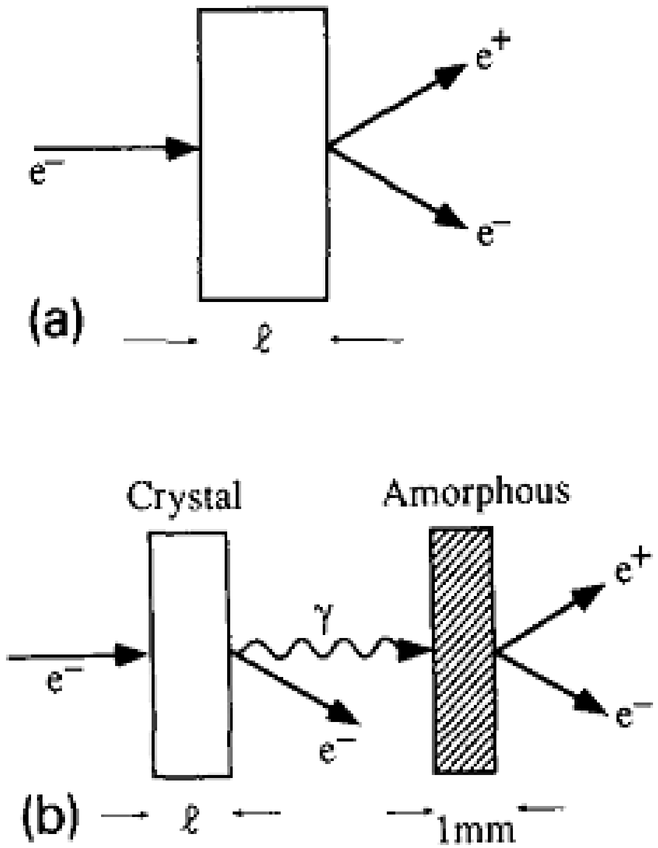
INNOVATIVE POSITRON SOURCE

CLIC, ILC, Muon Collider

Innovative positron source

Positron source using channeling in a tungsten crystal

X. Artru [a], V.N. Baier [b], R. Chehab [c,*], A. Jejcic [d]



(a) Solution attractive because both processes, channeling photon production and pair creation, occur in the same medium.

(b) Hybrid source may be of interest since the amorphous target in which pairs are produced can be heated more.

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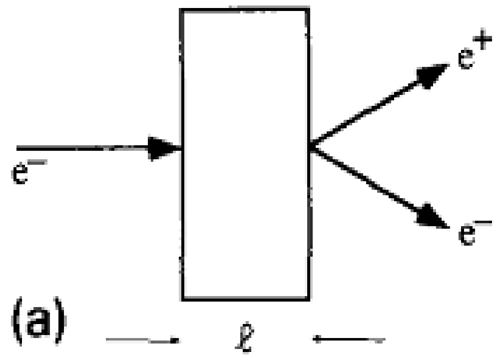

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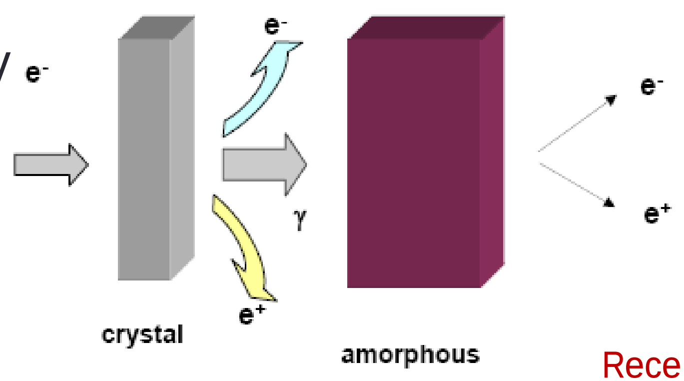
KEK 7 GeV e-



(b) Hybrid source may be of interest since the amorphous target in which pairs are produced can be heated more.

Recent test at KEK NIMB 402 (2017) 58 with a <111> W crystal

I.Chaikovska and R.Chehab (LAL Orsay) already involved in the Muon Collider group and would like to collaborate with the Ferrara group and V. Tikhomirov for further study.

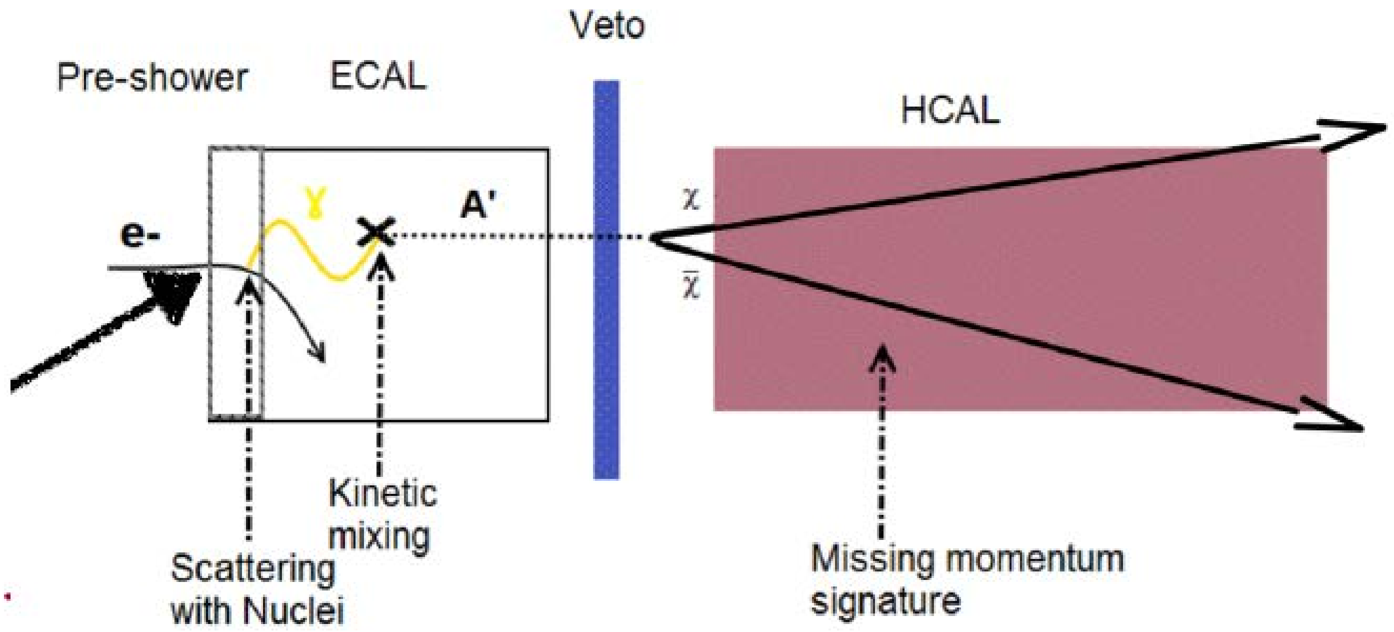
Summary

- Pair production enhancement in an axially oriented high-Z crystal (such as W) can be exploited for a gamma-converter with large λ_{int}/X_0 – KLEVER proposal;
- Reduction of X_0 in scintillator crystals can be investigated to realized compact calorimeters/preshowers for HEP and gamma-satellites – possible PRIN proposal;
- Intense synchrotron-like radiation in an aligned W crystal can be used to increase the yield for a positron source for future colliders – LAL proposal for linear and muon colliders.

THANK YOU FOR THE ATTENTION!

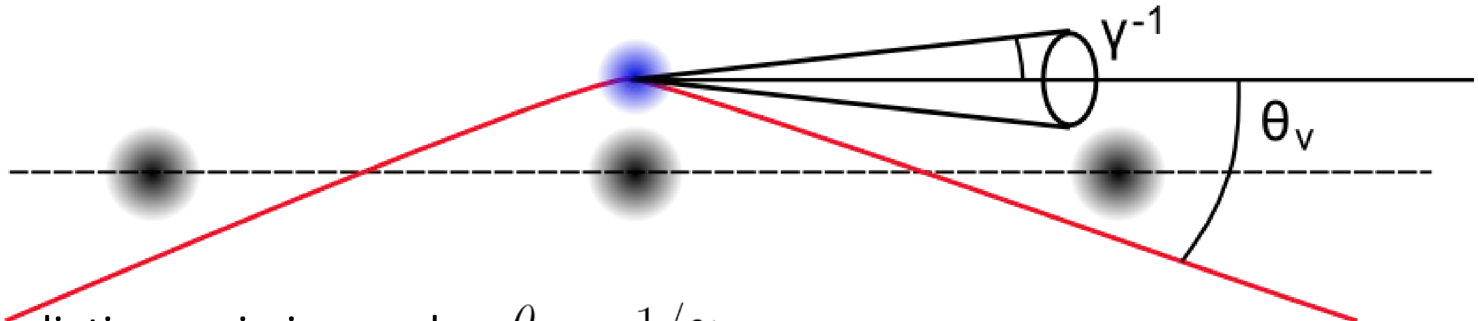
BACK UP SLIDES

NA64 missing energy



Synchrotron-like radiation in crystals

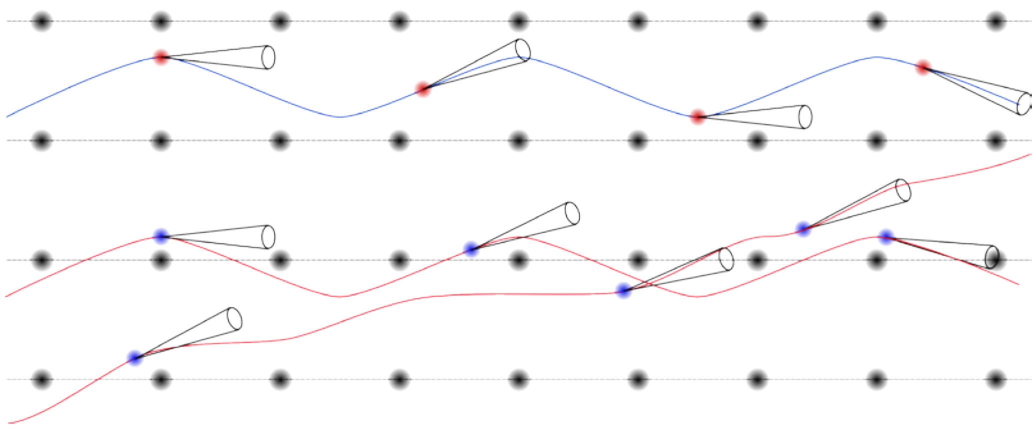
At energies of >10 GeV



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

Deflection angle: $\theta_v = V_0/m$

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



"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 $X = \gamma E/E_0 \geq 1$ – 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.

An algorithm for radiation in crystals

Integration of the Baier-Katkov formula

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.

SMALL ANGLE APPROXIMATION: Since the angle between particle trajectories and crystal planes or axes is small and at ultrarelativistic energies the radiation angle $1/\gamma$ is much smaller than unity, the formula (1) can be rewritten as:

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

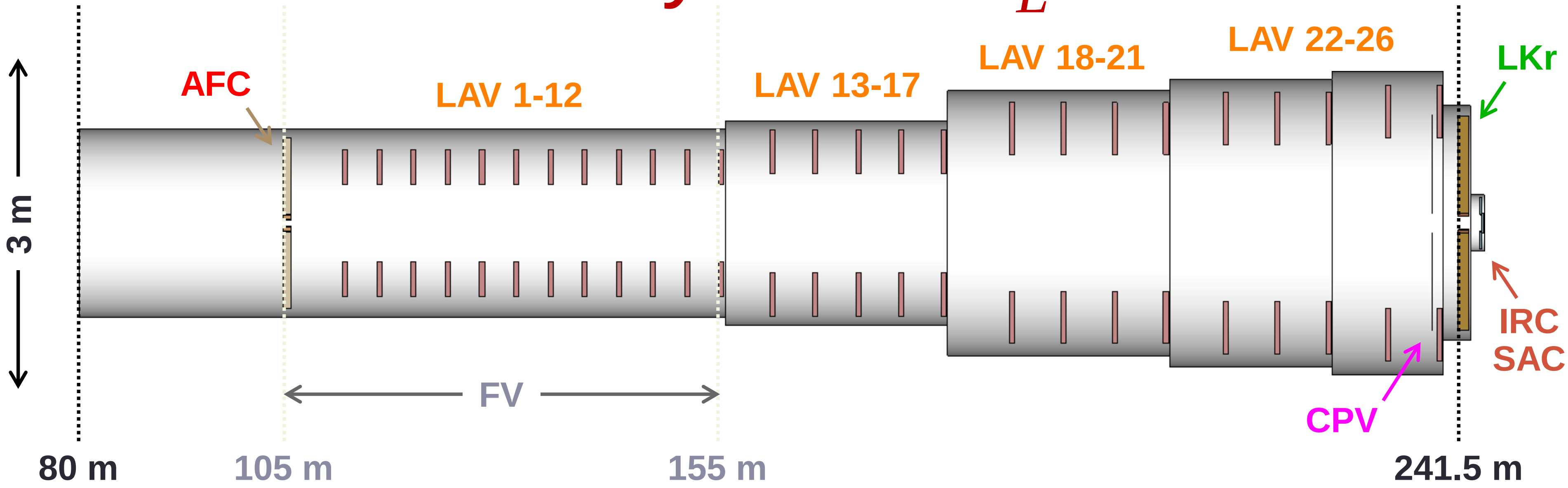
where $$C = \mid \boldsymbol{I}_\perp \mid^2 + \gamma^{-2} \frac{\omega^2}{\varepsilon^2 + \varepsilon'^2} \mid J \mid^2 \qquad (3)$$

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

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

L. Bandiera, et al., Nucl. Instrum. Methods Phys. Res., Sect. B 355, 44 (2015).

Detector layout for $K_L \to \pi^0 \nu\nu$

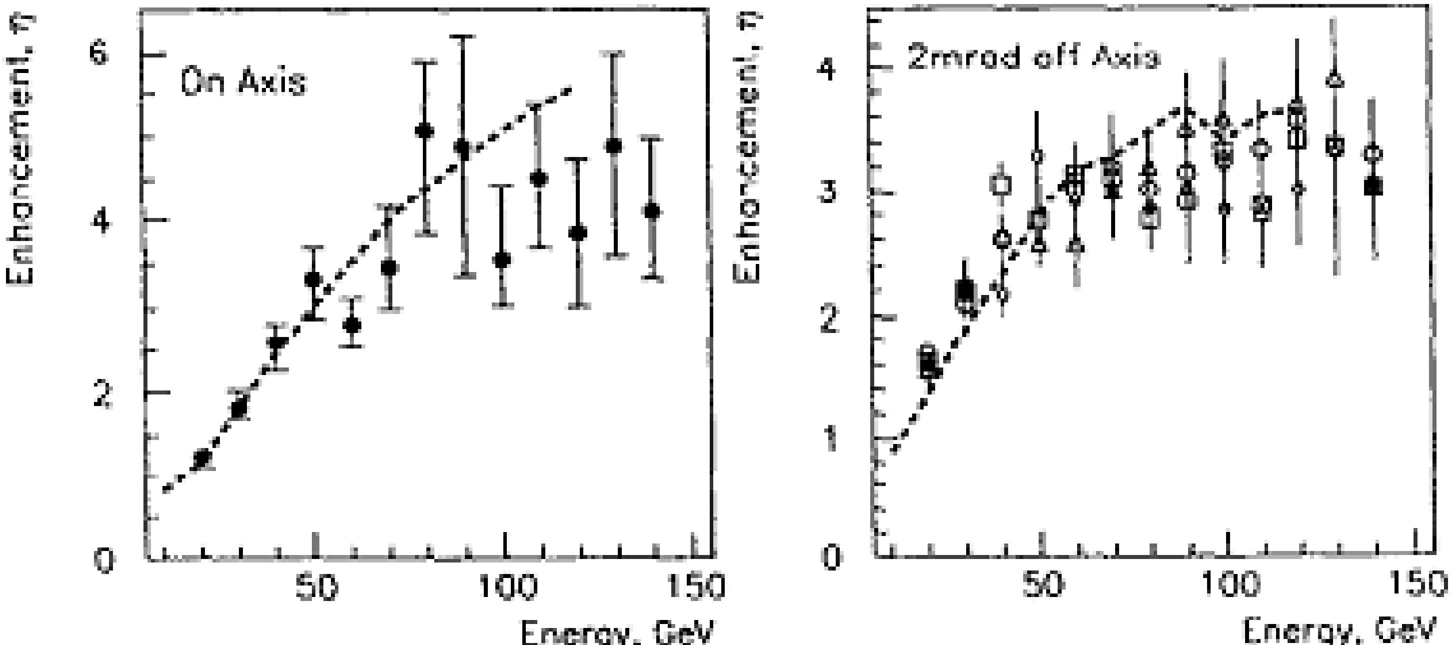


Main detector/veto systems:

AFC	Active final collimator/upstream veto
LAV1-26	Large-angle vetoes (26 stations)
LKr	NA48 LKr calorimeter
IRC/SAC	Small-angle vetoes (SAC in neutral beam)
CPV	Charged-particle veto

Courtesy of M. Moulson

… also to Pair Production



Measurement of pair-production by high energy photons in an aligned tungsten crystal

R. Moore Nuclear Instruments and Methods in Physics Research B 119 (1996) 149-155

Tungsten gamma-converter – study for NA48