EPSI R&D: Developing an Innovative Electron-Positron Discrimination Technique for Space Applications

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on behalf of the EPSI collaboration

EPS-HEP 2025
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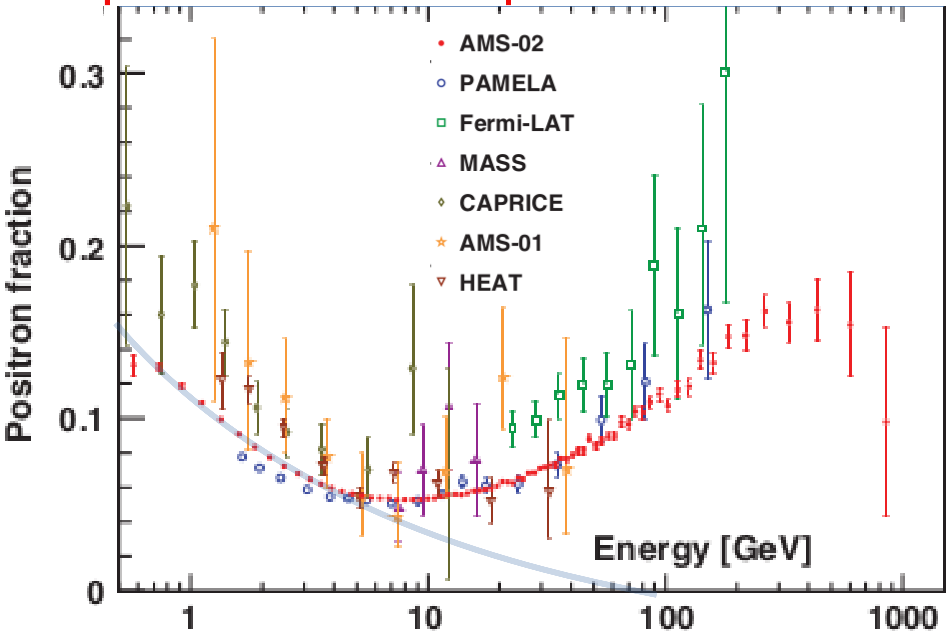
Motivation

Positron Fraction
(PAMELA, AMS-02, Fermi-LAT)
Spectrometric experiments

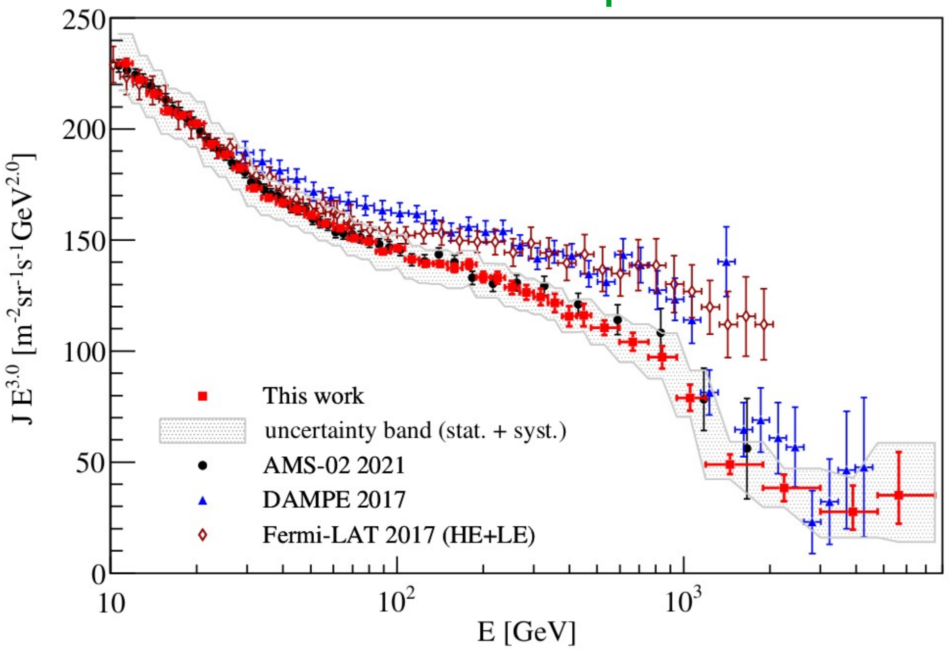


Positron excess with respect to pure secondary production may indicate the possible presence of a primary positron source (Pulsar/SNR/DM?): To better understand this excess, it is important to extend the current measurement above 1 TeV

Spectrometer-based experiments are ideal for this measurement but are limited in energy by technological issues, which may be overcame in the long term only by complex instruments like the ones proposed by ALADInO/AMS100 projects

Motivation

Electron+Positron Flux
(CALET, DAMPE,... HERD)
Calorimetric experiments

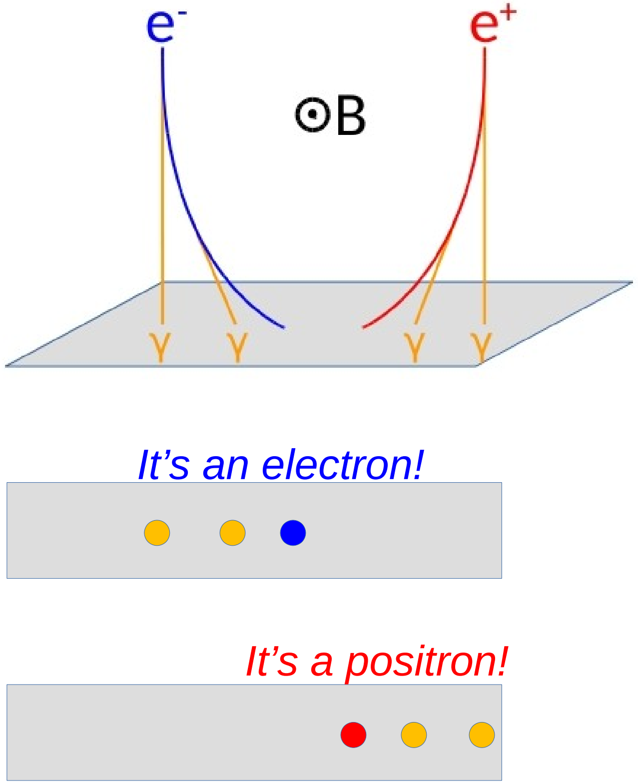


Calorimeter-based experiments are ideal for the extension of the current measurements to higher energies, hence present (CALET, DAMPE) and near-future (HERD) experiments will be based on a large calorimetric instrument

However, calorimeter-based experiments can*not* intrinsically distinguish electrons from positrons: the electron+positron flux can be measured, but the information that we can get on the positron excess is very indirect and uncertain.

Goal Develop a electron-positron discrimination technique that can be employed in a calorimeter-based experiment

Basic Idea



Since cosmic-ray experiments typically operate in Low Earth Orbits (LEO), we can exploit the particle bending due to the **geomagnetic field**

Knowing the structure of the geomagnetic field in a given point of the orbit, the simultaneous detection of the electron/positron and the emitted **synchrotron photons** is enough to univocally identify the charge sign of the detected particle.

Is it a new idea?

Originally proposed in 1972!

THE POSSIBILITY OF REGISTERING PRIMARY COSMIC ELECTRONS BY MEANS OF SYNCHROTRON RADIATION IN THE GEOMAGNETIC FIELD

O.F. Prilutskii
Moscow Engineering Physics Institute
Submitted 22 August 1972
ZhETF Pis. Red. 16, No. 8, 452 - 454 (20 October 1972)

Further development Stephens and Balasubrahmanyan
Journal of Geophysical Research: Space Physics 88.A10 (1983): 7811-7822

Several R&D and projects

This list may be incomplete!

AMS Hofer and Pohl *NIM A 416(1):59–63, 1998*

SRD Hofer, Kräber and Viertel *Nuclear Physics B 134:202-207, 2004*

CREST Yagi et al. *International Cosmic Ray Conference 2005, 3:425-428, 2005*

Sonya Galper, et al. *Journal of Physics: Conference Series, 798(1):012176, 2017*

NO!

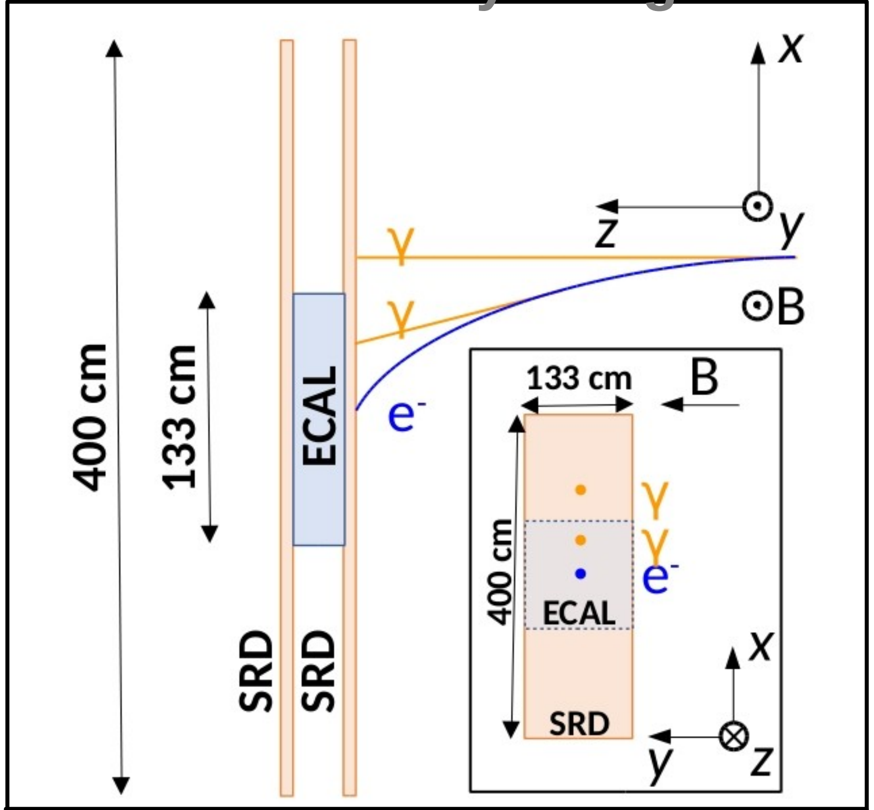
So what is new?

Most of past projects use a *calorimeter* mainly for instrument trigger and background-rejection, whereas the electron energy is reconstructed mainly (or only) using synchrotron photons

The **AMS** project use ECAL to reconstruct electron energy but in a spectrometer-based geometry

The ***EPSI*** project aims to use synchrotron photons just for *electron/positron discrimination* and exploit the advantages of a large ECAL in terms of resolution and acceptance with a novel design

Preliminary design



This is just a starting point to study the detection process, without considering a specific geometry of a future instrument

Detector geometry

Preliminary design

ECAL

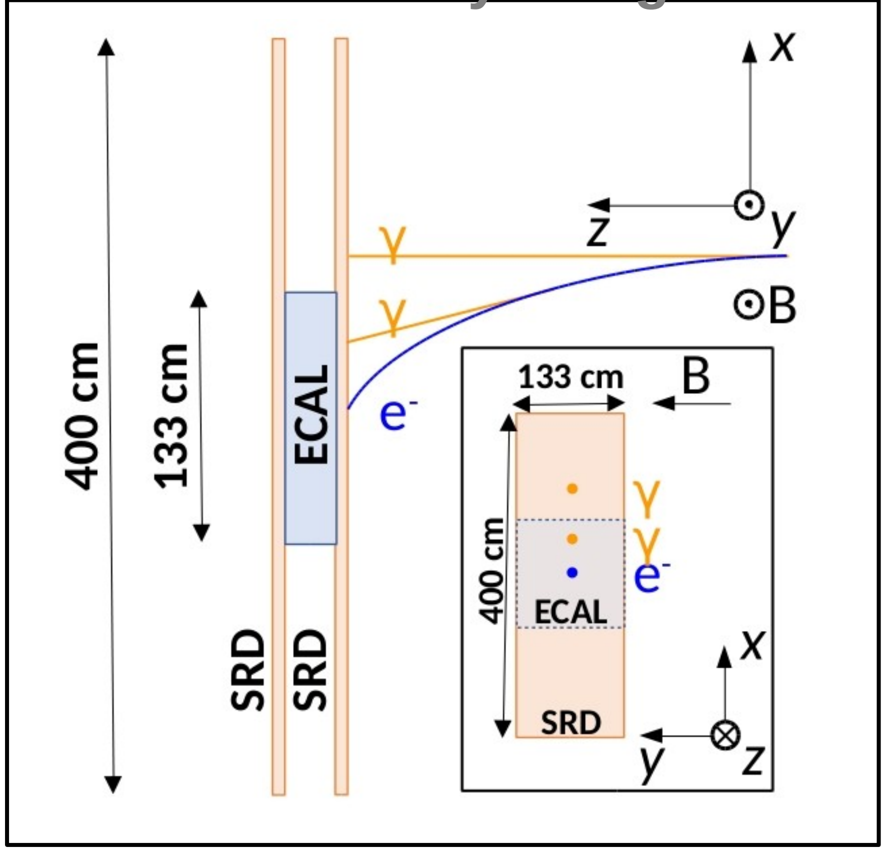
Electromagnetic CALorimeter

Main Purposes

- Energy reconstruction
- Track reconstruction
- E/H discrimination
- Instrument trigger

Possible implementation

- Fine granularity
- CsI+PD single cell
- 1.33x1.33x0.25 m^3
- Assuming 2 tons



SRD

Synchrotron Radiation Detector

Main Purposes

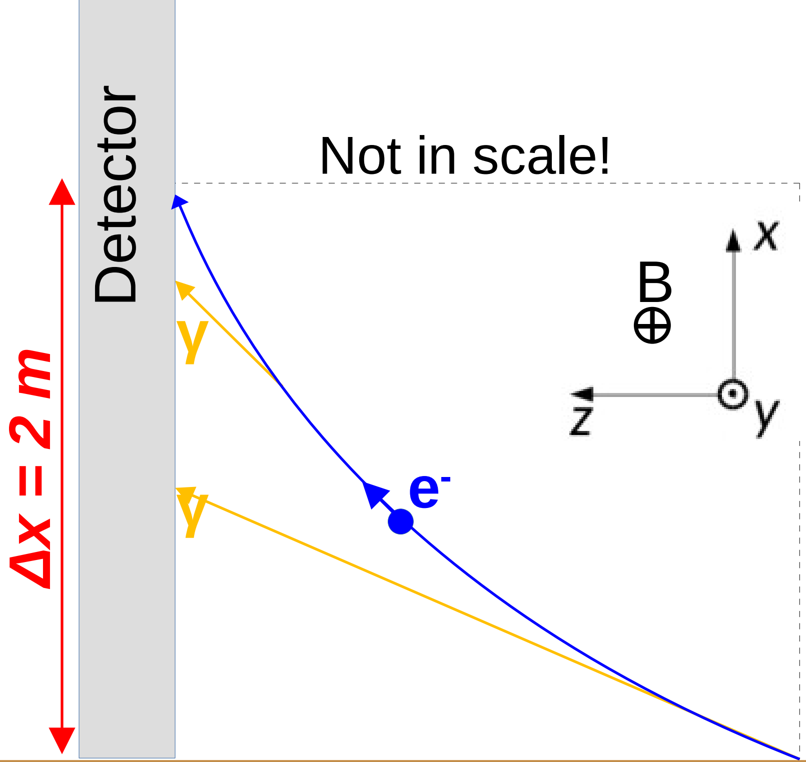
- Synchrotron photons
- Point reconstruction
- Energy reconstruction for e^-/e^+ discrimination

Possible implementation

- Fine granularity
- Crystal+SiPM single cell
- 2 opposite single layers
- Surface of 4x1.33 m^2

Detector requirements

Let us consider a 1 TeV electron, perpendicular to a 0.4 G field, impinging at detector center



The average number of photons reaching the detector is

$<N> = 4.51$

having a critical energy of synchrotron emission of

$\varepsilon_C = 26.78\ keV$

$<N> \propto \sqrt{E}$

$\varepsilon_C \propto E^2$

$E_{electron}$	<N>	ε_c [keV]
500 GeV	3.19	6.69
1 TeV	4.51	26.78
10 TeV	14.28	2677.60

Since at least two synchrotron photons are necessary to identify the charge sign, a **high detection efficiency** in the **soft X-ray region** is necessary, while keeping the *cost* limited in order to scale the device to a large area

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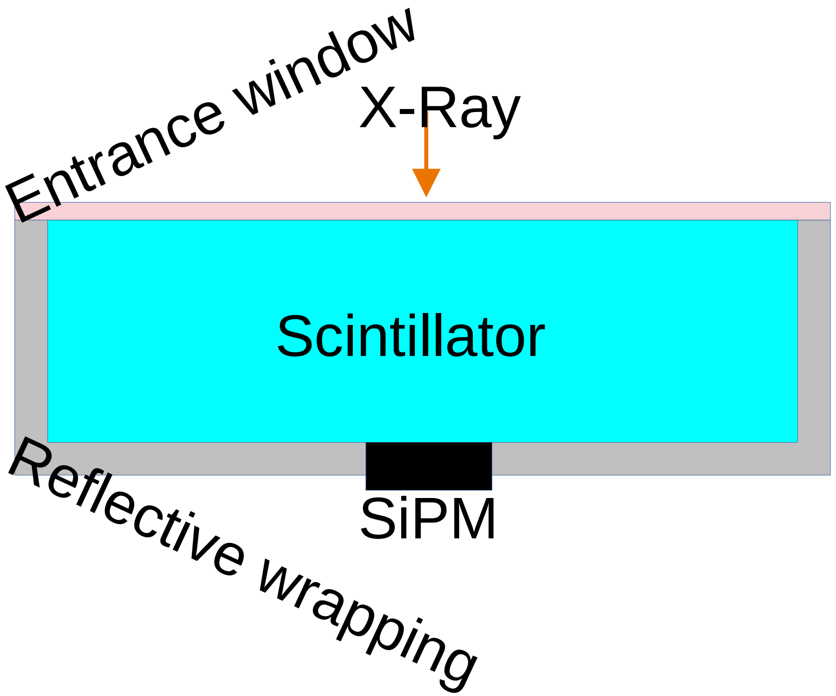
GOAL: High detection efficiency for X-rays with energy *1-100 keV*

Detector development

*Scintillator **size** of about 2cm x 2cm x 2.5mm*

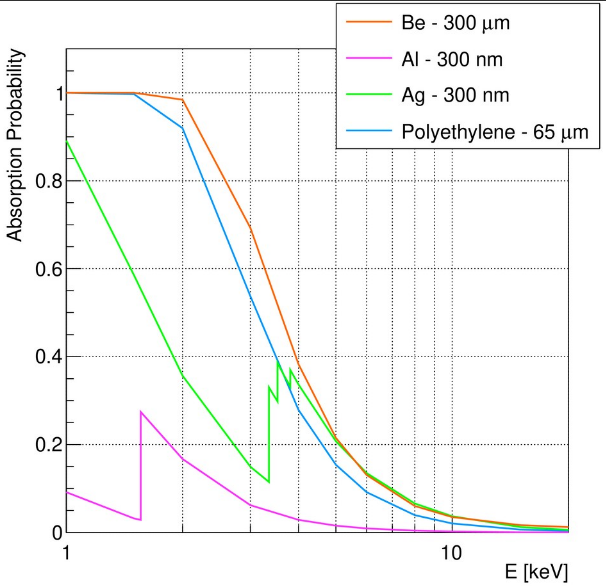


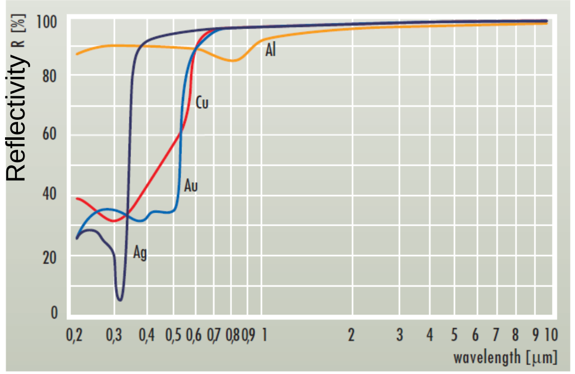
*Need of high <u>light-yield</u> and possibly fast **crystals***

	Light Yield [γ/MeV]	Decay Time [ns]
CsI(Tl)	54000	900
GAGG(Ce)	60000	<150

*Need of a large-area and high <u>photodetection efficiency</u> **SiPM***

*Need of high <u>reflectivity</u> and low <u>X-absorption</u> **coating***





Scintillator ***size*** of about 2cm x 2cm x 2.5mm

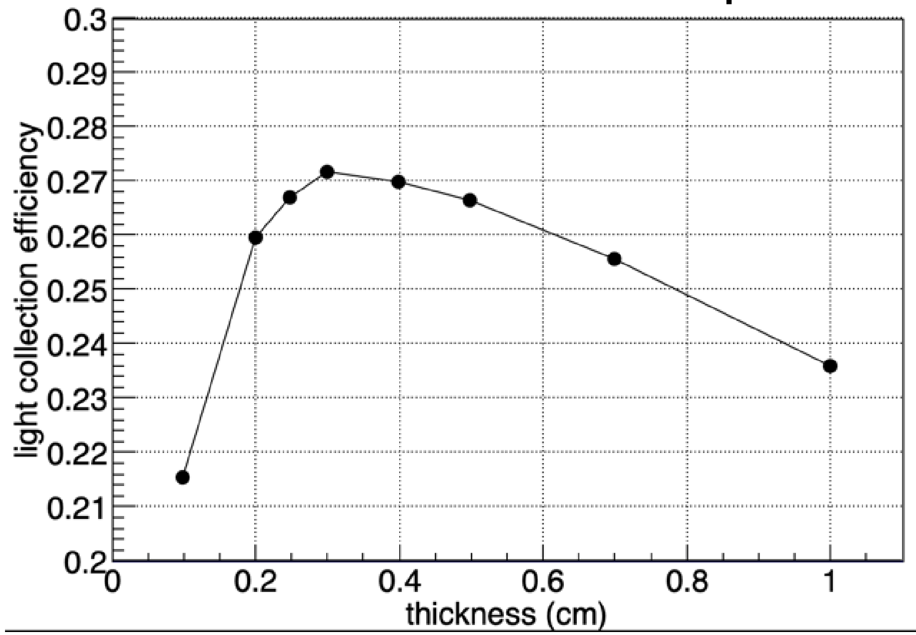
Cell size

Area

Synchrotron photons can be separated by astrophysical background since they lie on the *electron bending plane* with a RMS dispersion of 9.3 mm (for a 1 TeV electron in a 0.4 G field)

A segmentation of 2cm x 2cm is a reasonable compromise between background rejection and number of channels

Optical simulation of a 10 keV X-ray for different detector depths



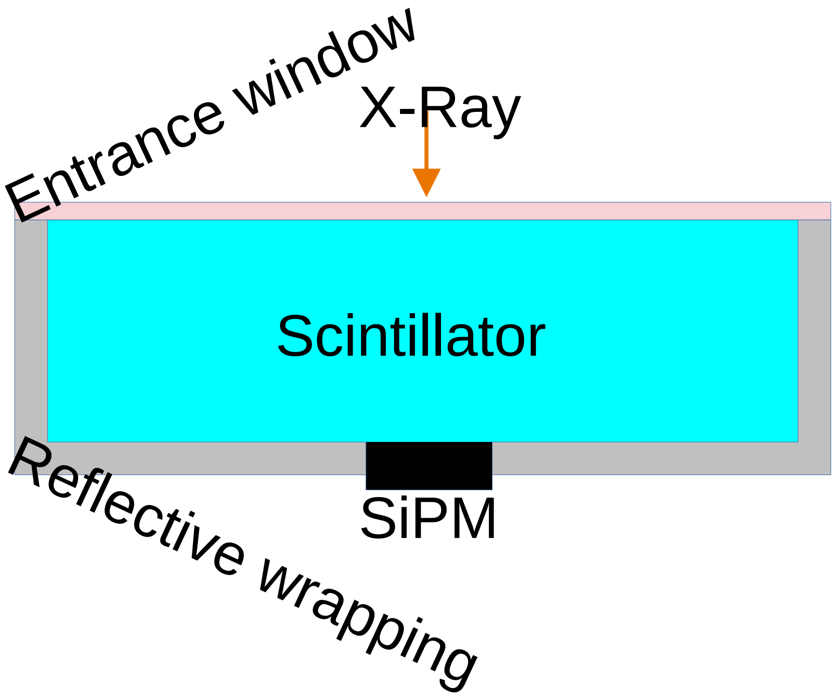
Thickness

A depth of 3 mm maximizes photon collection efficiency against self-absorption in the crystal and optical photon losses at crystal edges

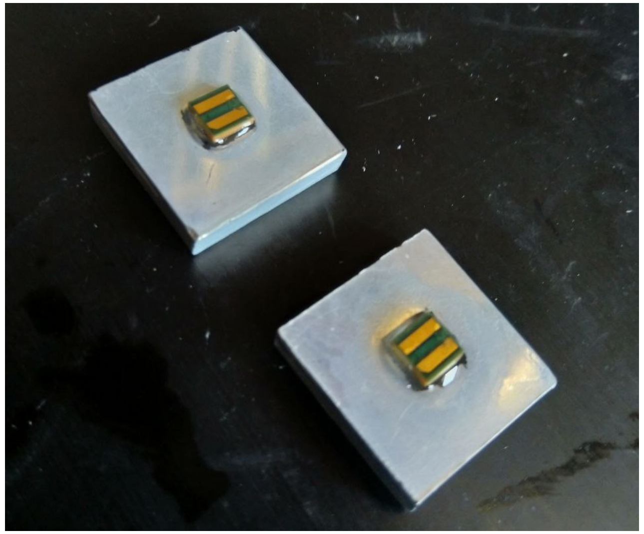
Need of high <u>reflectivity</u> and low <u>X-absorption</u> ***coating***

Cell coating

In all tests we made so far, we wrapped scintillator with <u>Vikuiti ESR</u> (reflectivity>98%) but in future we will use a thin Al deposition (500 nm) as the entrance window



CsI:Tl crystals covered by 300 nm Al deposit



We tested <u>Al deposition</u> on spare crystals by using our *sputtering machine*: deposition was successful, but we have to characterize the CsI-Al optical properties

Different <u>roughness of crystal surface</u> will be tested in laboratory and with simulations to maximize light collection efficiency

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Ministero dell'Università e della Ricerca

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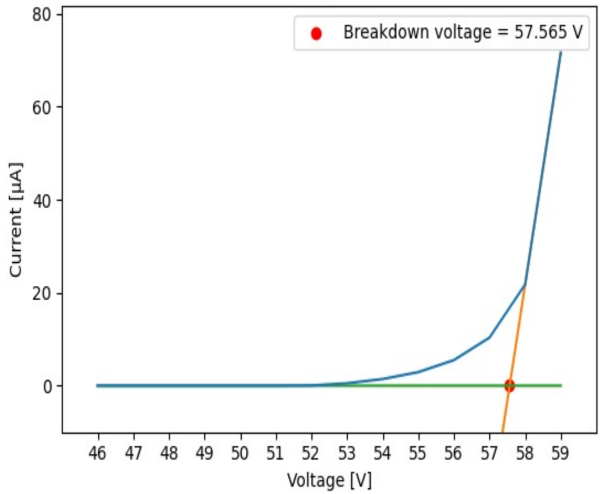
Need of a large-area and high <u>photodetection efficiency</u> ***SiPM***

Cell sensor

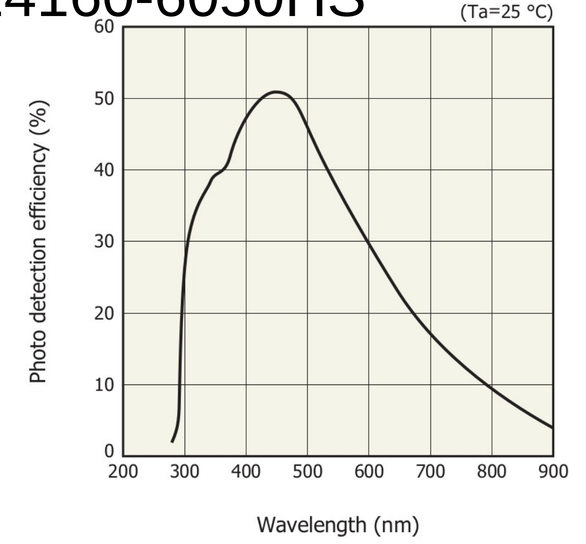
Test 6mmx6mm SiPM:
- S13360-6075PE
- S14160-6050HS

Full characterization of SiPM in terms of Photon Detection Efficiency and Dark Count as a function of overvoltage and temperature in order to:
- define the best candidate
- define optimal overvoltage

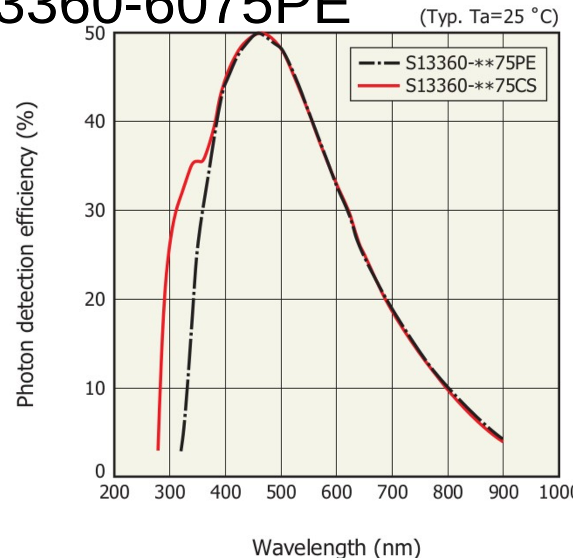
IV characterization in climatic chamber



S14160-6050HS

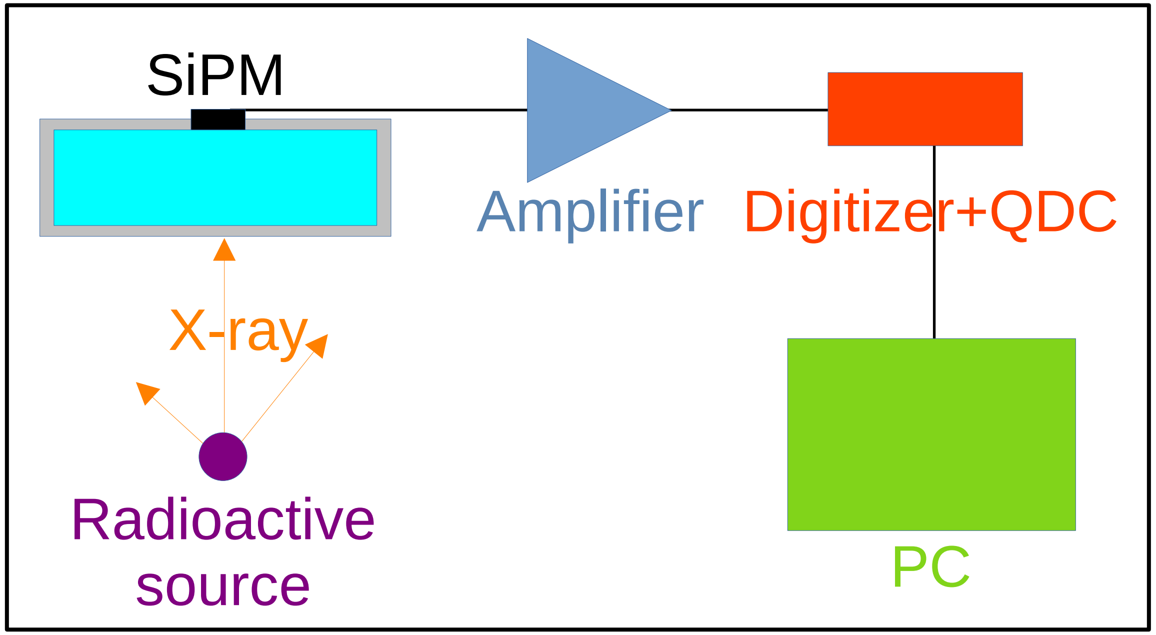


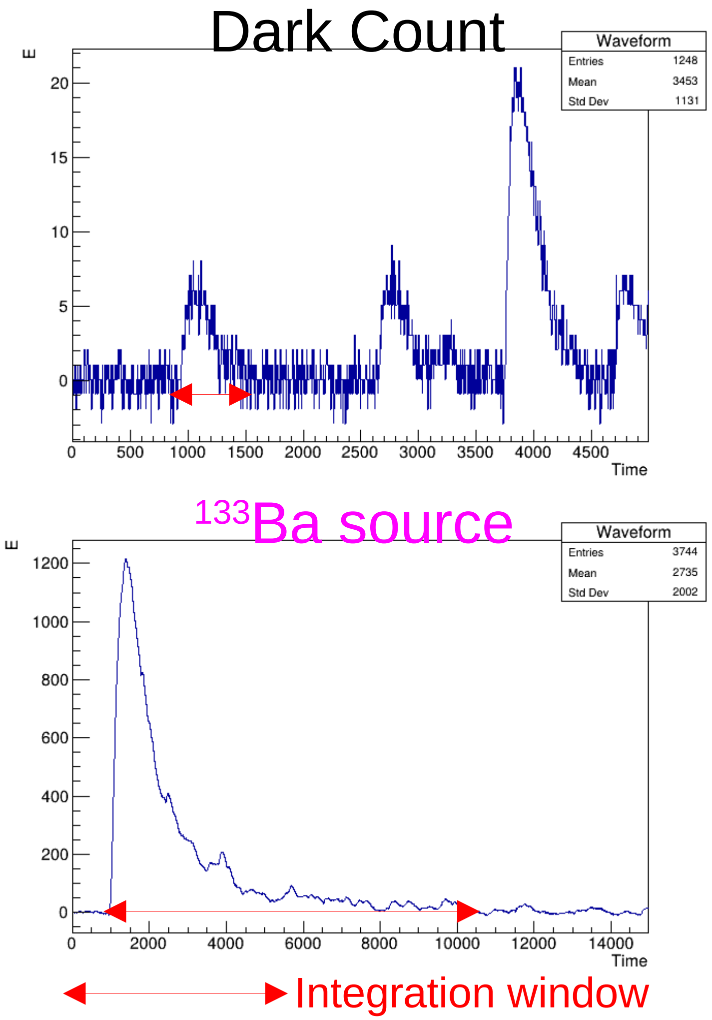
S13360-6075PE



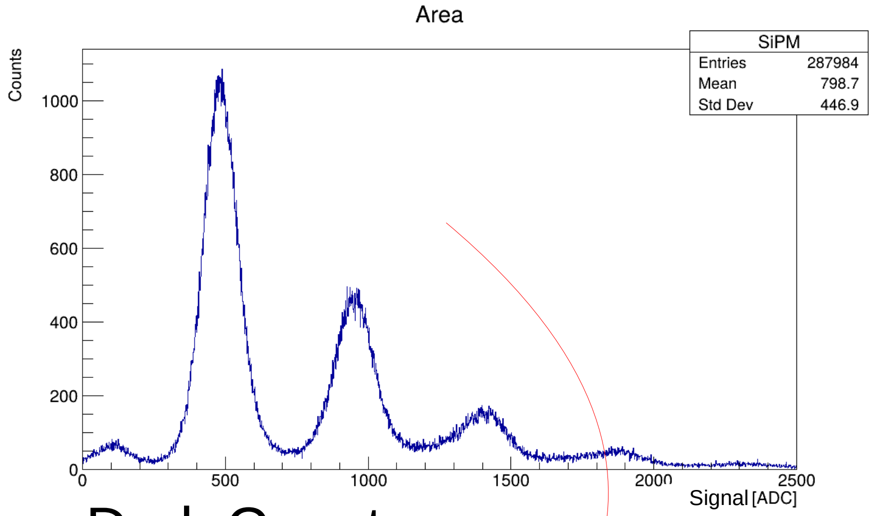
Laboratory system

To estimate *light collection efficiency*, laboratory system must be able to detect dark count distribution to express X-ray signal in terms of SiPM cell signal (*cells*)

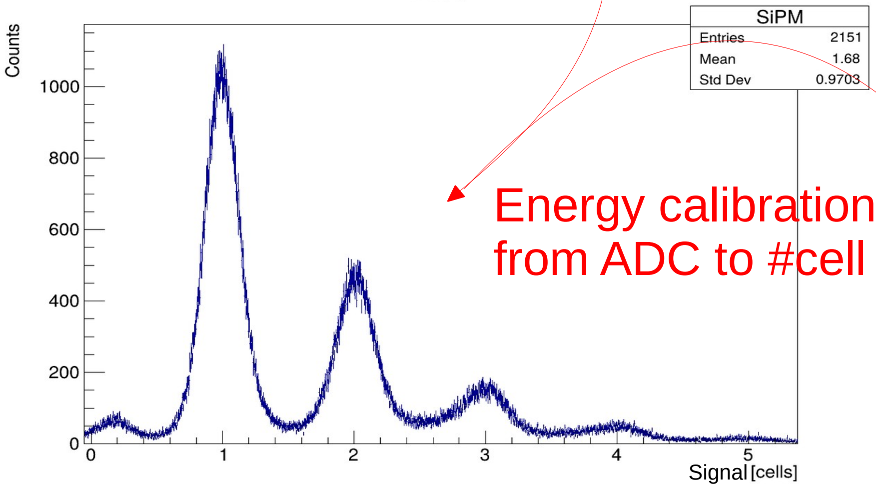




Pedestal and signal

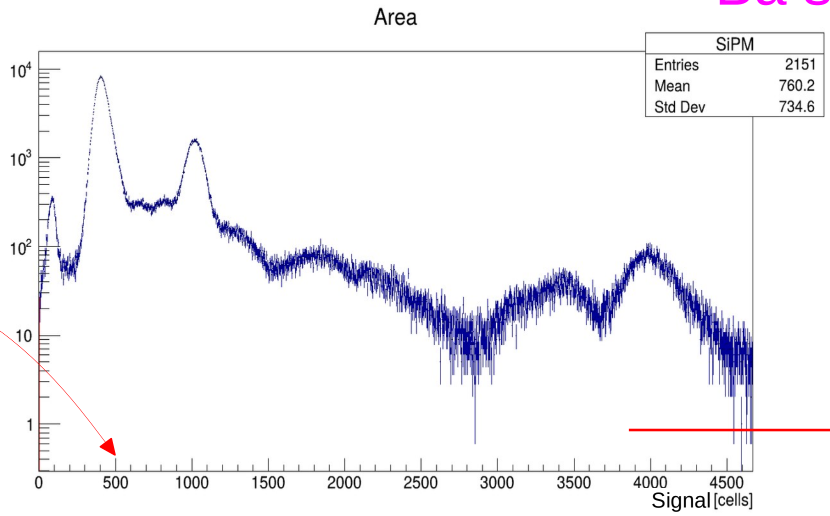


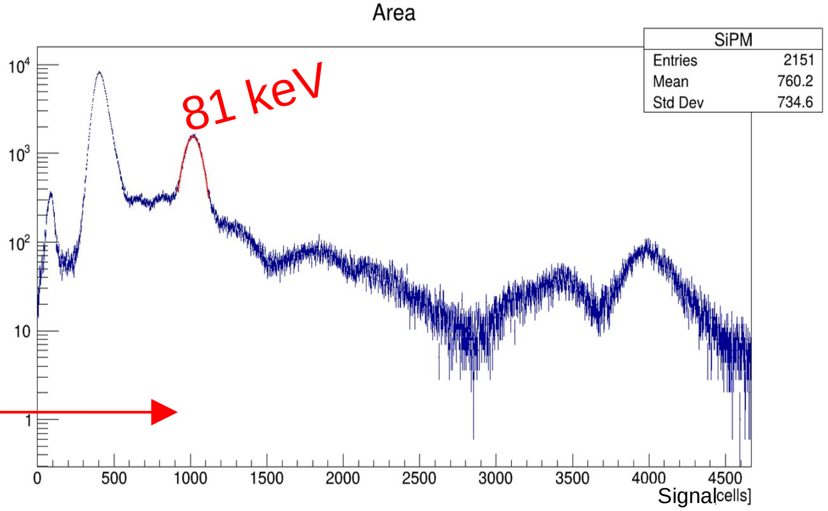
Dark Count



Energy calibration from ADC to #cell

^{133}Ba source

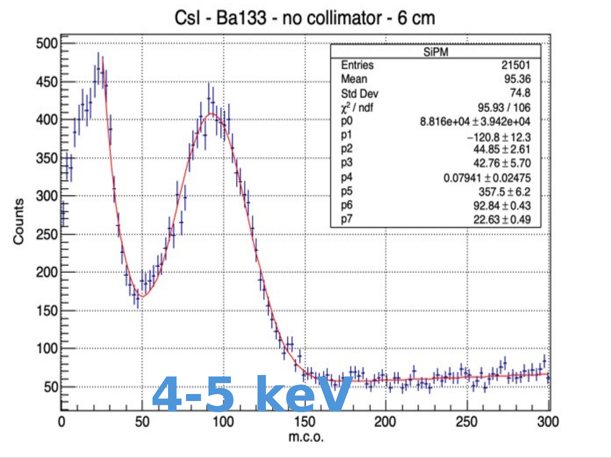


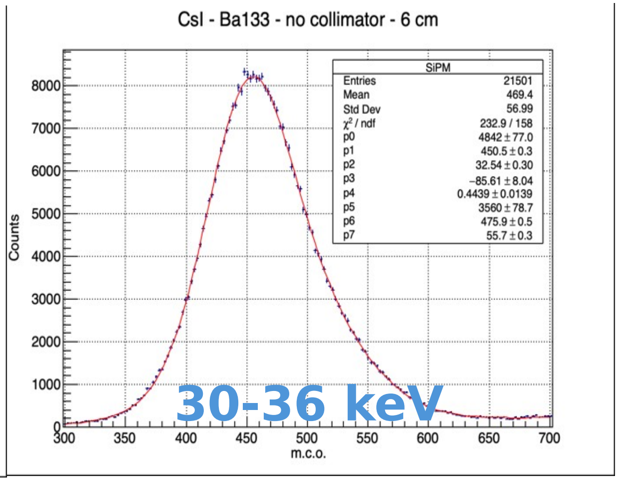


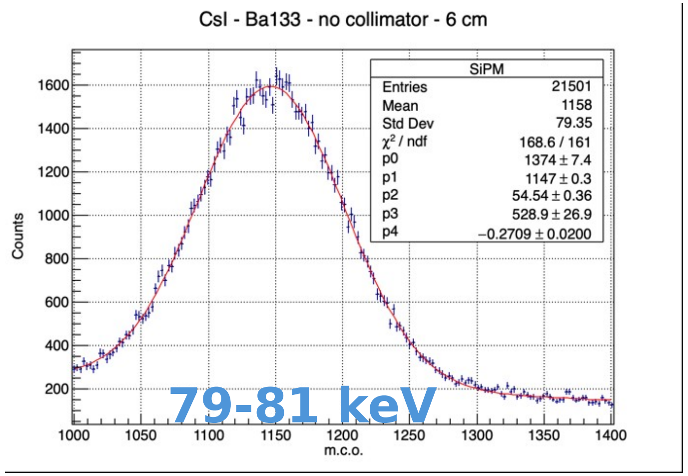
Gaussian fit to extract mean and RMS

CsI:Tl response

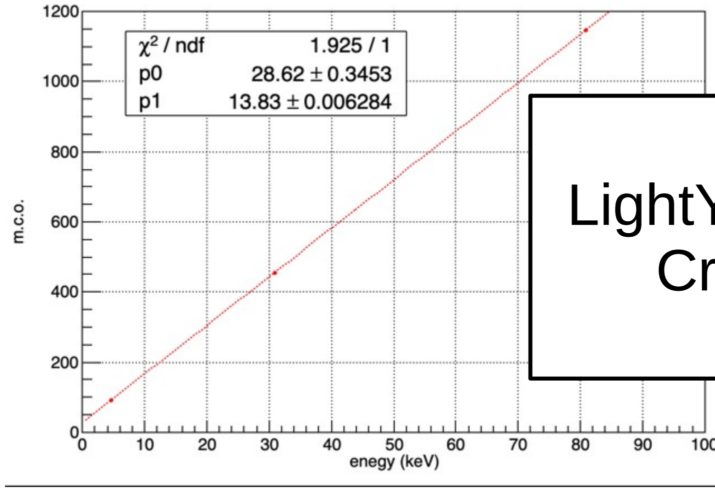
Preliminary







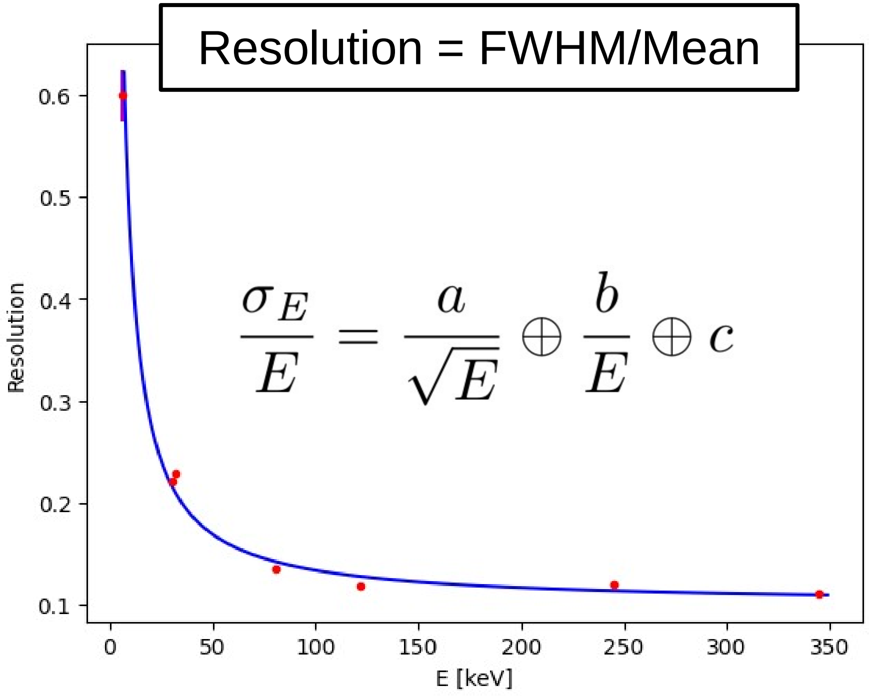
Good linearity at low energy



Considering:
LightYield = 54 ph / keV
CrossTalk = 55%
PDE = 40%

Light collection efficiency = 35-40%

CsI:Tl response

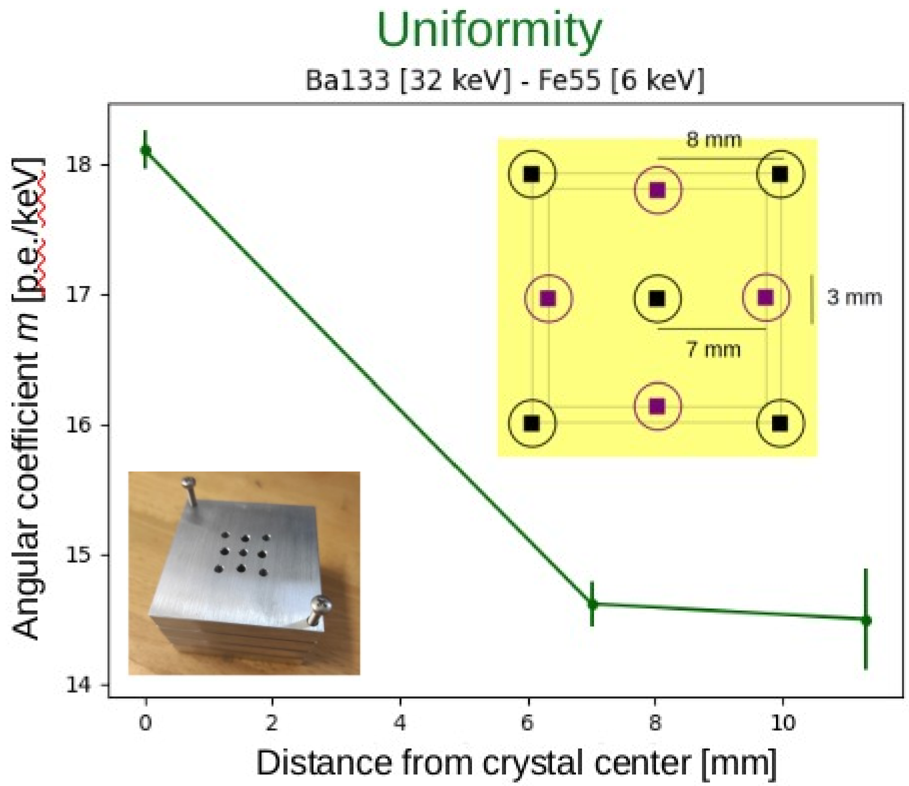


E [keV]	Resolution*100				
6.03	59.88	+/-	2.53		
30.85	22.06	+/-	0.34		
32.06	22.87	+/-	0.35		
81.00	13.49	+/-	0.18		
121.78	11.87	+/-	0.16		
244.70	12.08	+/-	0.16		
344.28	11.14	+/-	0.15		
b:	-3.73	+/-	1.05	rel:	-0.28
a:	0.81	+/-	0.19	rel:	0.24
c:	0.10	+/-	0.01	rel:	0.10

Significant electronic noise term at low energy

10% constant term at high energy

20% reduction in light collection efficiency between crystal center and crystal corners



Preliminary

Summary

EPSI is an R&D, financed by PRIN 2022 funds, which aims to investigate a novel e^-/e^+ discrimination technique at high energies for future calorimeter-based experiments

This technique requires to develop a *synchrotron radiation detector* with high efficiency in the soft X-ray region, which must be enough cheap to be scaled to a large area

A simple system based on CsI/GAGG crystal, wrapped with Vikuiti ESR, and coupled to a large area SiPM already satisfies the basic requirements *down to a few keV*

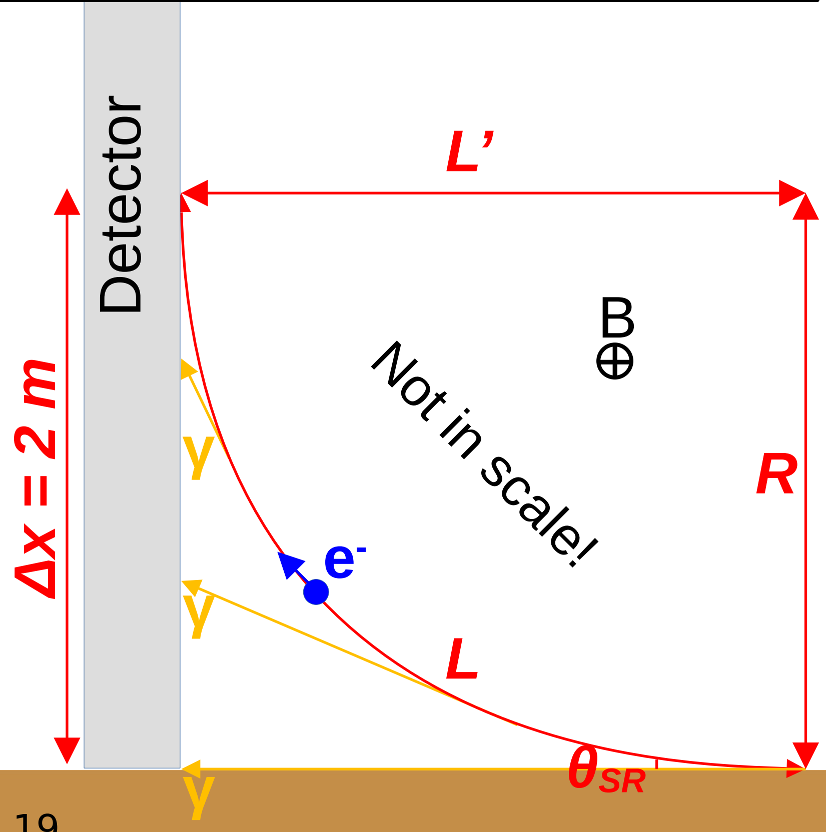
Scintillation light collection efficiency will be further improved by studying the effect of crystal roughness and optimizing the operation condition of SiPM sensors

To reach *1 keV*, we will make use a thin entrance window obtained with Al deposition, which is expected to slightly reduce the total scintillation light collection efficiency

Thank you!

Some computations (I)

Let us consider a 1 TeV electron, perpendicular to a 0.4 G field, impinging at detector center



Curvature radius

$$R[m] = \frac{p[GeV]}{0.3\ B[T]} \sim 83 \times 10^3\ km$$

...since $R << \Delta x$:

$$L' \sim L$$

$$\theta \sim L/R \sim 0.22\ mrad$$

...assuming Δx = 2 m:

Effective track length

$$L \sim \sqrt{2\,R\,\Delta x} \sim 18.3\ km$$

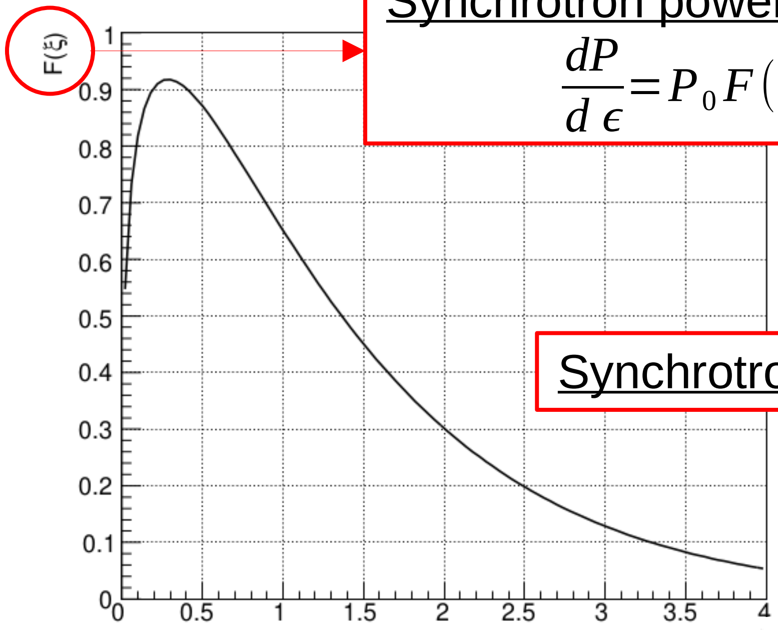
RMS Emission angle

$$< \theta_{SR}^2 >^{1/2} = \frac{1}{\gamma} = \frac{m}{E} \sim 0.51\ \mu rad$$

Some computations (II)

Let us consider a 1 TeV electron, perpendicular to a 0.4 G field, impinging at detector center

Considering a 1 TeV electron in B = 0.4 G field



$\xi = \epsilon / \epsilon_c$

Synchrotron power spectrum

$$\frac{dP}{d\,\epsilon} = P_0 F(\xi)$$

Synchrotron photon energy

Average number of γ reaching the detector

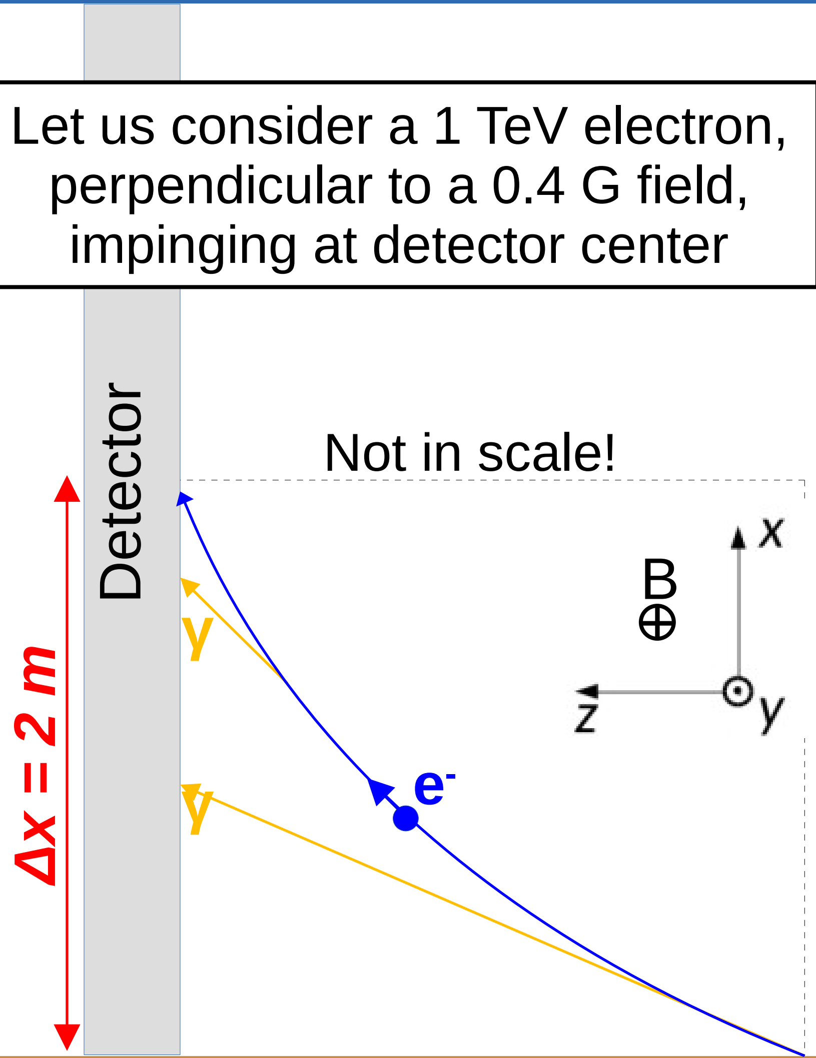
$$< N > = < \frac{dN}{dl} > L = \frac{5\sqrt{3}}{6}\alpha\gamma\sqrt{\frac{2\,\Delta x}{R}} = 4.51$$

Critical energy of synchrotron emission

$$\epsilon_c = \frac{3}{2}\hbar c\frac{\gamma^3}{R} = \frac{3}{2}\frac{\hbar e B}{m^3 c^4}E^2 = 26.78\ keV$$

Detection cell size

Let us consider a 1 TeV electron, perpendicular to a 0.4 G field, impinging at detector center



The dispersion of synchrotron photon emission angle is
$\sigma_\theta = 0.51\ \mu rad$
which translates into a position dispersion at detector of
$\sigma_y < L * \sigma_\theta = 9.3\ mm$

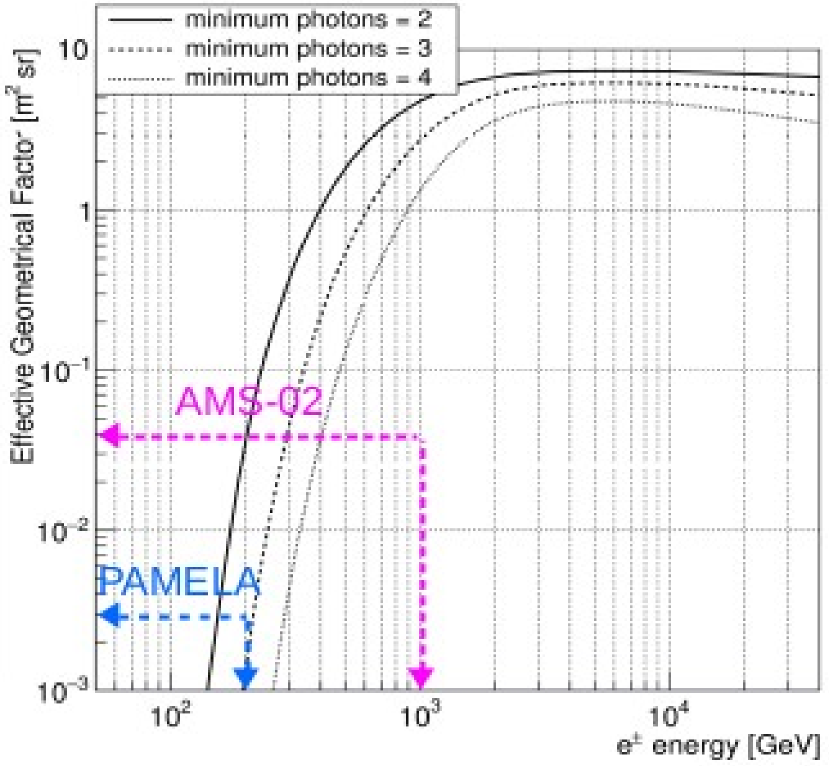
Synchrotron photons can be separated by astrophysical background since they lie on the electron bending plane: for this separation, it is enough a segmentation such that each detection channel have a size of about 1 x 1 cm^2

Effective geometric factor

Assuming a SRD with 100% detection efficiency in the range 1-100 keV

Considering Earth shadow and generic direction

Only SRD selection is applied



$\langle N \rangle \propto \sqrt{E}$

$\varepsilon_C \propto E^2$

→

$E_{electron}$	<N>	ε_c [keV]
500 GeV	3.19	6.69
1 TeV	4.51	26.78
10 TeV	14.28	2677.60

- The detection technique works well above 1 TeV
- The detection technique is limited below 100 GeV

Below a few hundreds of GeV we can use the back-tracing technique used by Fermi for charge-sign discrimination

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Protons and Nuclei

Synchrotron radiation generated by protons and nuclei cannot be detected since

$$\langle N \rangle \propto \sqrt{E} * Z^{5/2}/M$$
$$\varepsilon_C \propto E^2 * Z/M^3$$

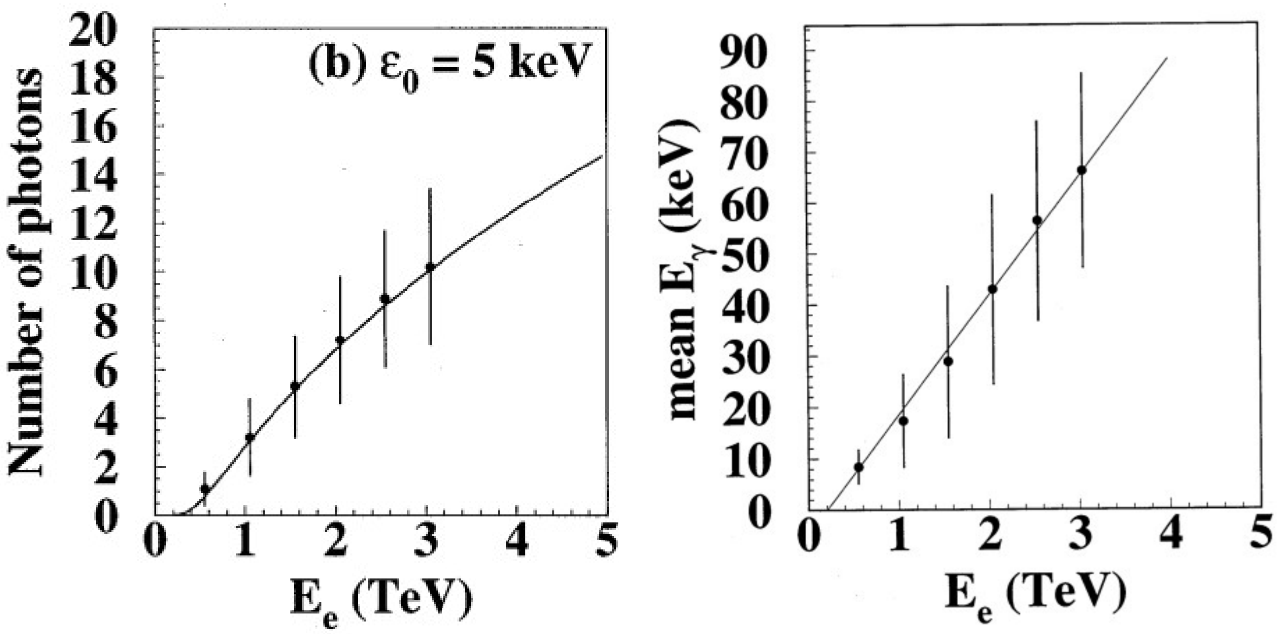
For example, a 1 PeV proton has $\langle N \rangle = 0.05$ and $\varepsilon_C = 4.4\ eV$, below detection limit

CON: We cannot separate nuclei from antinuclei

PRO: We can increase proton rejection factor

Calibration of the energy scale

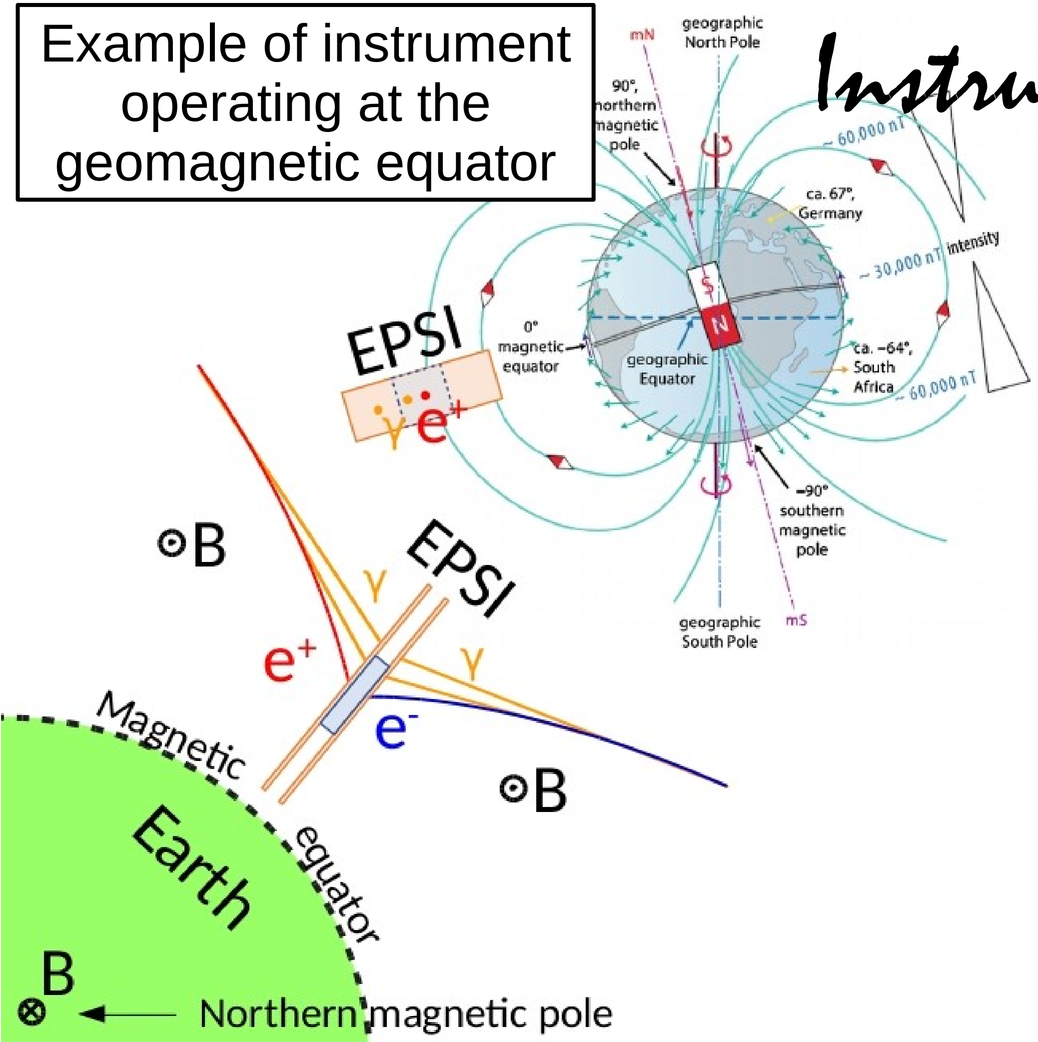
From *H. Hofer, M. Pohl/Nucl. Instr. and Meth. in Phys. Res. A 416 (1998) 59–63*



The number and mean energy of synchrotron photons depend on the electron energy, thus it can be used to get an independent measurement of the electron energy

This is useful to check the absolute energy scale calibration of the calorimeter, which is crucial for calorimeter-based experiments like CALET, DAMPE, Fermi-LAT

Instrument optimization



Optimize the **design** of the space instrument in terms of geometric factor, charge-sign reconstruction, energy/track resolution, background rejection

Carefully estimate **background** sources due to:

- Sun X-rays
- Astrophysical X-rays
- Low energy charged cosmic rays
- Backscattering from calorimeter

Study the best **orbit** both in terms of maximize the *bending effect* of the geomagnetic field and of minimizing the impact of *X-rays from the Sun*