Advanced Tracking System for Crystal Physics

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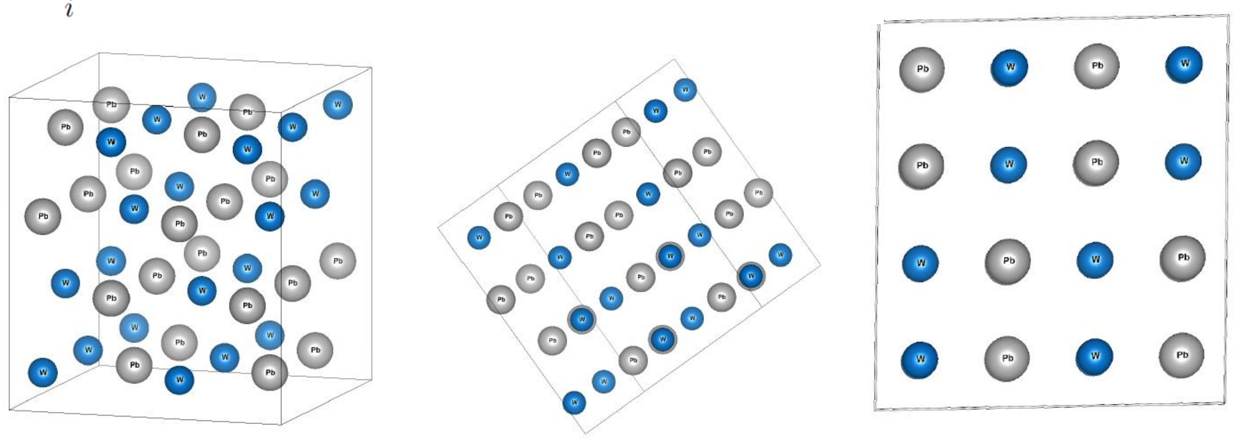
Overview

- What **crystals** and **directional effects** are
- **Channelling** in **straight** and **bent** crystals
- The **GALORE** and **e+BOOST** projects
- The INSULAB **Test System**
- **Upgrading** the test system to **match** the experiments **requirements**
- Laboratory and on beam **characterization** of the **upgraded system**
- **Preliminary** beamtests **results** of the two experiments

What are crystals?

- Materials in which their **microscopic constituents** (either atoms, molecules or ions) are arranged in a **highly ordered microscopic structure**, forming a **crystal lattice** that extends in all directions
- Depending on the relative orientation with an observer, the crystal **may or may not show its ordered structure**

$$\boldsymbol{r} = \sum_i n_i \boldsymbol{a_i} = n_1 \boldsymbol{a_1} + n_2 \boldsymbol{a_2} + n_3 \boldsymbol{a_3} \qquad \text{with } n_i \in \mathbb{N}$$



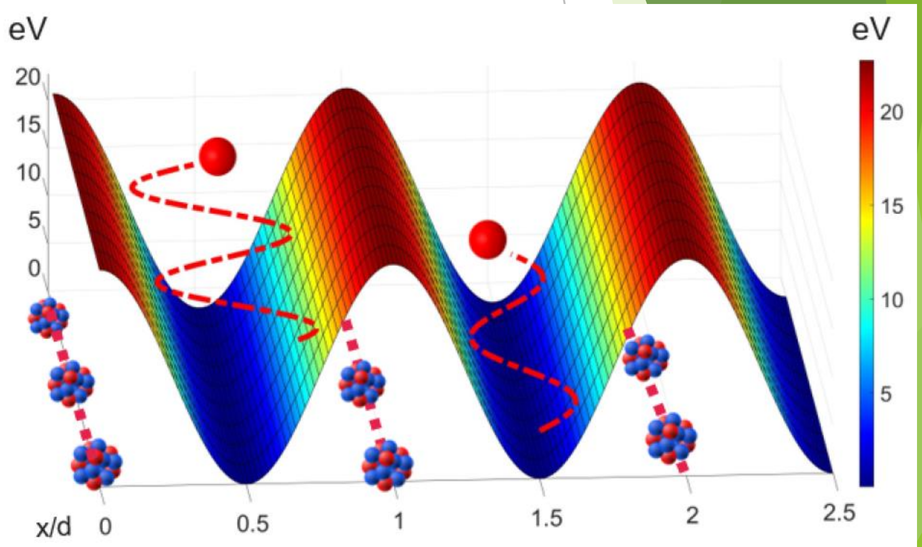
(a) Non oriented

(b) Planar

(c) Axial

What is Channelling?

- Stark (1912) predicted the existence of “**easy passages**” along “open channels” **in crystal lattice**
- Lindhard (1964): **theoretical description** of the phenomenon
- The interaction of an impinging particle with the crystal atoms/ions is described with a **screened Coulomb potential** of the whole crystal lattice
- Two types of channelling: **axial** and **planar**
- A particle is **trapped** in a **potential well** and forced to propagate **oscillating** within the potential well itself

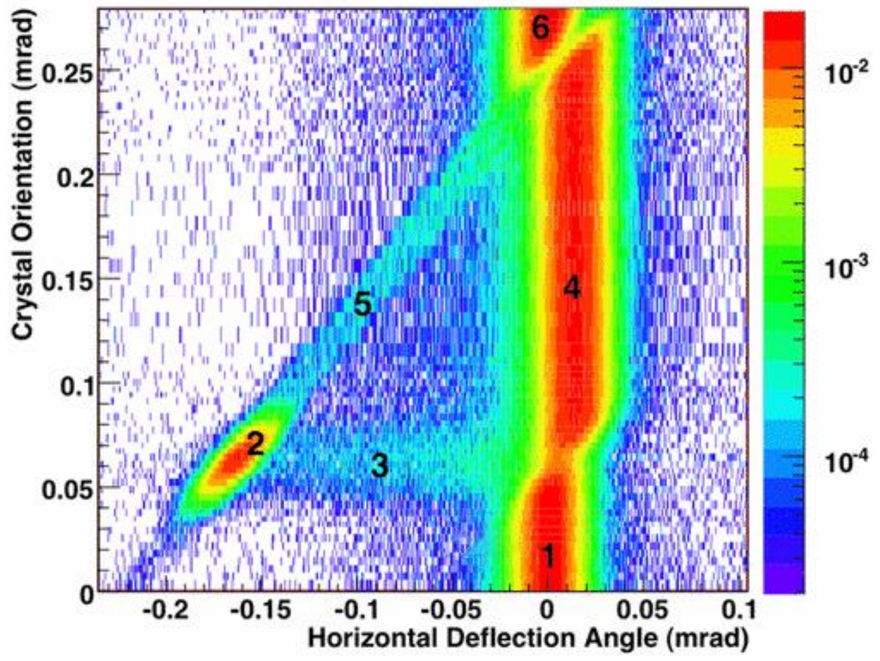


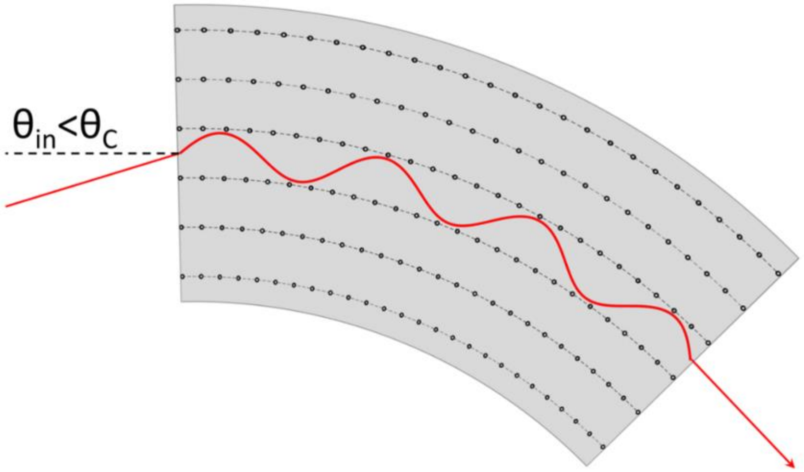
Channelling in bent crystals

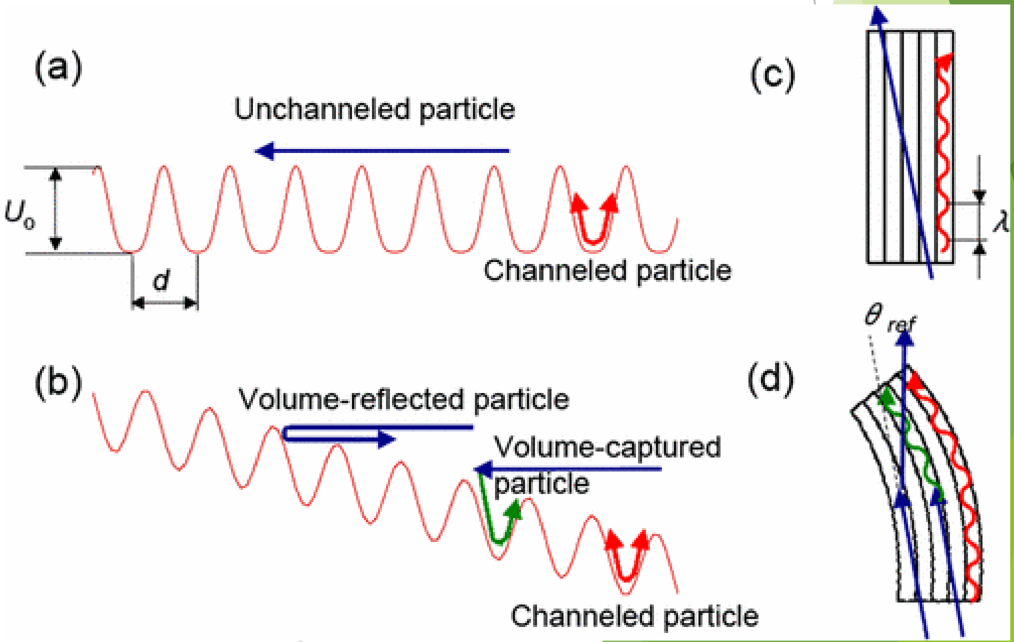
- Critical angle: angular acceptance for channelling phenomenon (2) to happen

$$\theta_c \approx \sqrt{\frac{U(\rho)}{\frac{1}{2}pv}}$$

- If a **crystal** is **bent** along the direction of motion, the net effect for a channelled particle is a **deflection** of its trajectory
- Other phenomena: Dechannelling (3), Volume Reflection (4), Volume Capture (5)

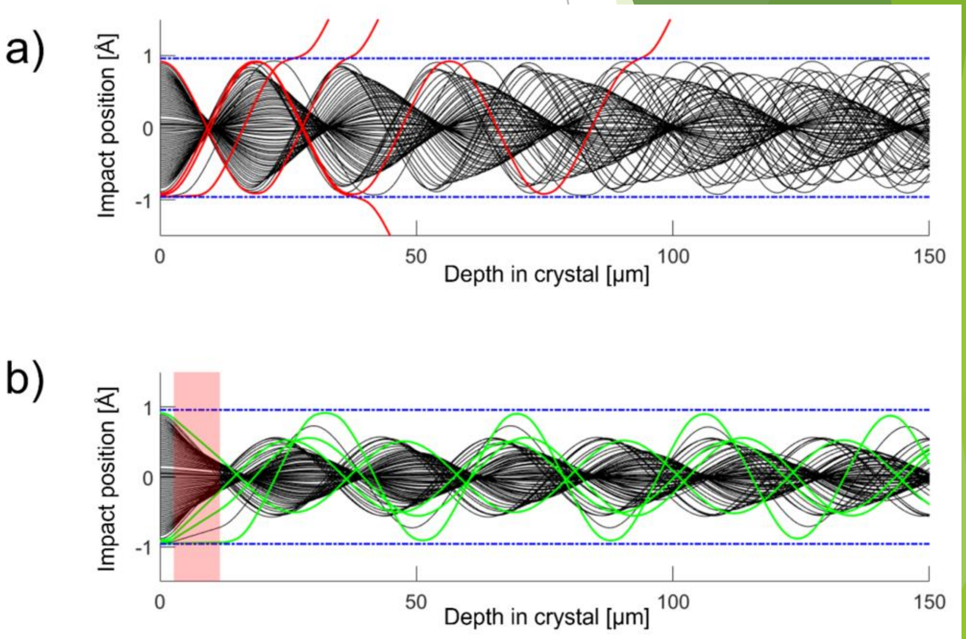






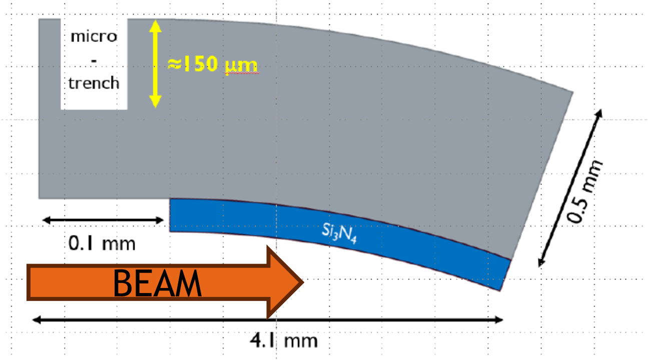
GALORE

- Project funded by INFN (Istituto Nazionale di Fisica Nucleare)
- Development of a **new generation** of **bent crystals**
- Goal: increase **channelling efficiency** up to ~100%
- Idea: the insertion of a **lattice interruption** at the very beginning of the crystal should act as a **focusing lens**



Channelling efficiency: percentage of the particles which impinge within the crytical angle and maintain the channelling condition along the whole crystal

Sketch of the crystal in the XZ plane

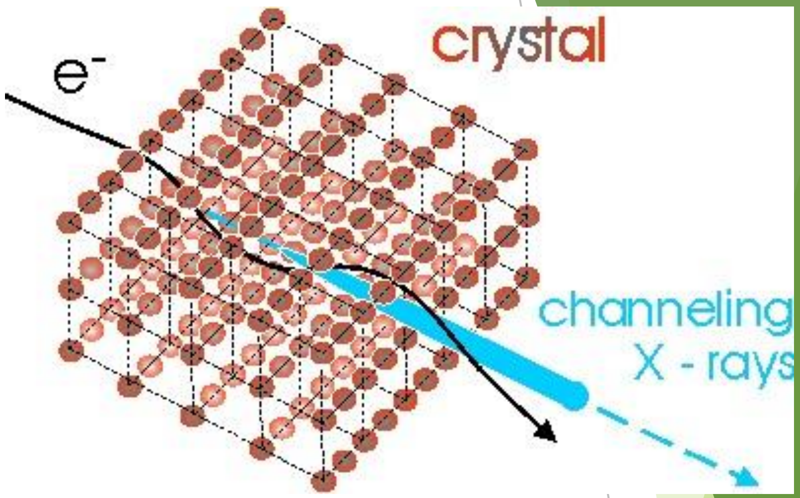


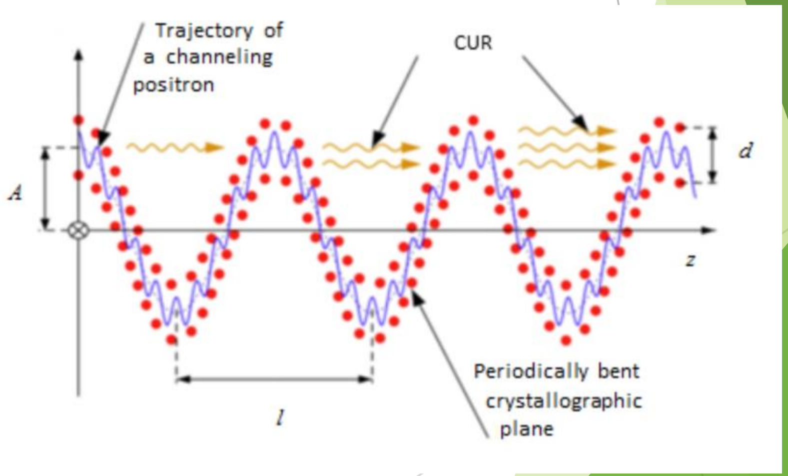
Radiation production

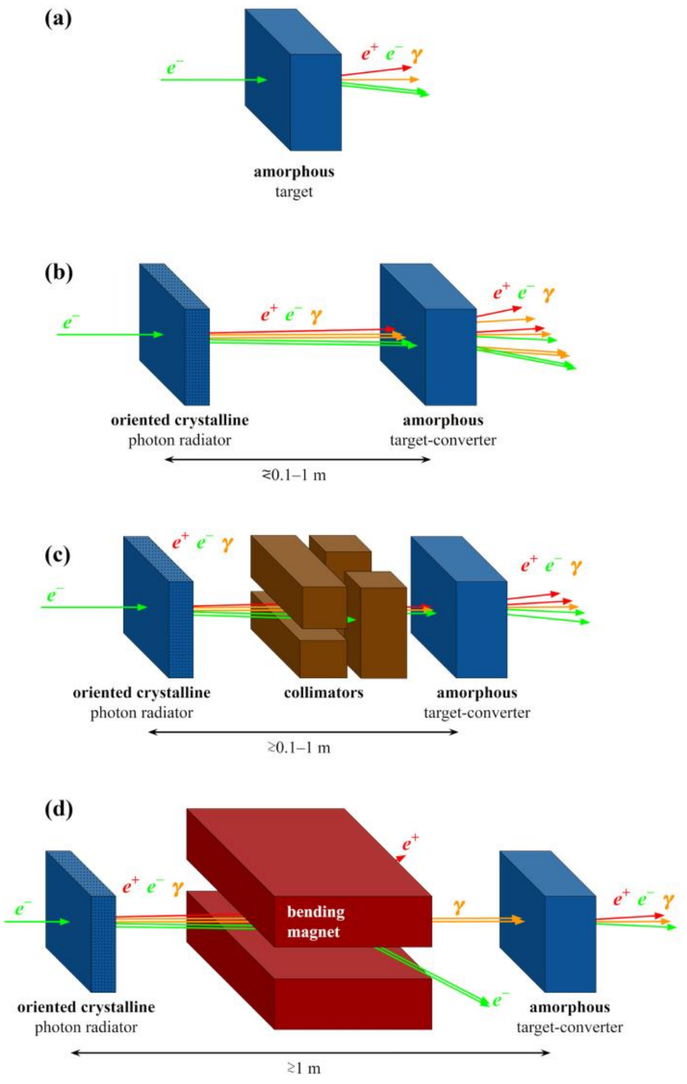
- An accelerated charged particle **emits radiation**
- For **electrons**, by using a quantum model → **Bethe-Heitler** approximation for **bremsstrahlung**

$$\frac{d\sigma}{d\hbar\omega} = \frac{16}{3} Z^2 \alpha r_e^2 \frac{1}{\hbar\omega}\left[1 - \frac{\hbar\omega}{E} + \frac{3}{4}\left(\frac{\hbar\omega}{E}\right)^2\right] \ln\left(183\, Z^{-1/3}\right)$$

- **Coherent bremsstrahlung: increase** in the **radiation production** by an electron which scatters coherently on many atoms along its way inside an **oriented crystal**







A crystal-based hybrid positron source

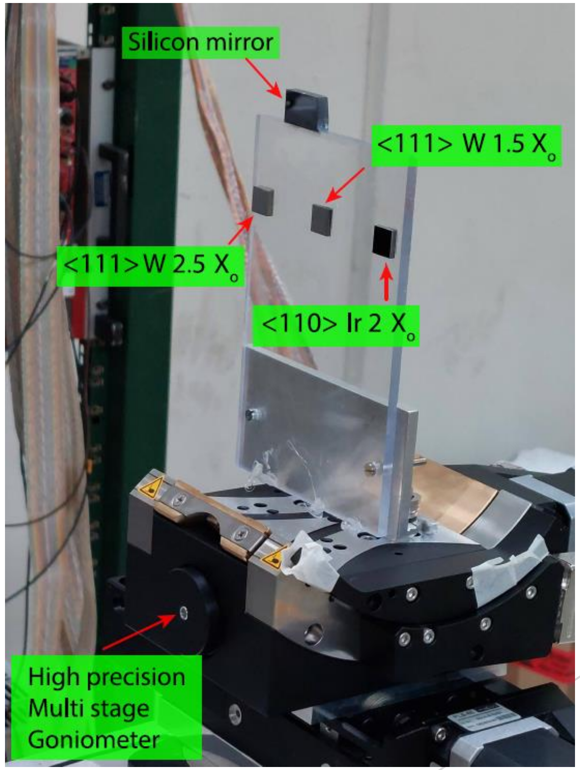
- **Positron source**: key element for future **particle colliders**
- **Conventional** approach: electron beam on high-density and high-Z target
- Hybrid design: **oriented crystal** for **producing photons** which can convert into electron-positron pairs inside an **amorphous converter**
- **Collimator** or bending **magnets** may improve the performance
- e+BOOST project
  - Funded by the Italian University and Research Minister as **PRIN** (Progetti di Rilevante Interesse Nazionale)
  - Goal: test different **crystal radiators**

Two projects, same requirements

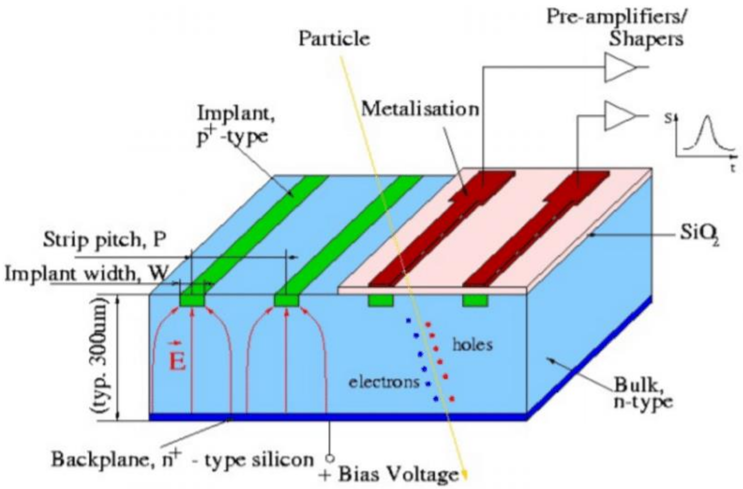
The GALORE and e+BOOST projects require

- High-resolution particle tracking
- Particle beams with **small profiles** and **small angular divergence**
- However, as the **beam size** is **reduced**, the **angular divergence increases**

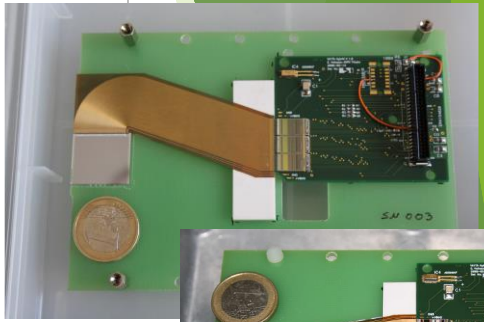
- Need to **select** only a **small portion** of the **beam** to acquire a **large enough statistics**
- This thesis work focused on the **upgrade** of the **electronics** to allow for the collection of the required statistics in a **limited time**

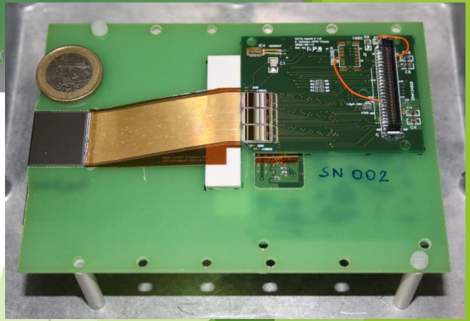


The INSULAB silicon tracking detectors

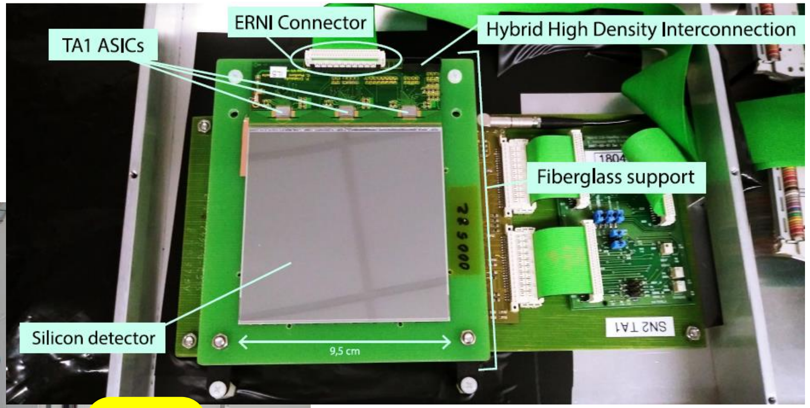


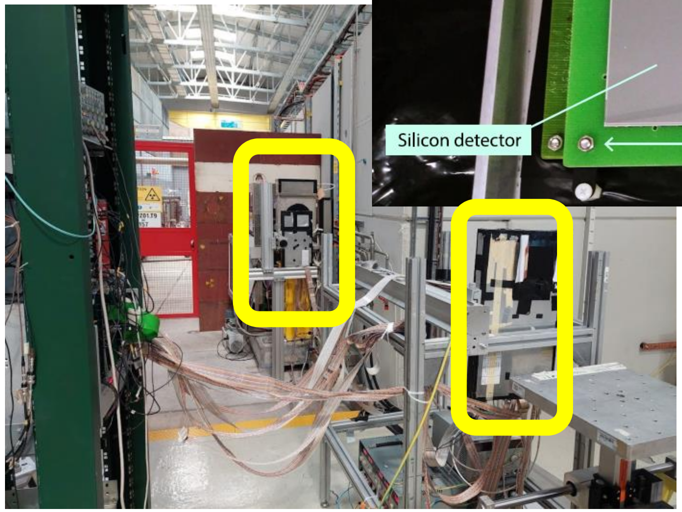
- Each **microstrip** module can provide a **single coordinate**
  → Two modules in “XY” configuration



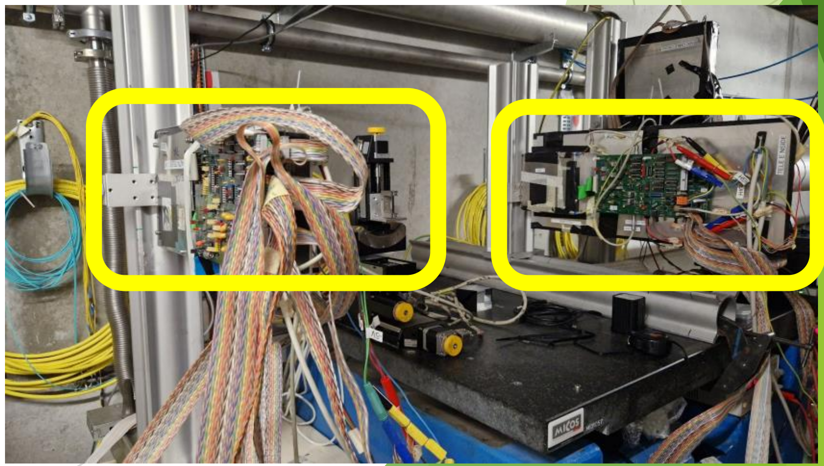


Beam Chambers:
- 9.5 x 9.5 cm^2
- 242 μm pitch



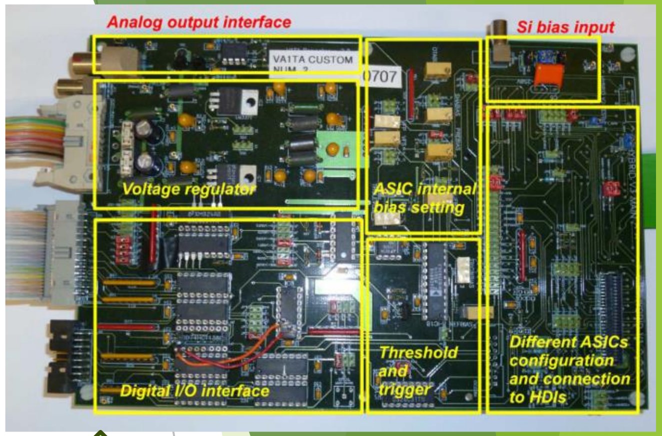


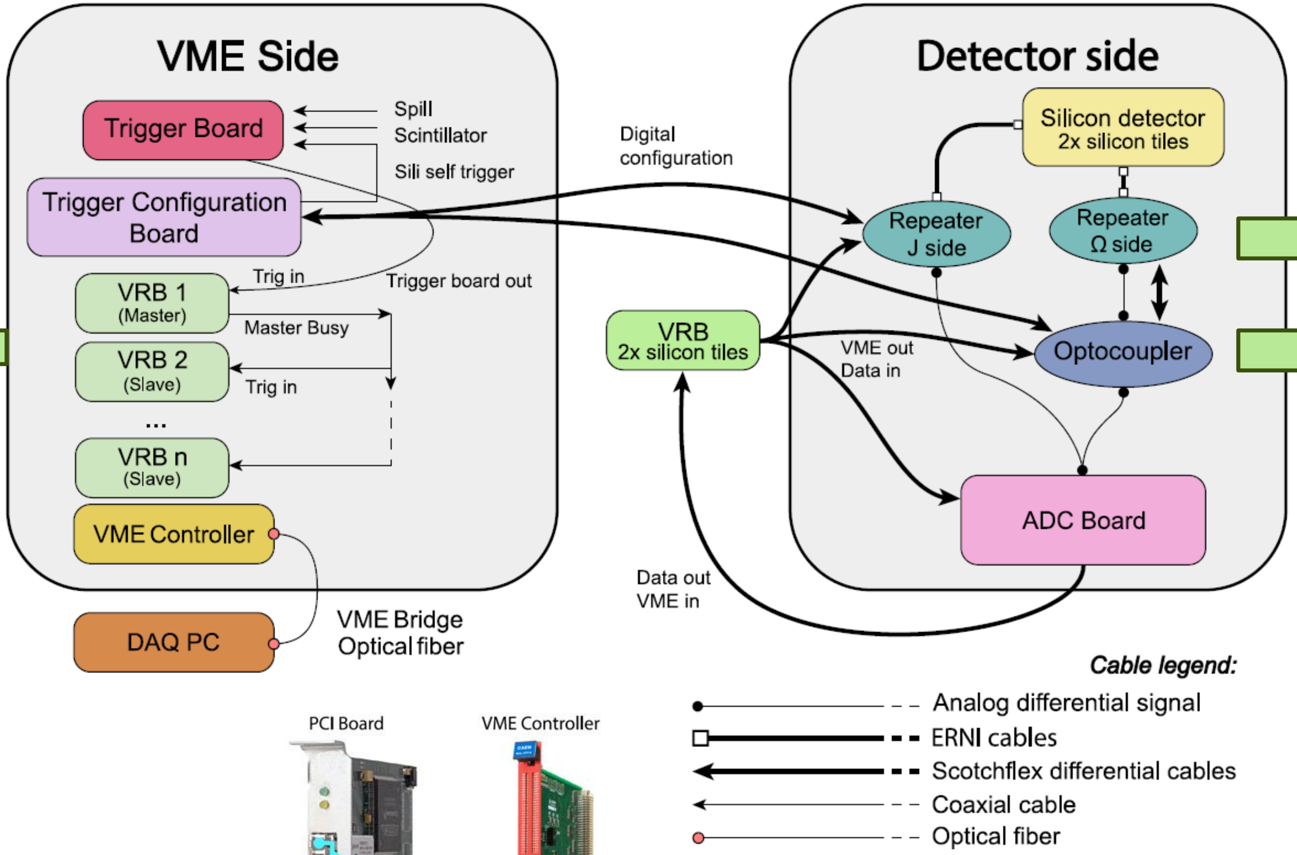
Beam Telescopes:
- 1.92 x 1.92 cm^2
- 50 μm pitch

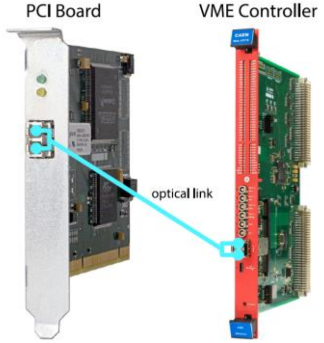


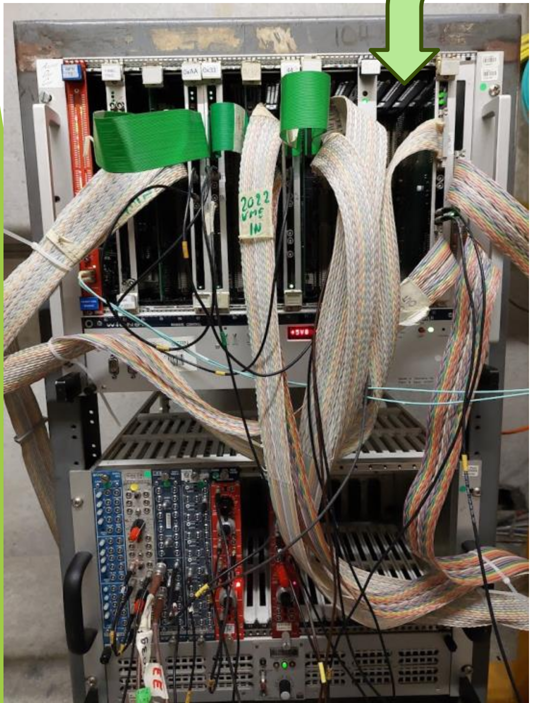
The readout electronics

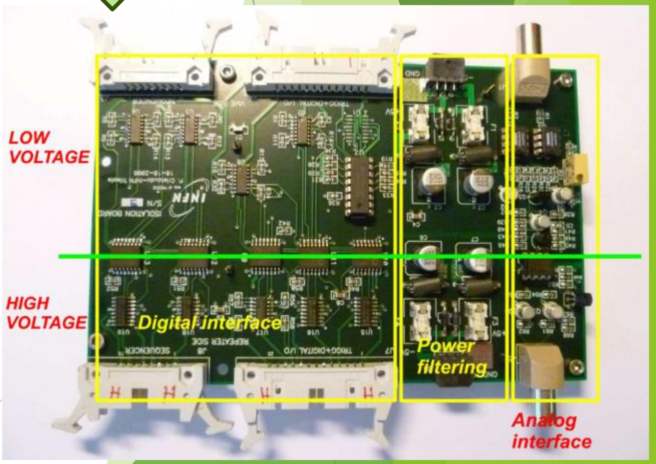
- Custom electronics boards
- Used to **read out** the detectors and **save** the physical **information** on a PC





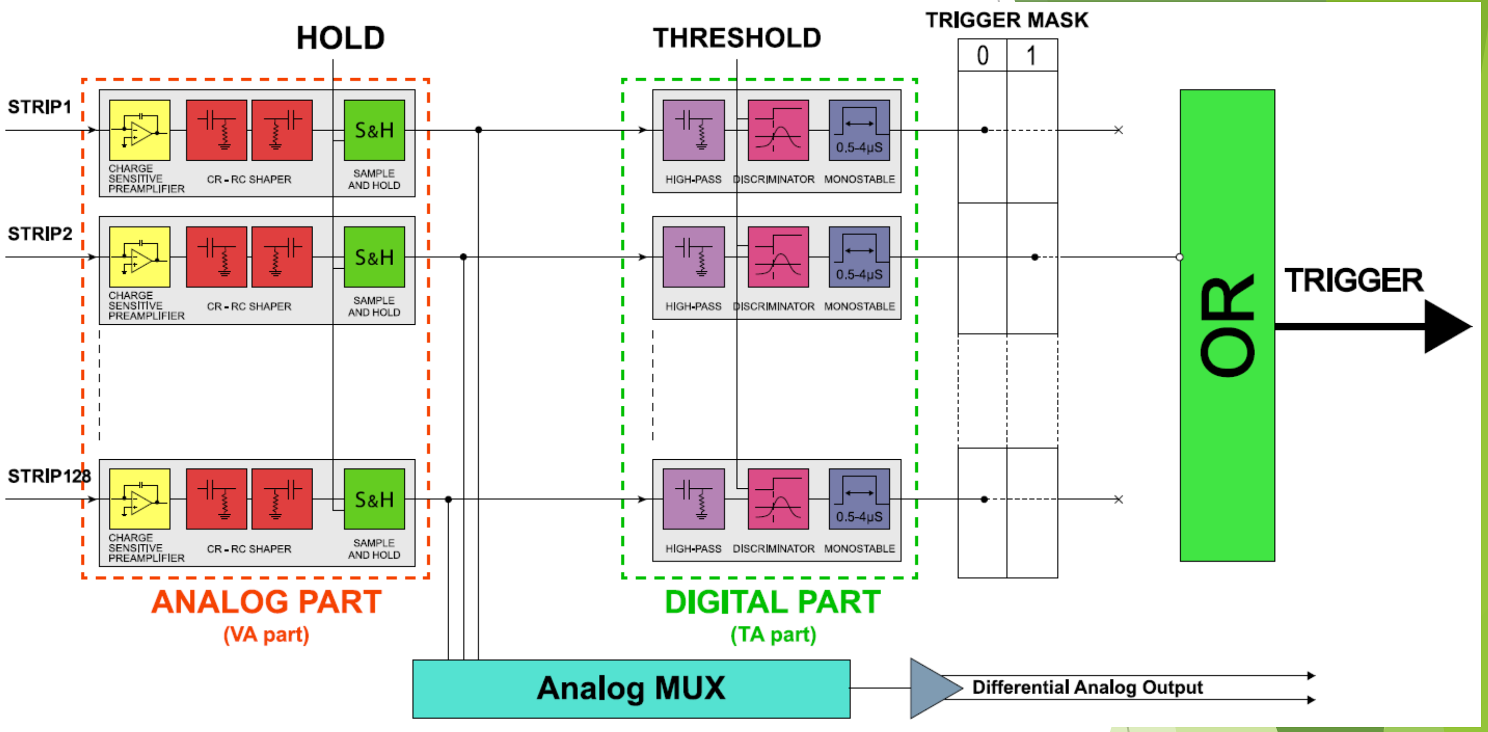


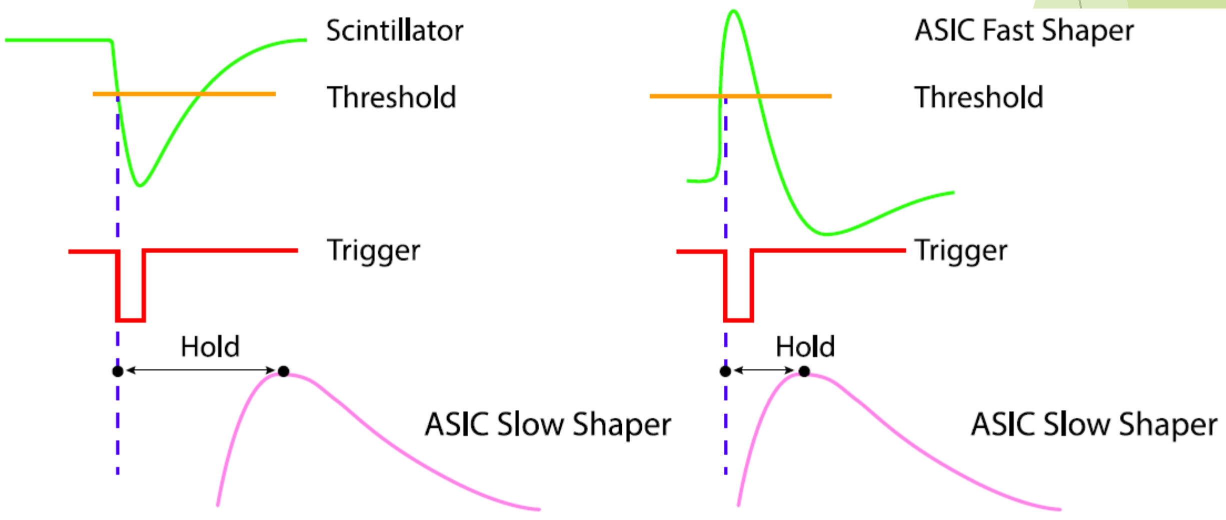




The ASICs

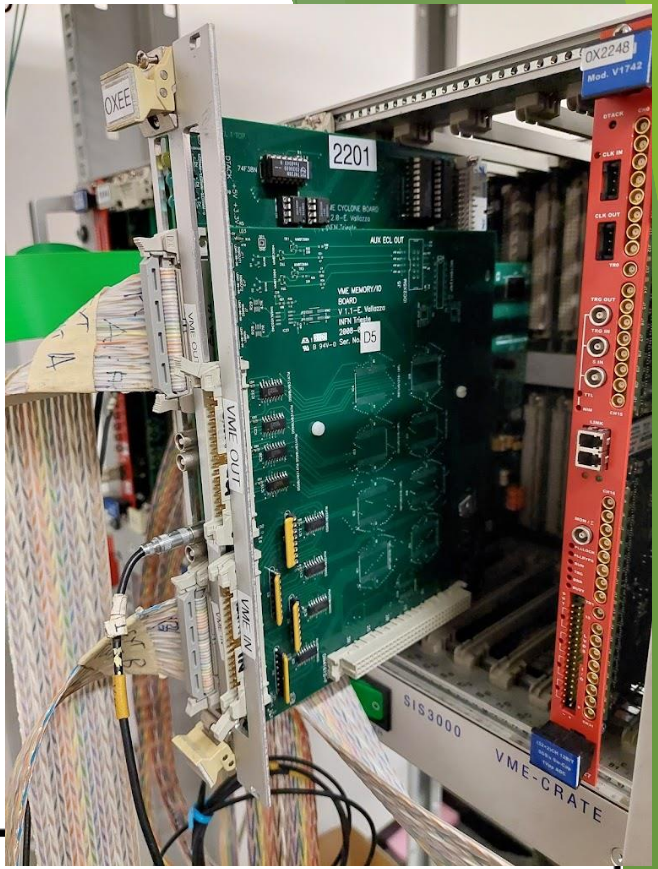
- Application Specific Integrated Circuits
- **Analog** part: **integrates** the deposited charge and **samples** the output signal at the peak
- **Digital** part: **generates a trigger** signal when a charged particle crosses a given interval of strips

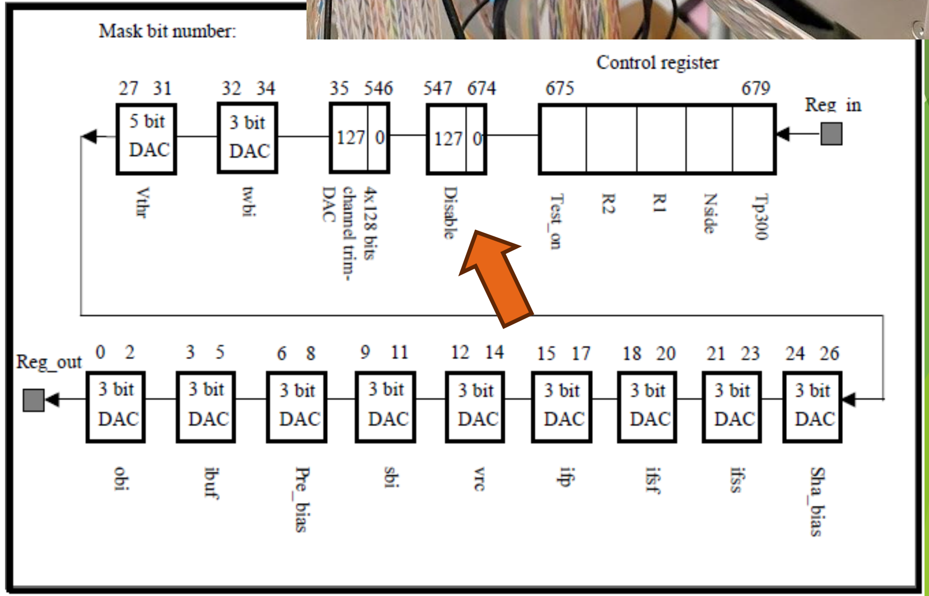




The Trigger Configuration Board

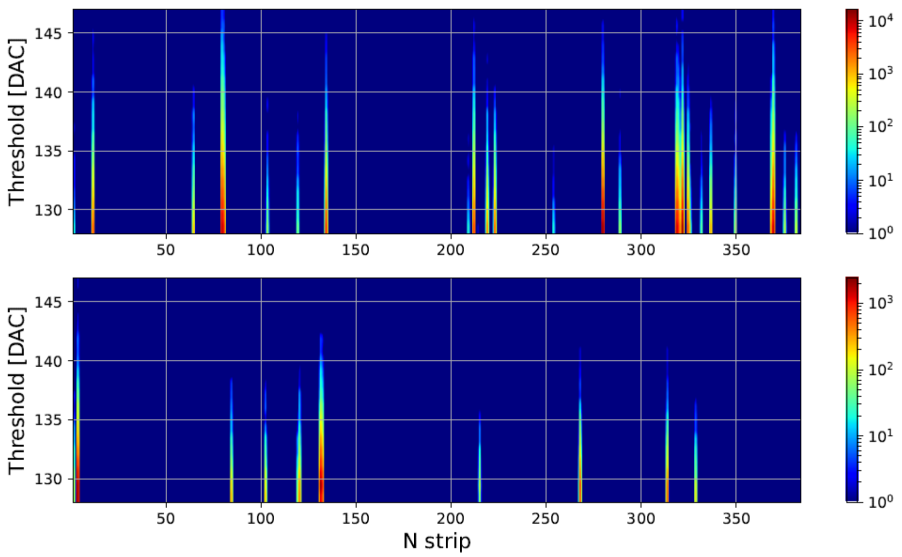
- VME Board with a Field Programmable Gate Array (FPGA)
- The firmware of the board was upgraded to:
  - Load the **Trigger Configuration Mask** in a Shift Register, including the strips on which to trigger
  - Load the **trigger thresholds** set by a DAC on the Repeater Board
  - **Receive** the **trigger signal** from **each silicon module**
  - Implement **logic conditions** on the signals of the detectors, such as the AND or the OR
- The software was also upgraded to control this board



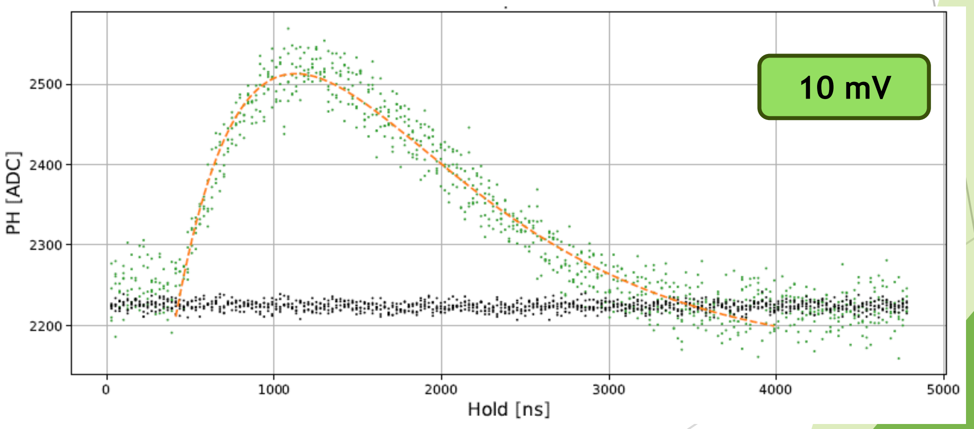


The ASICs Laboratory Characterization (1)

Noise trigger rate as a function of the Threshold for each strip: by excluding the noisy strips, it is possible to choose a low threshold

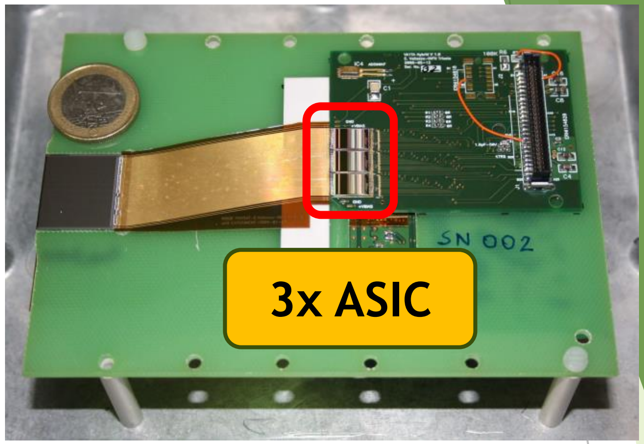


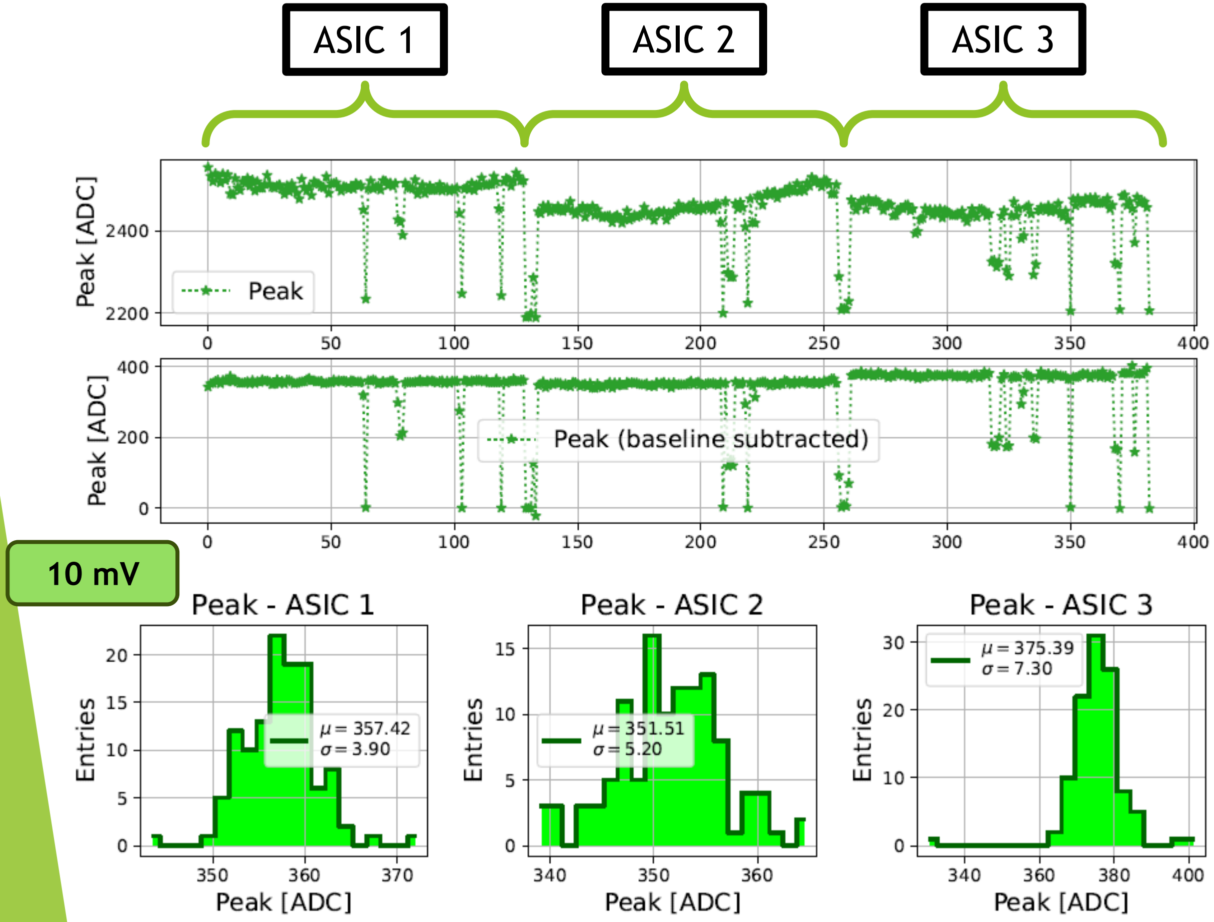
Study of the **analog response** of each channel with an external **calibration signal** of different amplitudes



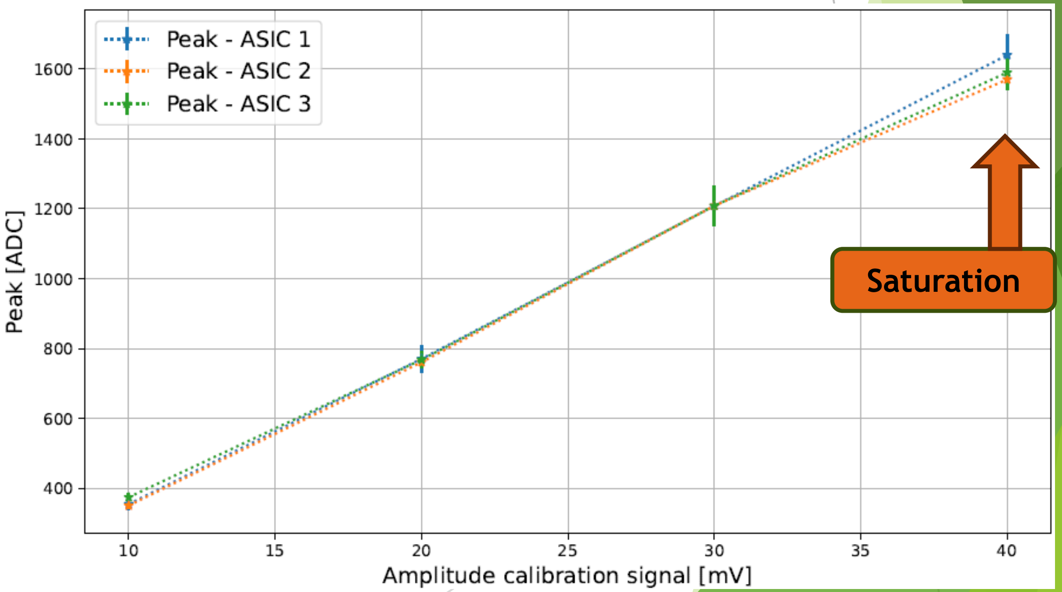
$$y\left(t\right) = k\left(t - t_0\right) e^{-(t-t_0)/\tau} + c$$

The ASICs Laboratory Characterization (2)

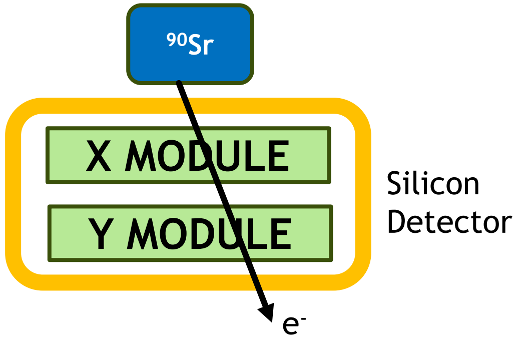




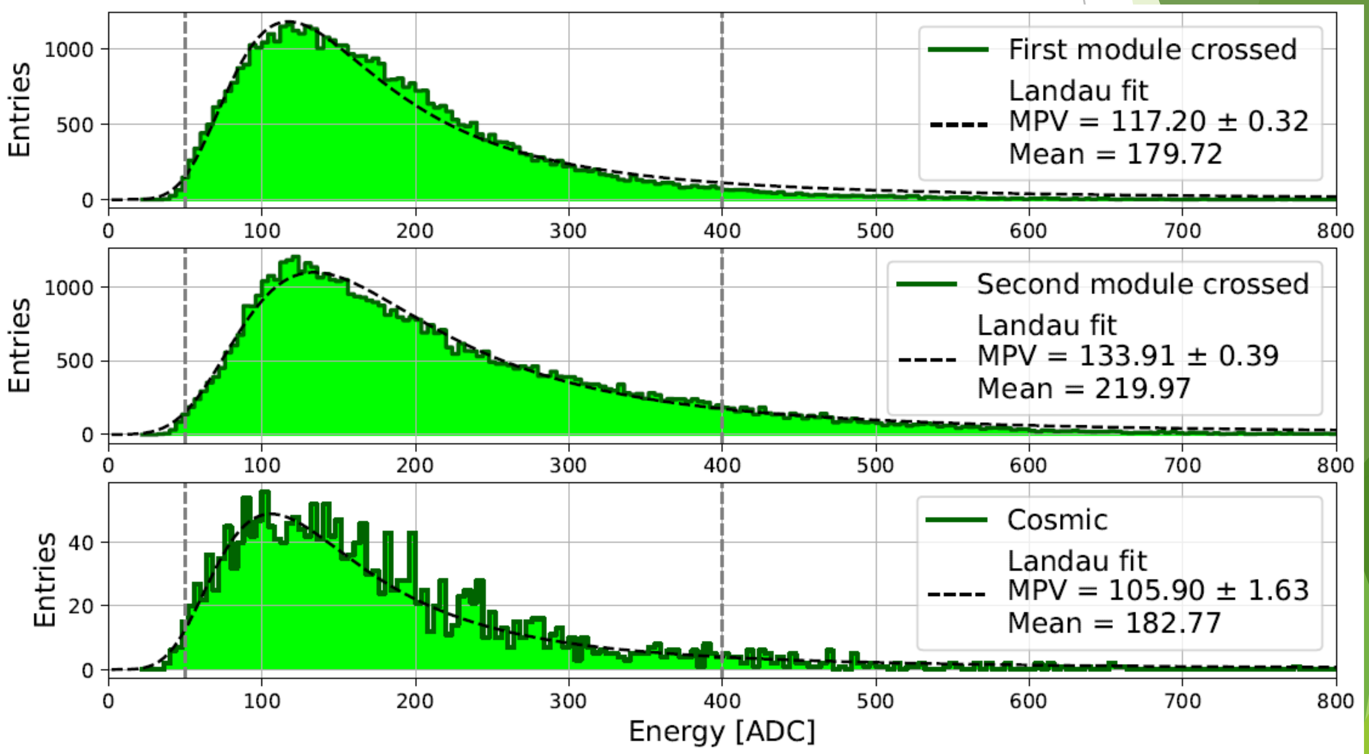
Mean value of the **peak** distribution as a function of the amplitude of the calibration signal



The ASICs Laboratory Characterization (3)



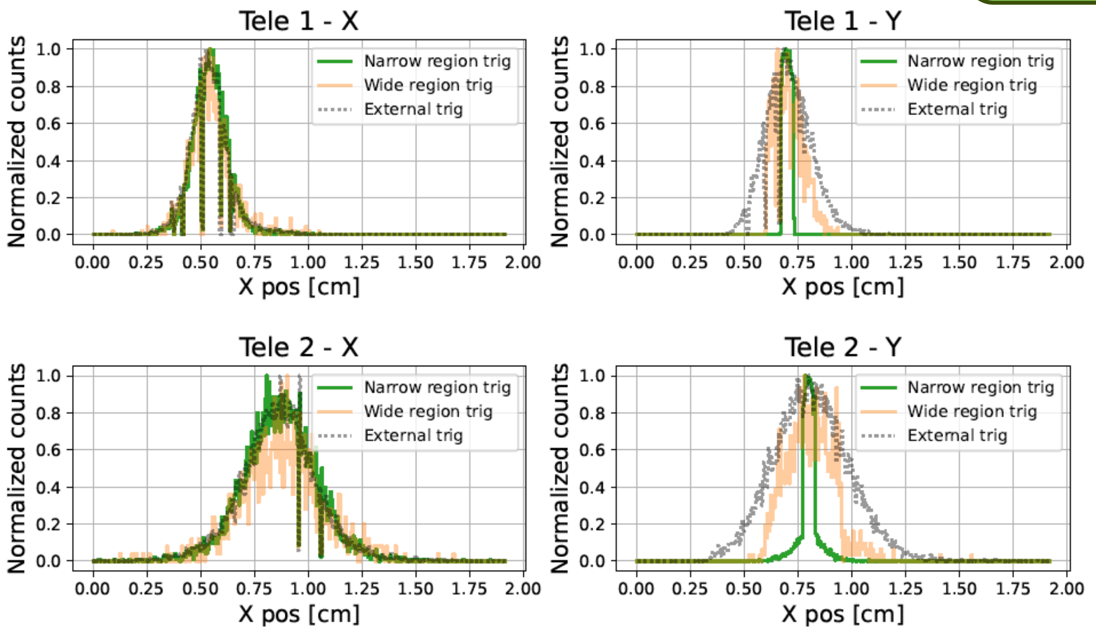
- Study of the ASICs **saturation** in terms of **MIPs** → how many **particles** the detector can **count**
- Cosmic rays: provide real MIPs
- ^{90}Sr: good approximation if placed directly over the module under study
- Linear up to 1400 ADC → Linear for 8-13 MIPs

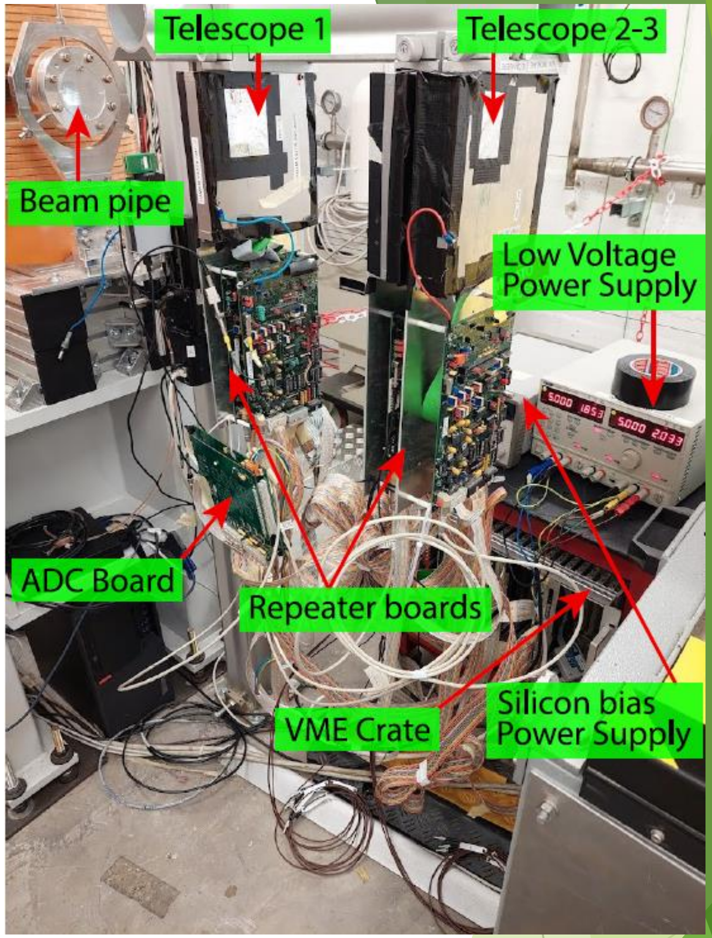


First on beam characterization April 2023 @ BTF Frascati

First real test with a beam: reducing the **trigger strip interval** results in a **reduction** of the **angular divergence**

Trigger: AND of the Y





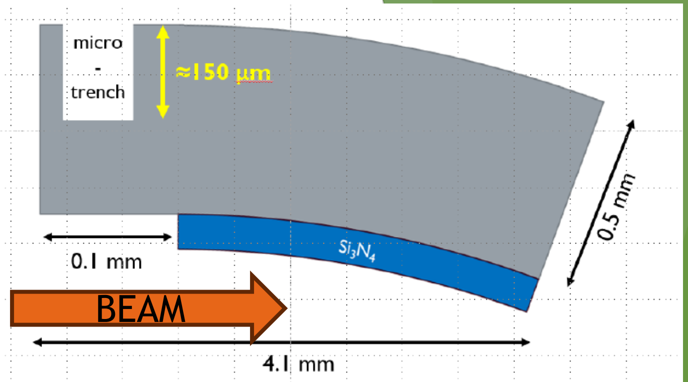
Region sili 1 (strips)	Region sili 2 (strips)	y angular divergence (mrad)
Ext trig	Ext trig	3.02 ± 0.02
120 - 190	130 - 190	2.39 ± 0.07
120 - 160	130 - 190	2.46 ± 0.14
120 - 160	140 - 180	2.10 ± 0.12
120 - 160	150 - 170	2.36 ± 0.32
130 - 150	150 - 170	1.87 ± 0.22
120 - 160	155 - 165	1.67 ± 0.15
135 - 145	150 - 170	0.93 ± 0.01

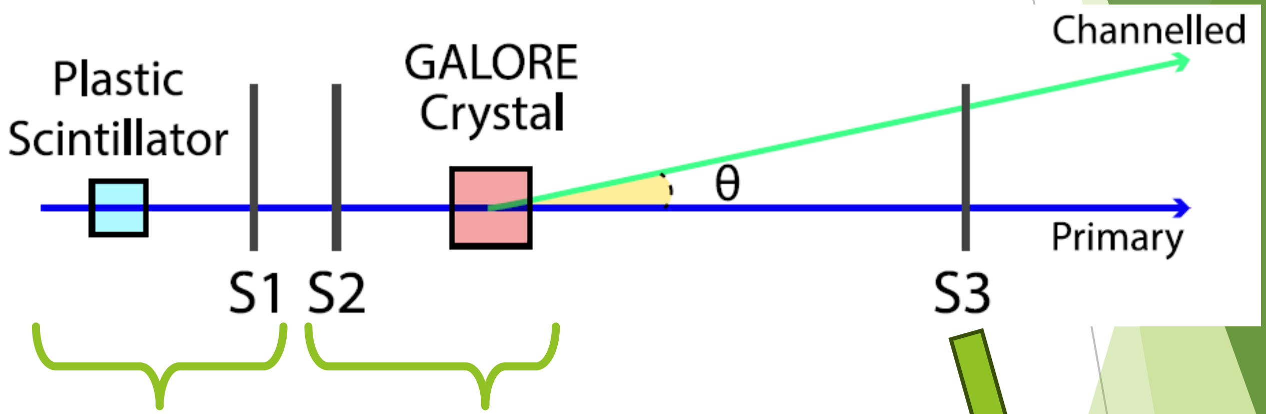
GALORE Beamtest
June 2023 @ H8

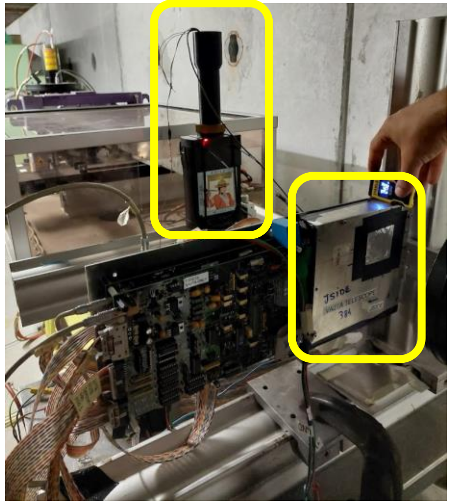
- Test of the **channelling efficiency**
- Need to **track** the **incoming** and **outgoing** particle
- The downstream detector (S3) must "see" both the **direct** and the **channelled** beam

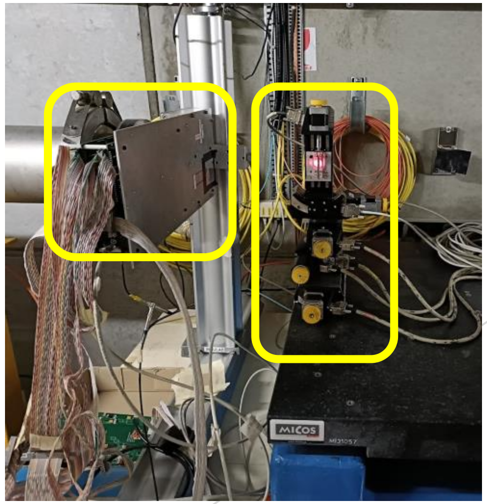
- The H8 beam is ~1cm → Need to **select** only particles impinging on the crystal

Sketch of the crystal in the XZ plane









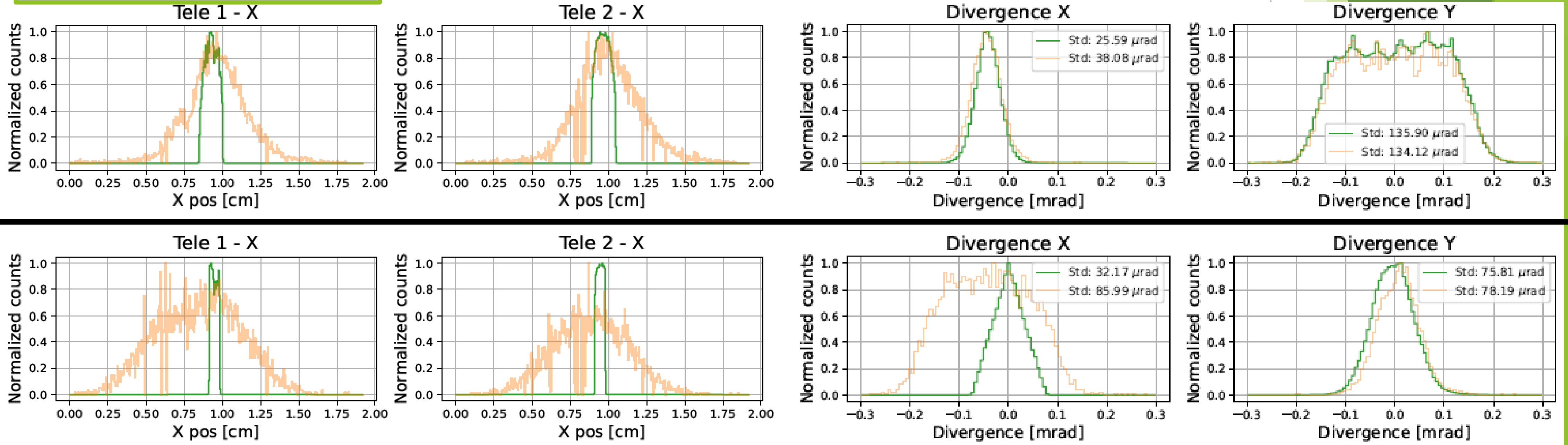
GALORE Beamtest (2)
Trigger interval

- **Reducing** the **trigger region** allowed the collection of a **large** enough **statistics**
- **Without** the self trigger upgrade, it would have been **impossible** to perform the beamtest

Select 3-5% of the whole beam → 20-30 times faster

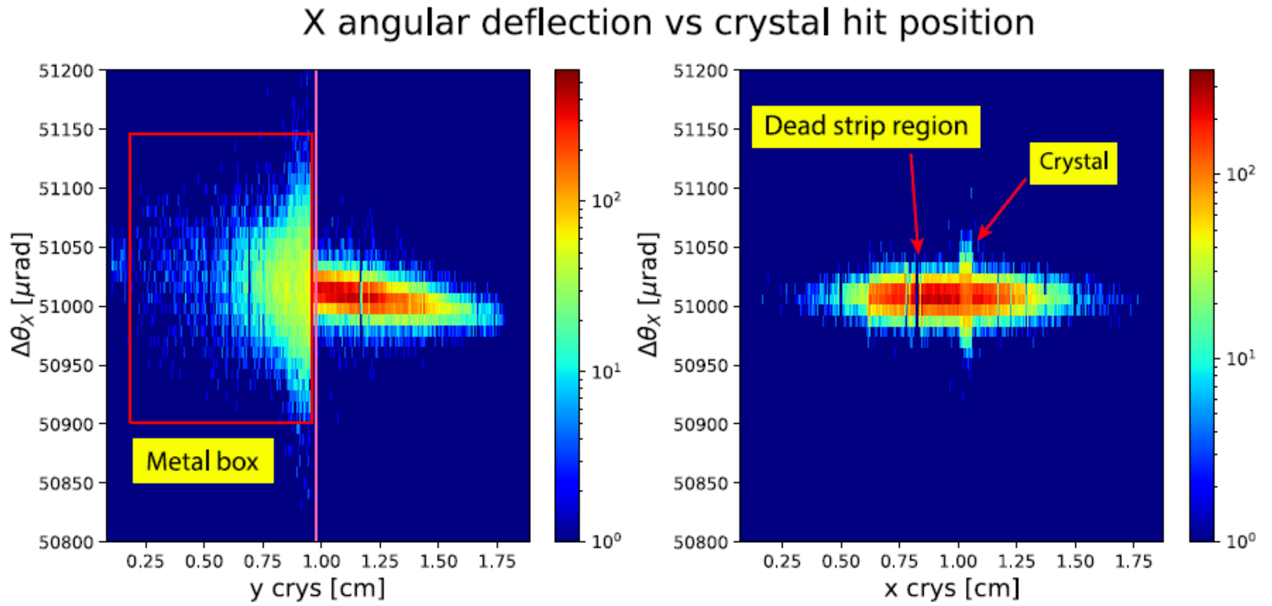
Select 20-25% of the whole beam → 4-5 times faster

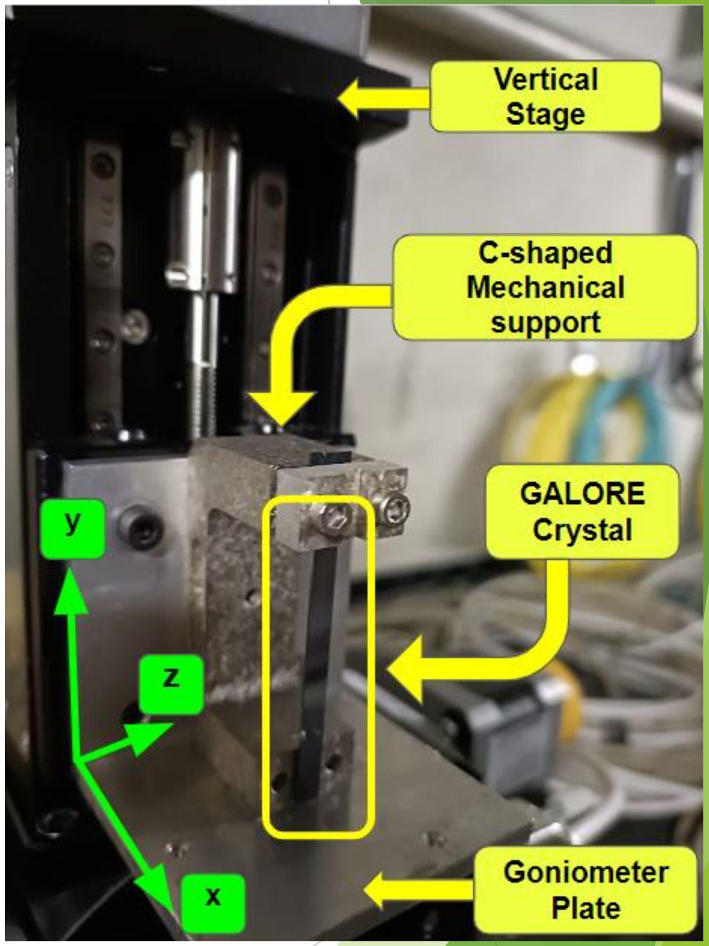
Trigger: AND of the X



GALORE Beamtest (3)
Aligning the crystal

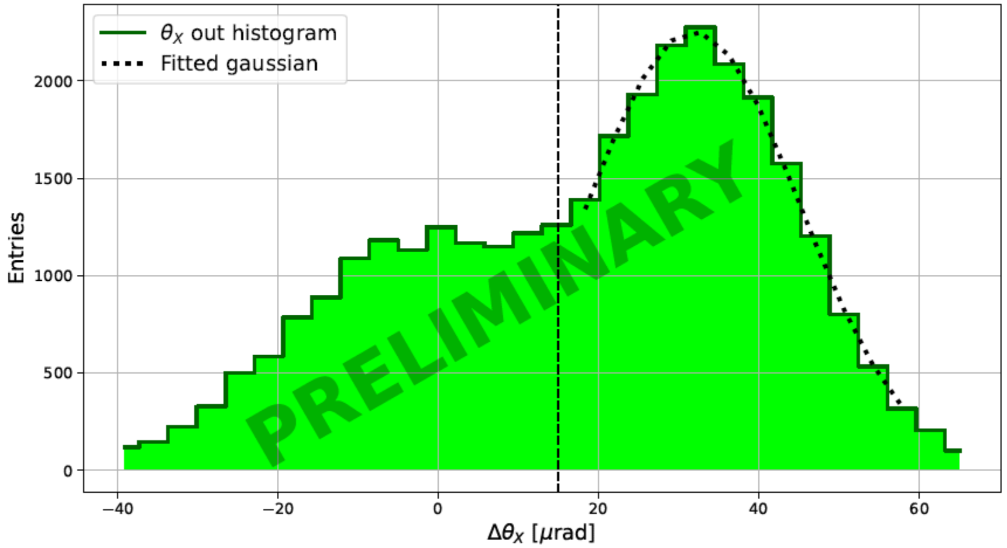
- The crystal must be **centered** on the beam
- Idea for **alignment**: particles **scatter** when they cross material, therefore the **rms** of the **angular deflection** distribution increases

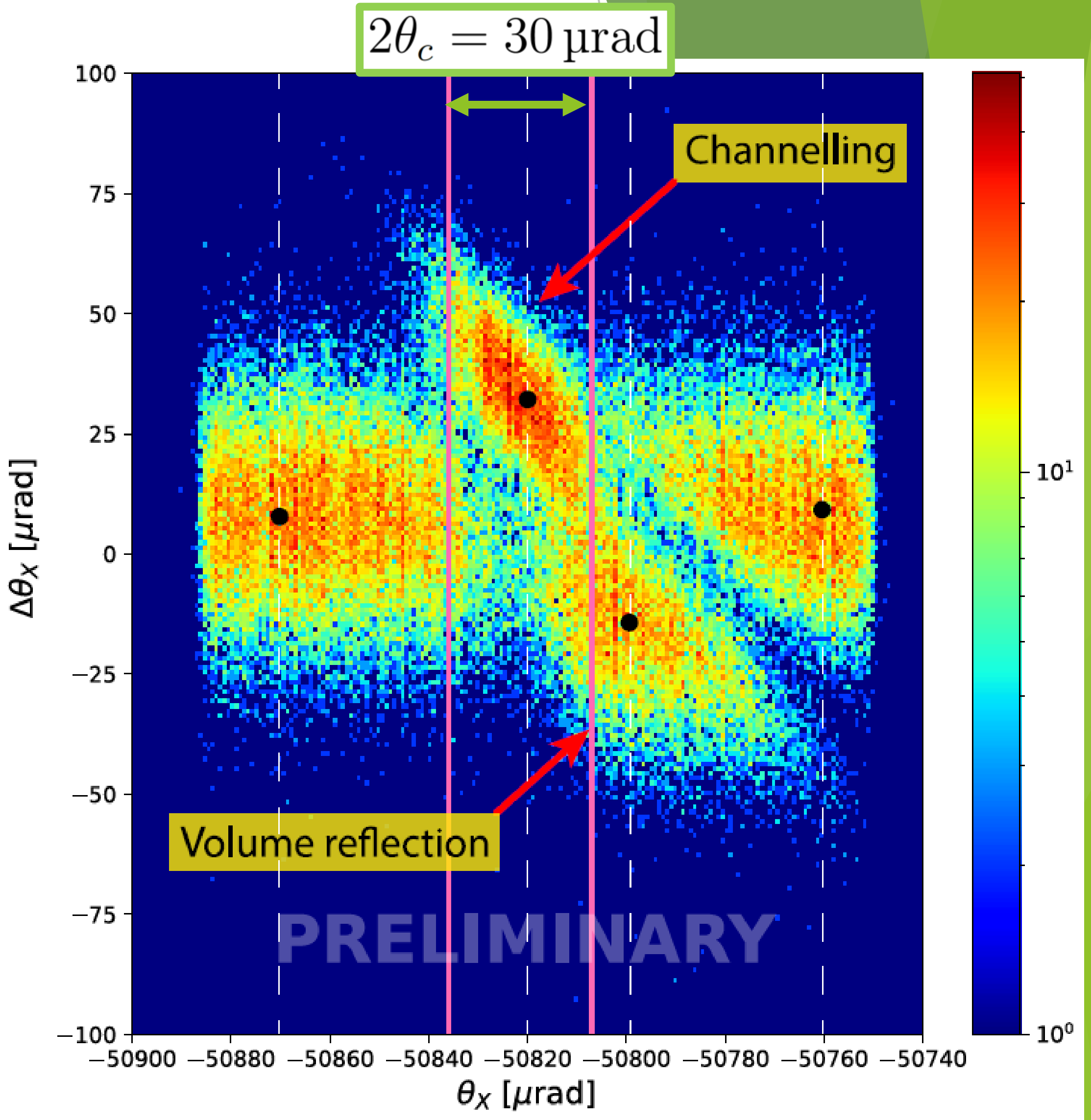




GALORE Beamtest (4)
Preliminary results

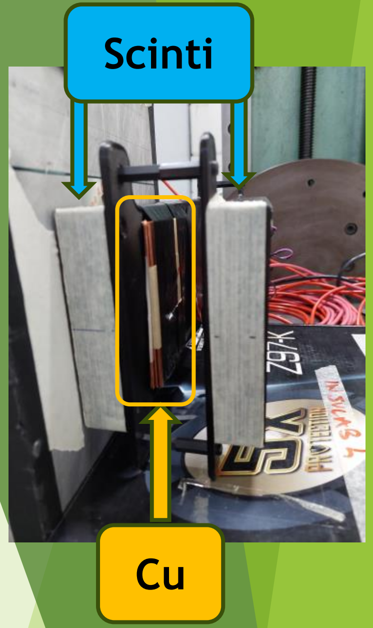
- 50 µm wide slice in the middle of the trench
- Vertical slice ± one critical angle wide
- Preliminary **channelling efficiency**: 65%
- Can be caused by **imperfections** in the crystal lattice

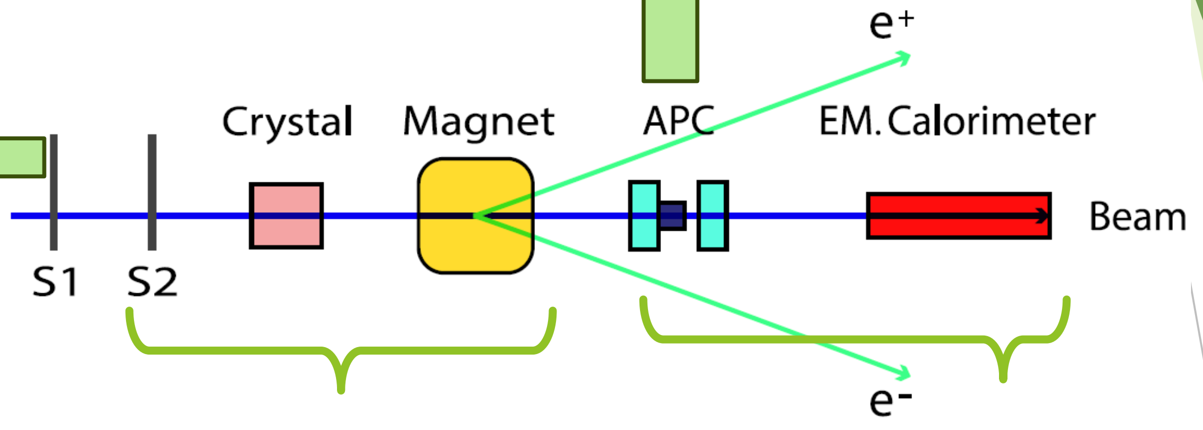


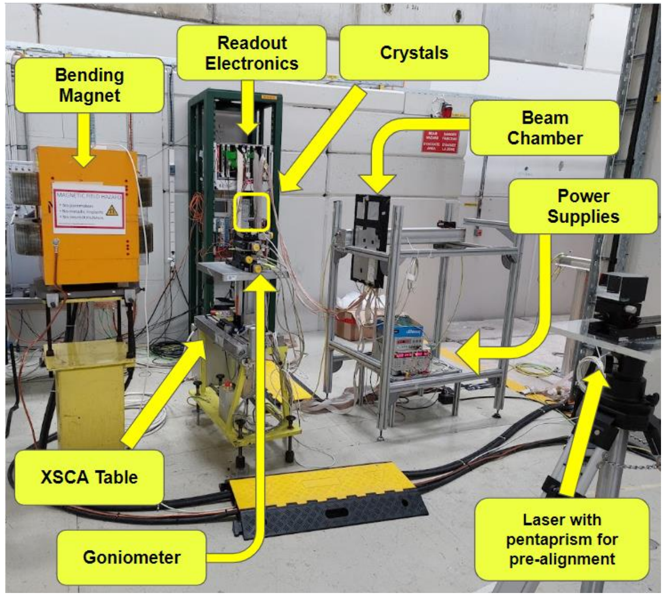


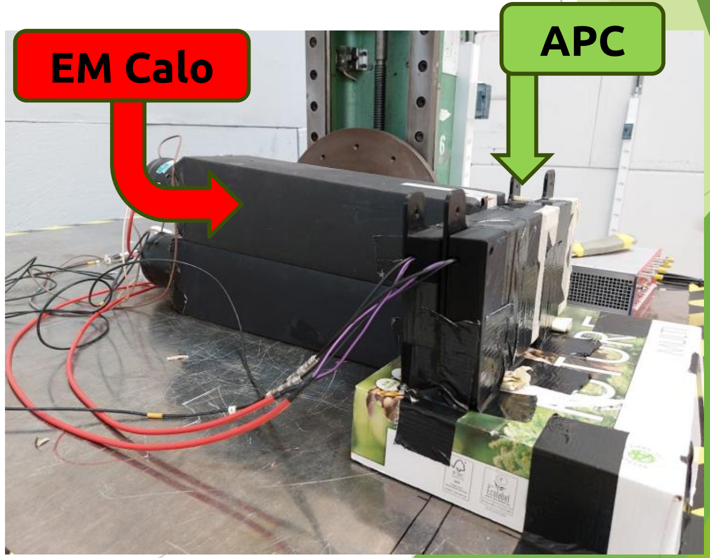
e+BOOST Beamtest August 2023 @ T9

Active Photon Converter:
Provides **average** information about the **multiplicity** of the photons



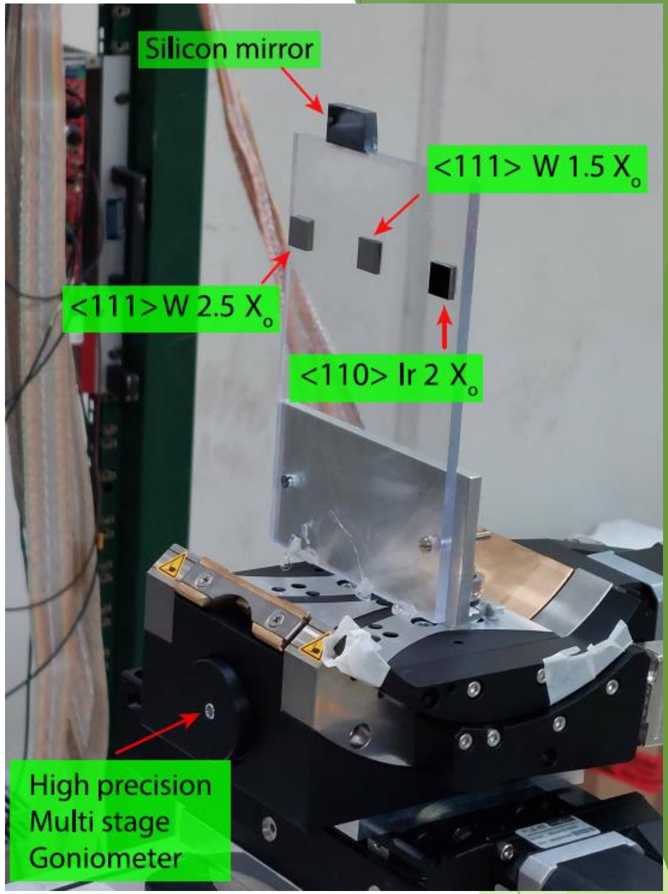


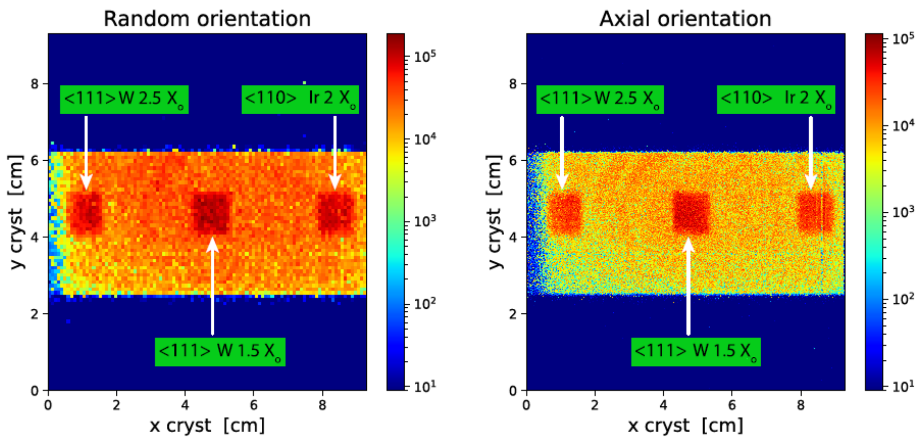


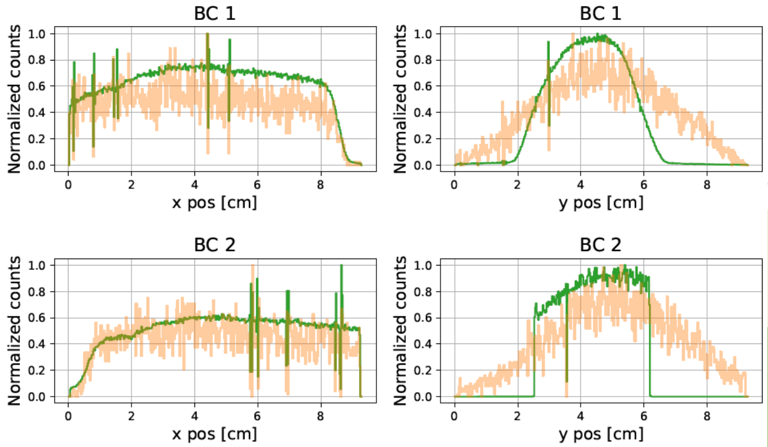


e+BOOST Beamtest (2)
Aligning the crystal

- **Easy task** with respect to the GALORE crystal
- A **direct effect** of the interaction between the beam and the crystal **can be measured**, namely the produced **radiation**
- However, a **very large statistics** is required with a **wide beam**
- Triggering on a 3cm wide vertical region allowed to acquire all the three crystals together

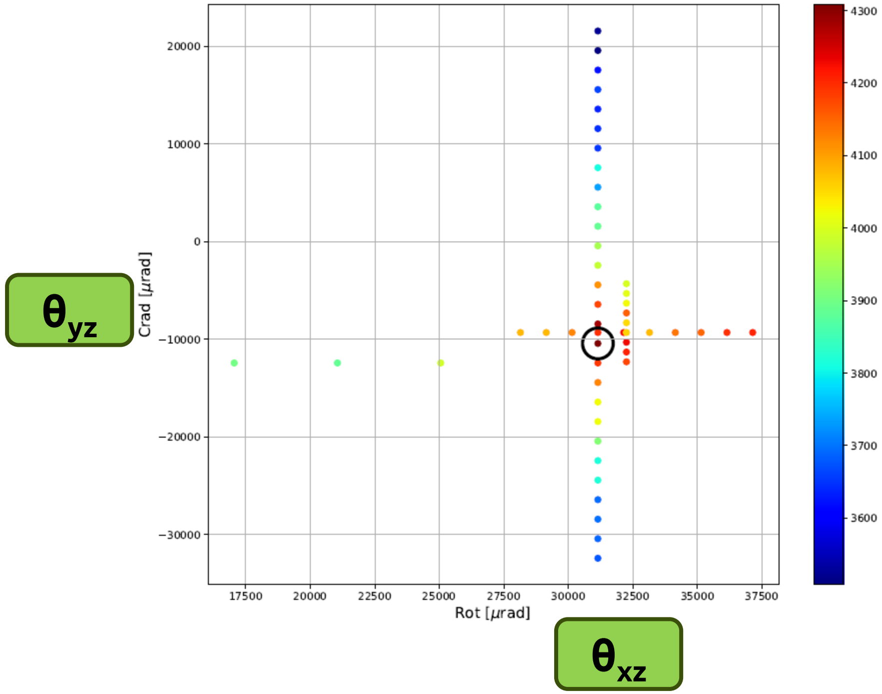




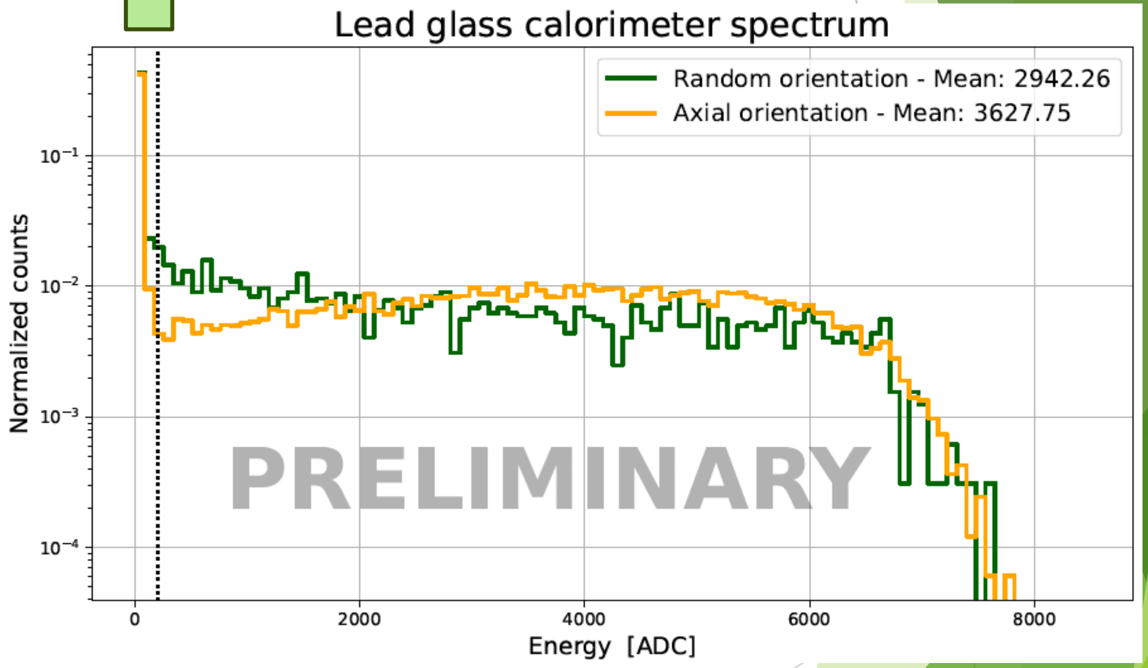


e+BOOST Beamtest (3)
Preliminary results

Axial: **+23%** radiation production
For <111> W 1.5 X_0



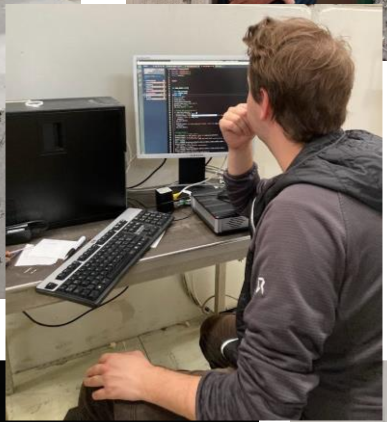
Stereogram for **orienting** the crystal in the **axial** direction



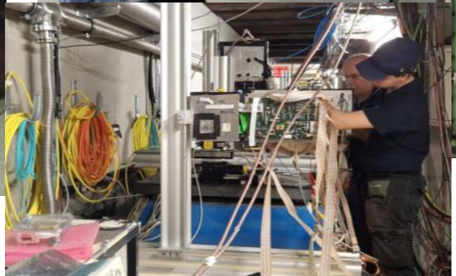
Energy deposited in the **calorimeter** for **non oriented** and **axial** orientation

Conclusions & outlooks

- The tracking system was upgraded to allow the silicon microstrip detectors to **self generate** a **trigger signal** when a charged **particle** crosses a given **strip interval** → Beam size and angular divergence reduced selecting a portion of the beam to **match** the **experimental requirements** of GALORE and e+BOOST
- The upgraded test system proved to **work properly**, for both the experiments, allowing the collection of a **statistics large enough** in a short time
- During the GALORE beamtest, **statistics** was **acquired** 20-30 times **faster**
- For the crystal-based hybrid positron source beamtests, different crystal radiators have been tested, and the relative **increment** in the produced **radiation** have been **measured**
- The **system** is **versatile**: in the **future** it can be applied to any kind of beamtest where a high-resolution particle tracking is needed, with the possibility to **select** a small portion of the beam thus **reducing** also the divergence, which is a fundamental parameter when studying oriented crystals



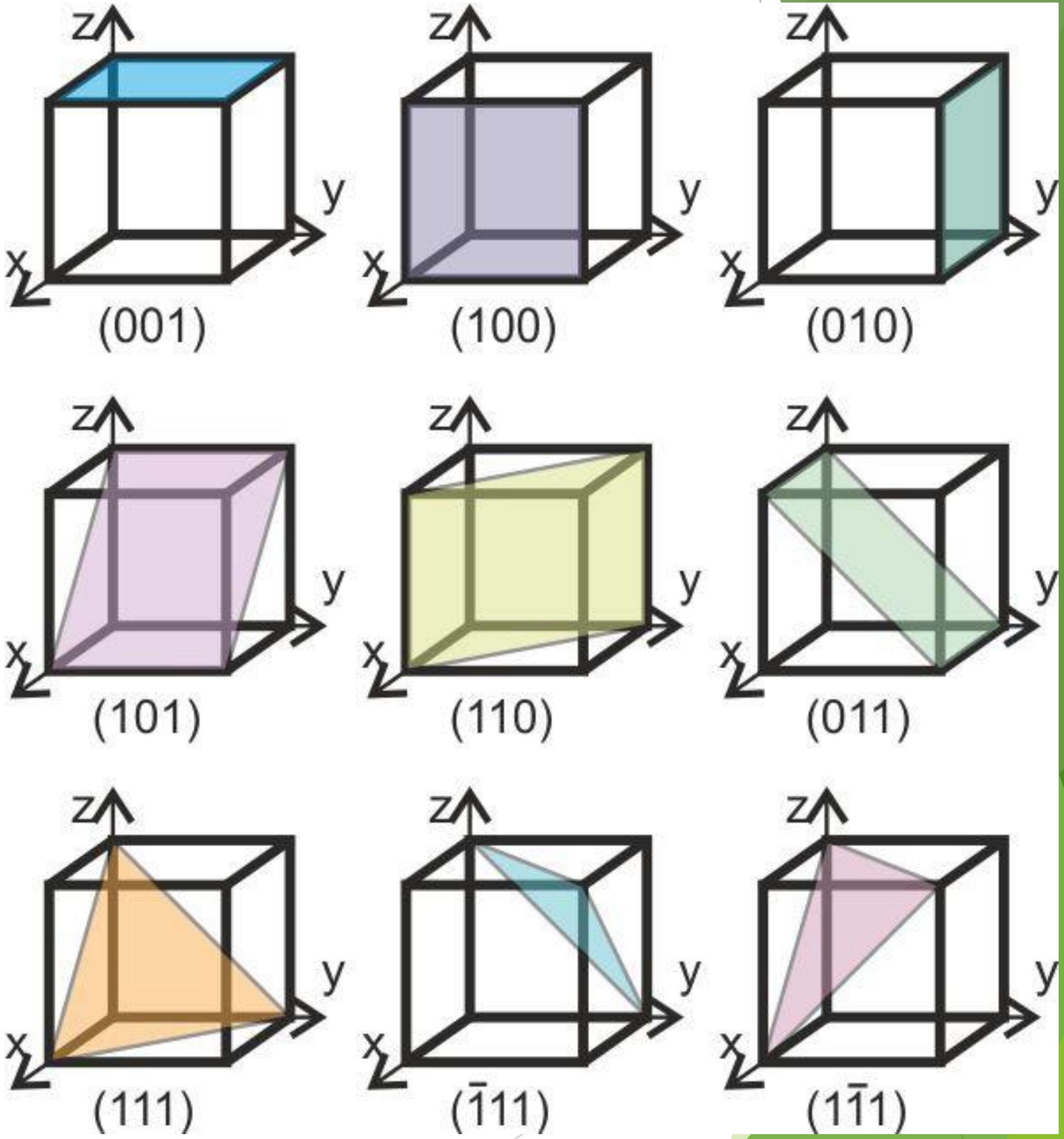
Thanks for your attention



Backup slides

Miller indices

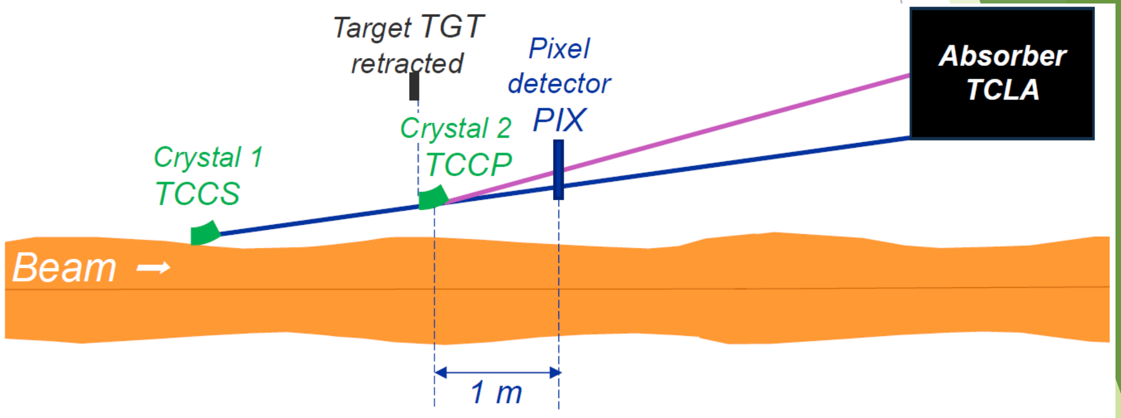
- $[hkl]$ represents a direction
- $\langle hkl \rangle$ represents a set of directions, that is all the $[hkl]$ equivalent directions under the symmetry group of the crystal. For instance, in a cubic crystal the $\langle 100 \rangle$ directions are $[100]$, $[010]$, $[001]$, $[\bar{1}00]$, $[0\bar{1}0]$ and $[00\bar{1}]$
- (hkl) represents a plane
- $\{hkl\}$ represents a set of all the planes equivalent under the symmetry group of the crystal, as for $\langle hkl \rangle$ in the direction case.

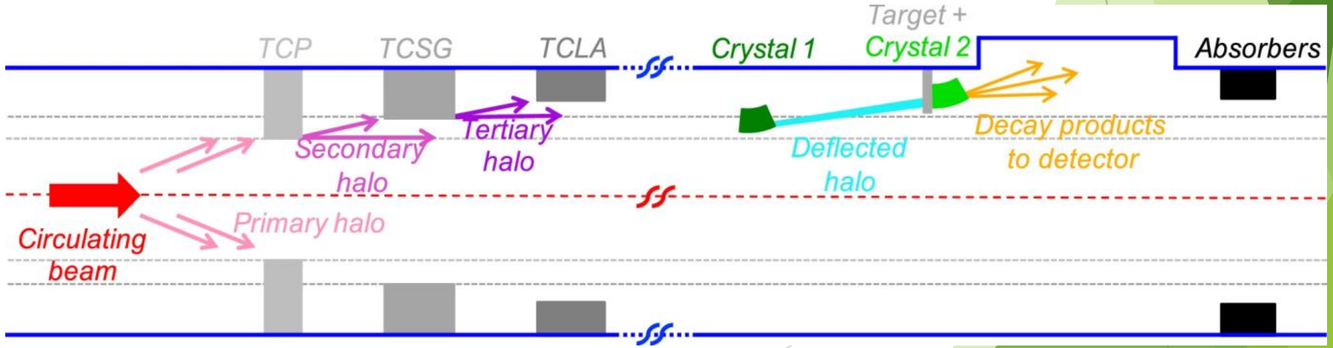


What are bent crystal already used for?

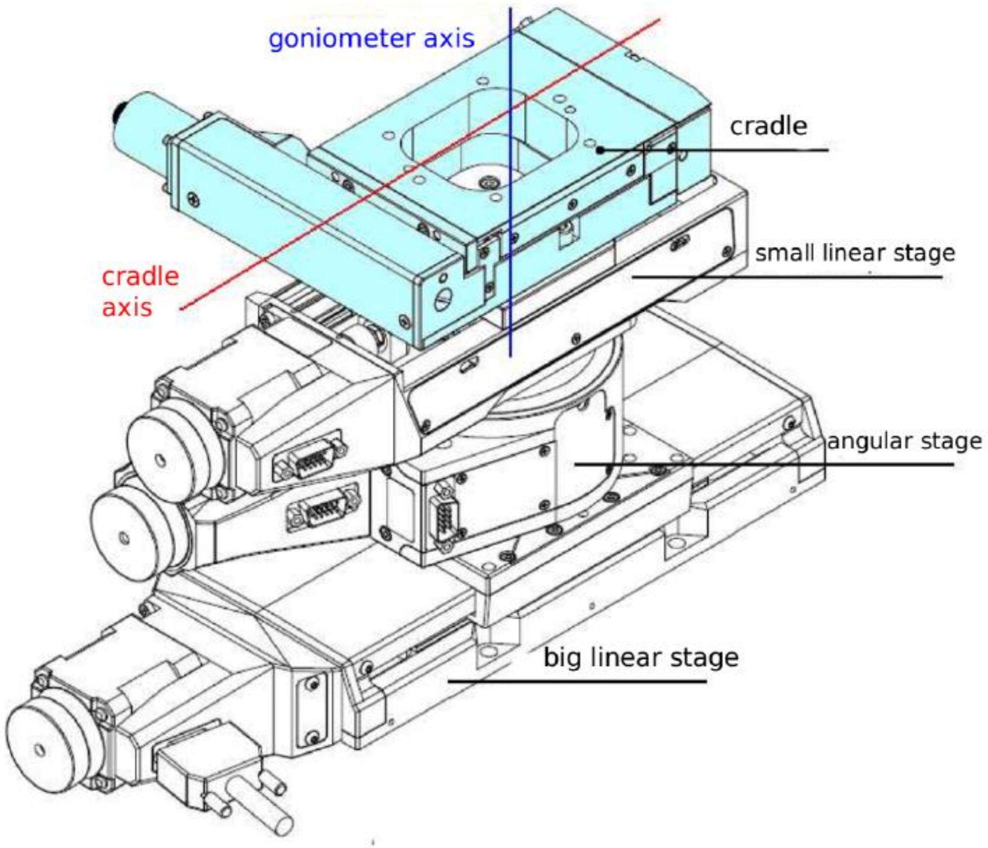
Few mm of crystals can act as **hundreds of Tesla magnets:**

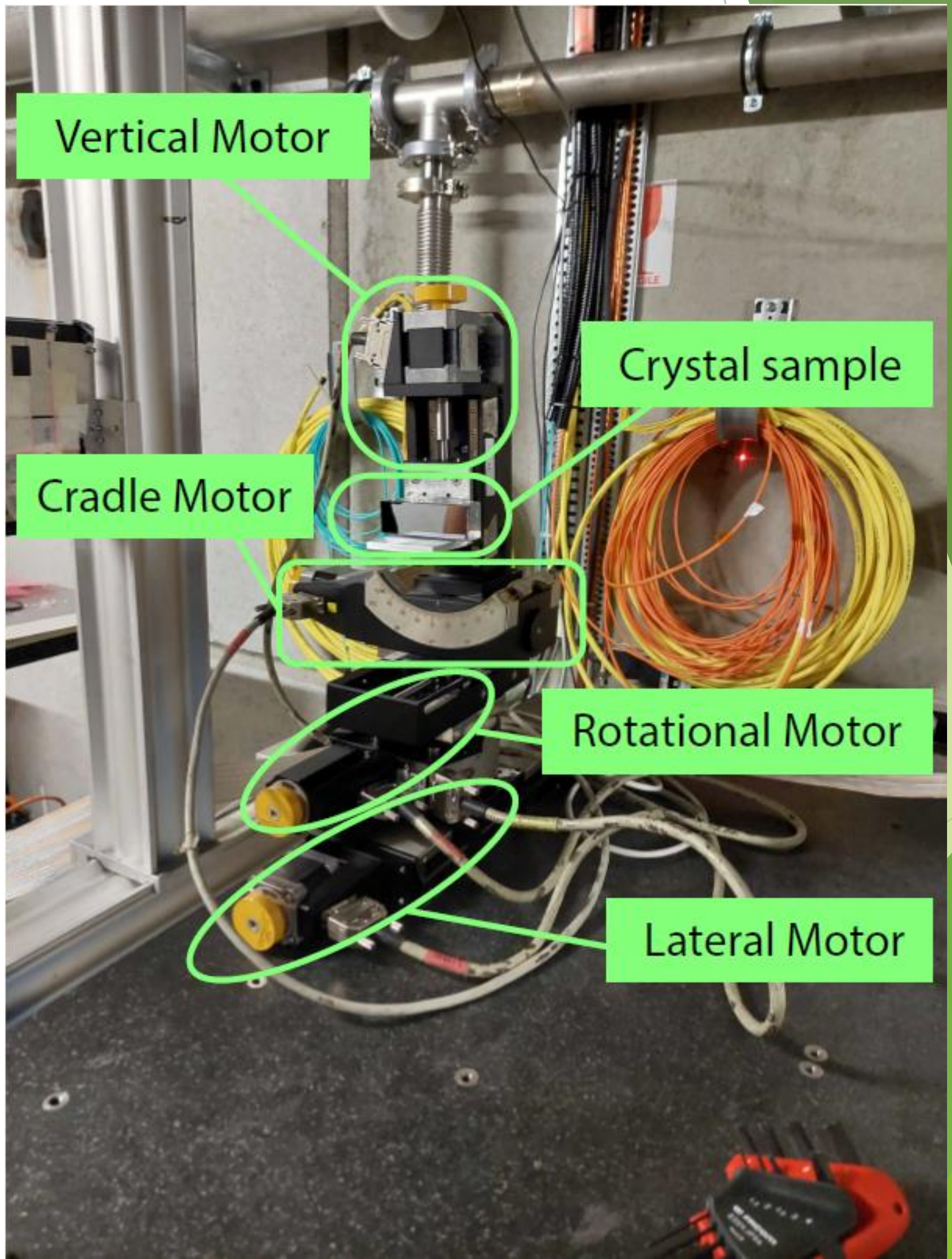
- Beam collimation
- Extracted beamlines
- **Physics Beyond Standard Models**: the magnetic moment of short-lived charmed baryons can be measured from the magnetic moment precession induced inside a bent crystal



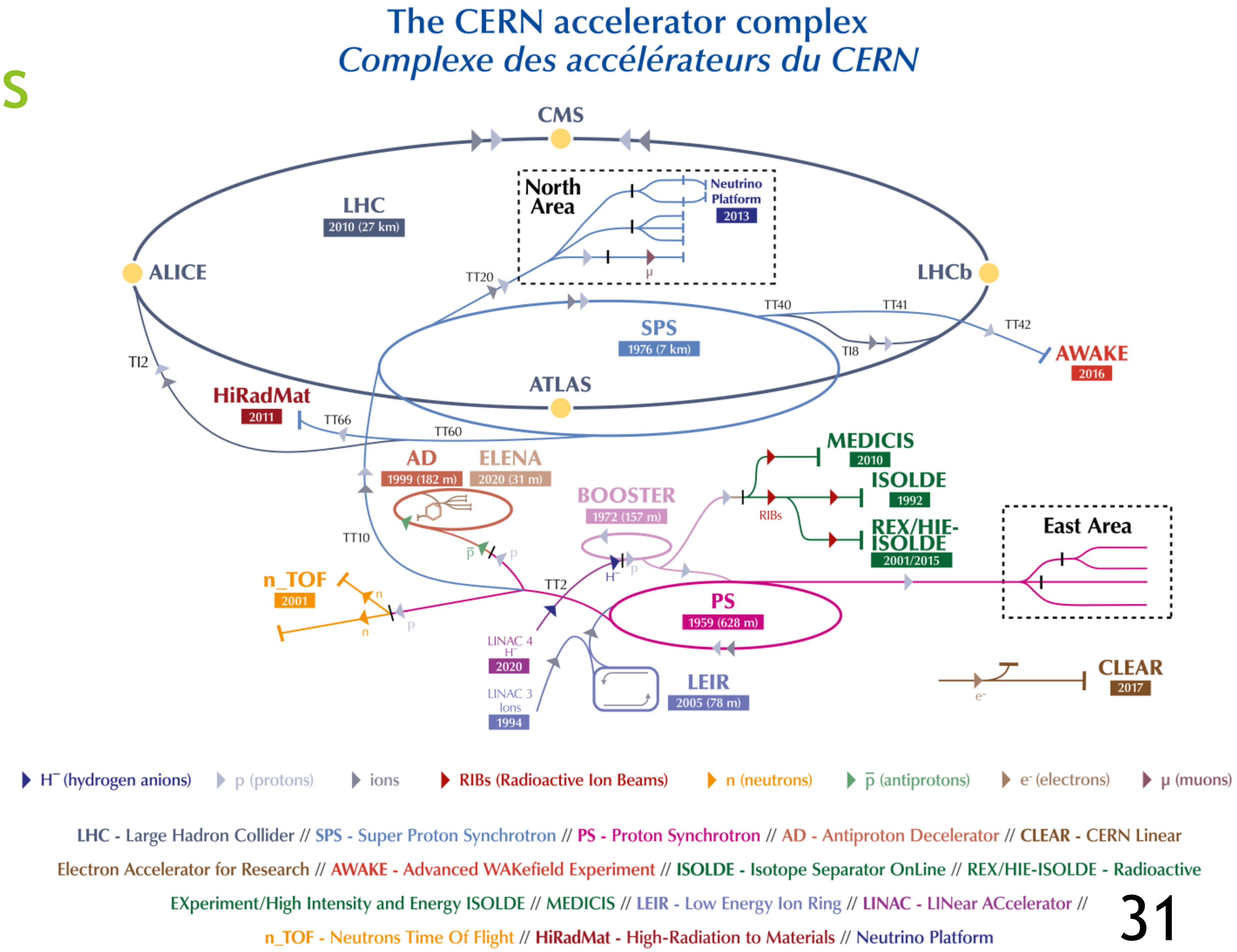


Multi-stage high-precision goniometer





CERN Beamlines



Main features of the ASICs

Table 3.1: Main features of the TA1 ASIC.

ASIC name	TA1
Process (N-well CMOS)	1.2 µm
Surface	$4.85 \times 6.9\,\mathrm{mm}^2$
Thickness	$\sim 600\,\mu\mathrm{m}$
Number of channels	128
Input pad size	$50 \times 90\,\mu\mathrm{m}^2$
Input pad pitch	100 µm
Control pad size	$90 \times 90\,\mu\mathrm{m}^2$
Control pad pitch	200 µm
ENC at 2 µs of peaking time	$165 \pm 6.11/\mathrm{pF}$
Peaking time	1 - 3 µs
Dynamic range	±5 MIPs
Current gain	$\sim 20\,\mu\mathrm{A/fC}$
Gain	25 mV/fC

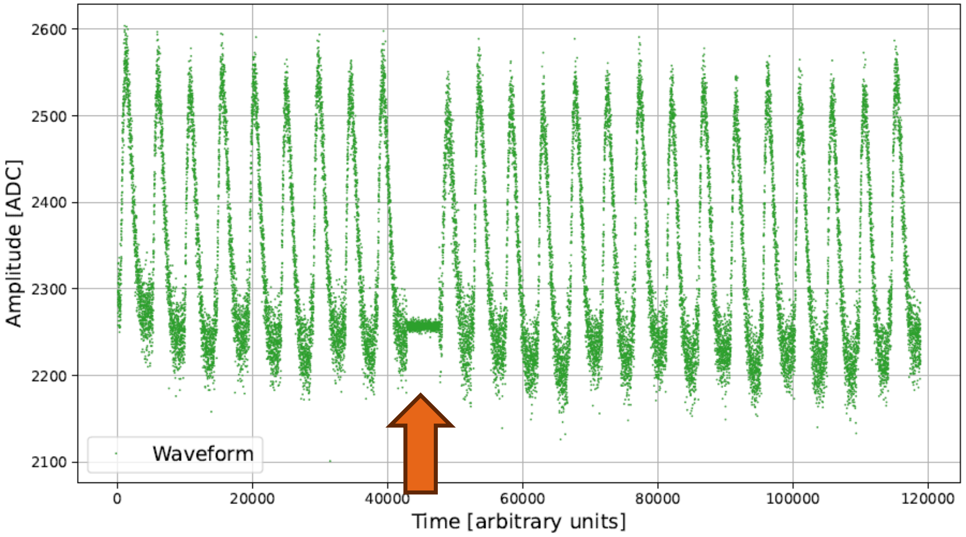
Table 3.2: Main features of the VA2 ASIC. Table from [78].

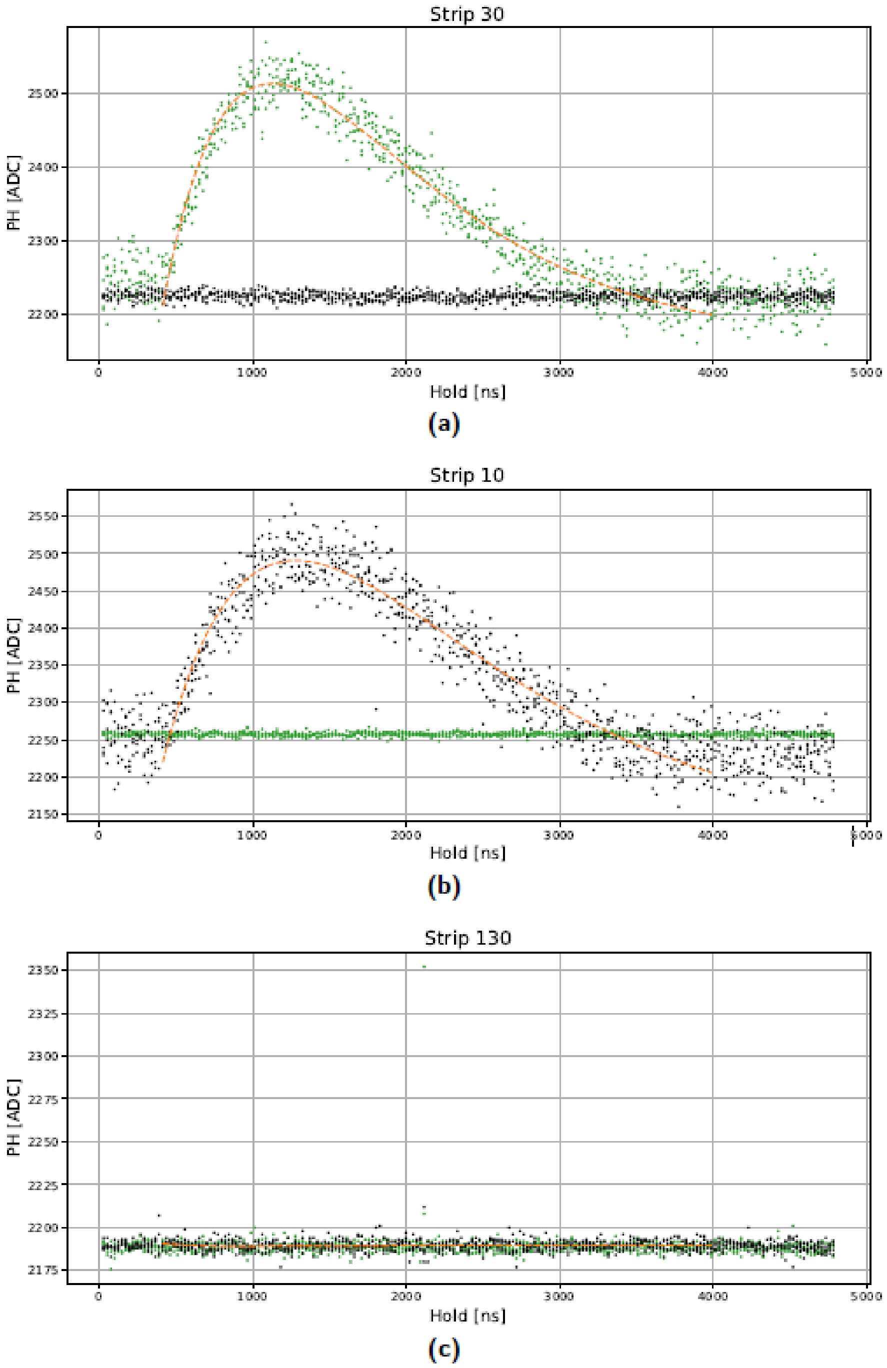
ASIC name	VA2
Process (N-well CMOS)	1.2 µm
Die surface	$6.18 \times 4.51\,\mathrm{mm}^2$
Die thickness	$\sim 600\,\mu\mathrm{m}$
Number of channels	128
Input pad size	$50 \times 90\,\mu\mathrm{m}^2$
Output pad size	$80 \times 90\,\mu\mathrm{m}^2$
ENC at 1 µs of peaking time	$80 + 15 \cdot C_d$ ($e-$ rms)
Power consumption	170 mW
Slow shaper peaking time	1 - 3 µs
Fast shaper peaking time	not present
Dynamic range	±4 MIPs
Current gain	$\sim 25\,\mu\mathrm{A/fC}$

Table 3.3: Main features of the VA1TA ASIC. Table from [78].

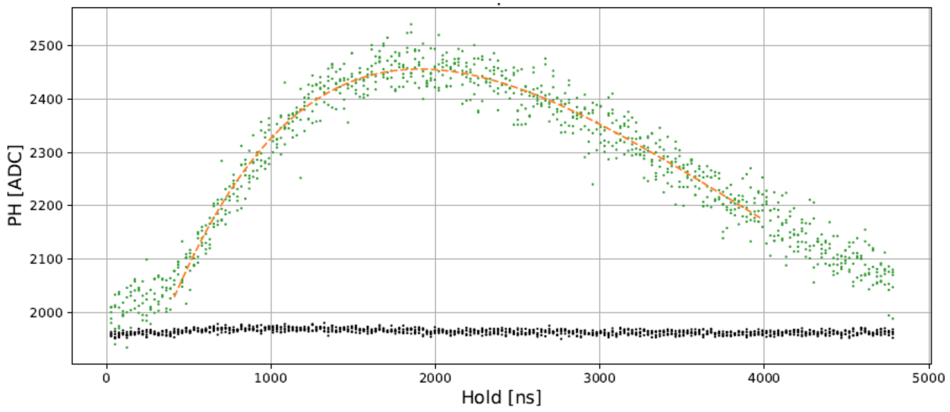
ASIC name	VA1TA
Process (N-well CMOS)	0.35 µm
Die surface	$9.28 \times 6.12\,\mathrm{mm}^2$
Die thickness	$\sim 725\,\mu\mathrm{m}$
Number of channels	128
Input pad size	$50 \times 90\,\mu\mathrm{m}^2$
Output pad size	$90 \times 90\,\mu\mathrm{m}^2$
ENC at 1 µs of peaking time	$180 + 7.5 \cdot C_d$ ($e-$ rms)
Power consumption	195 mW
Slow shaper peaking time	0.3 - 1 µs
Fast shaper peaking time	0.075 µs or 0.3 µs
Dynamic range	±10 MIPs
Current gain	$\sim 10\,\mu\mathrm{A/fC}$

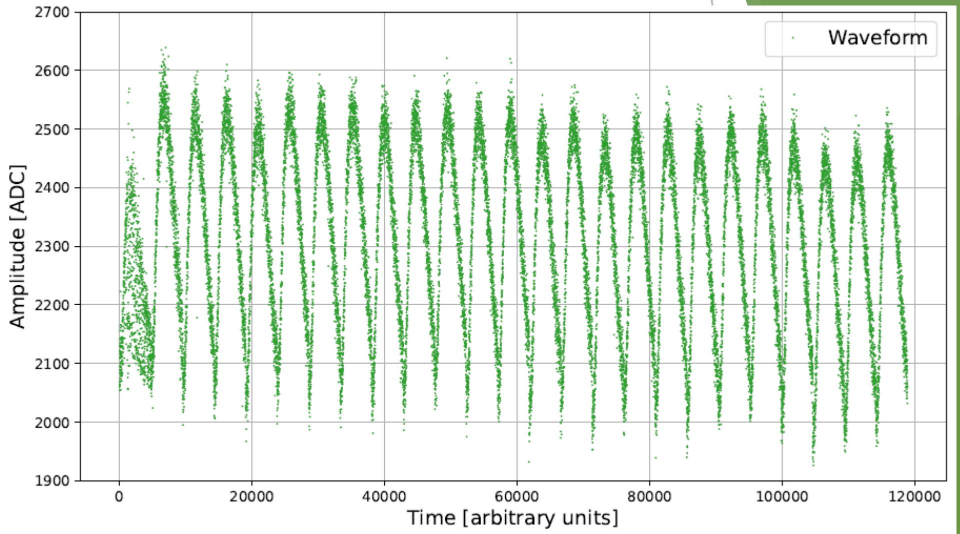
VA1TA Problematic channels

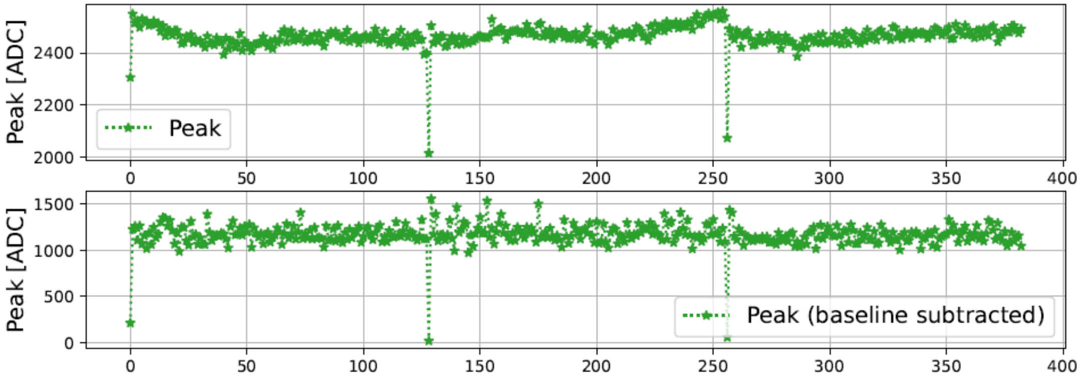


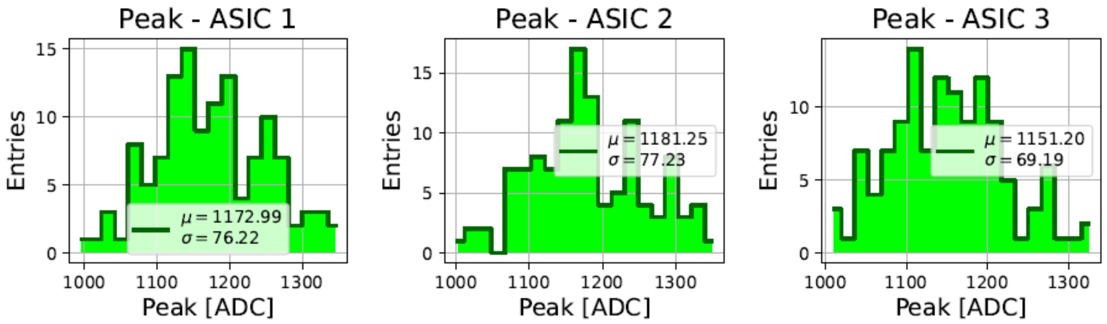


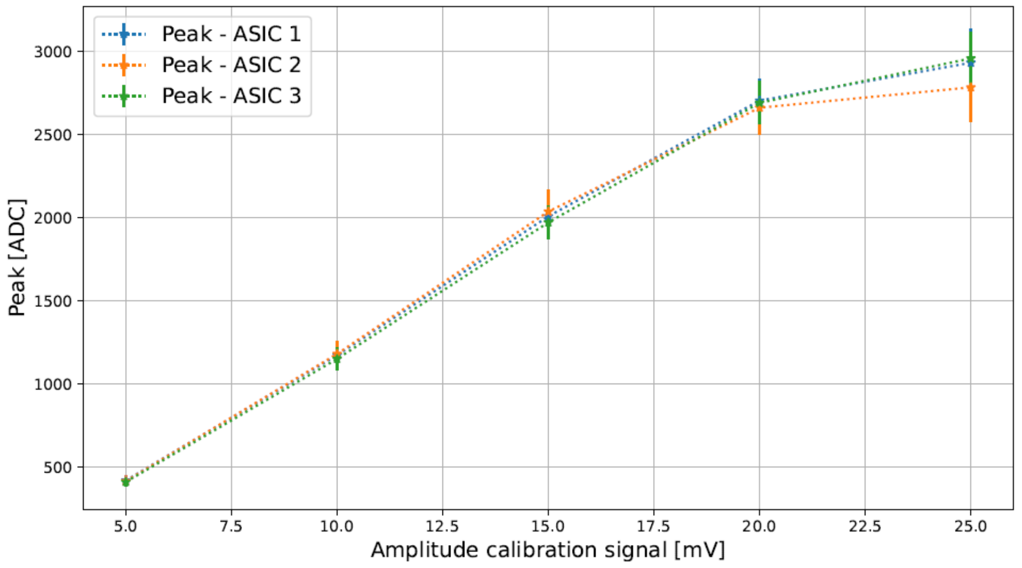
VA2TA Lab Characterization



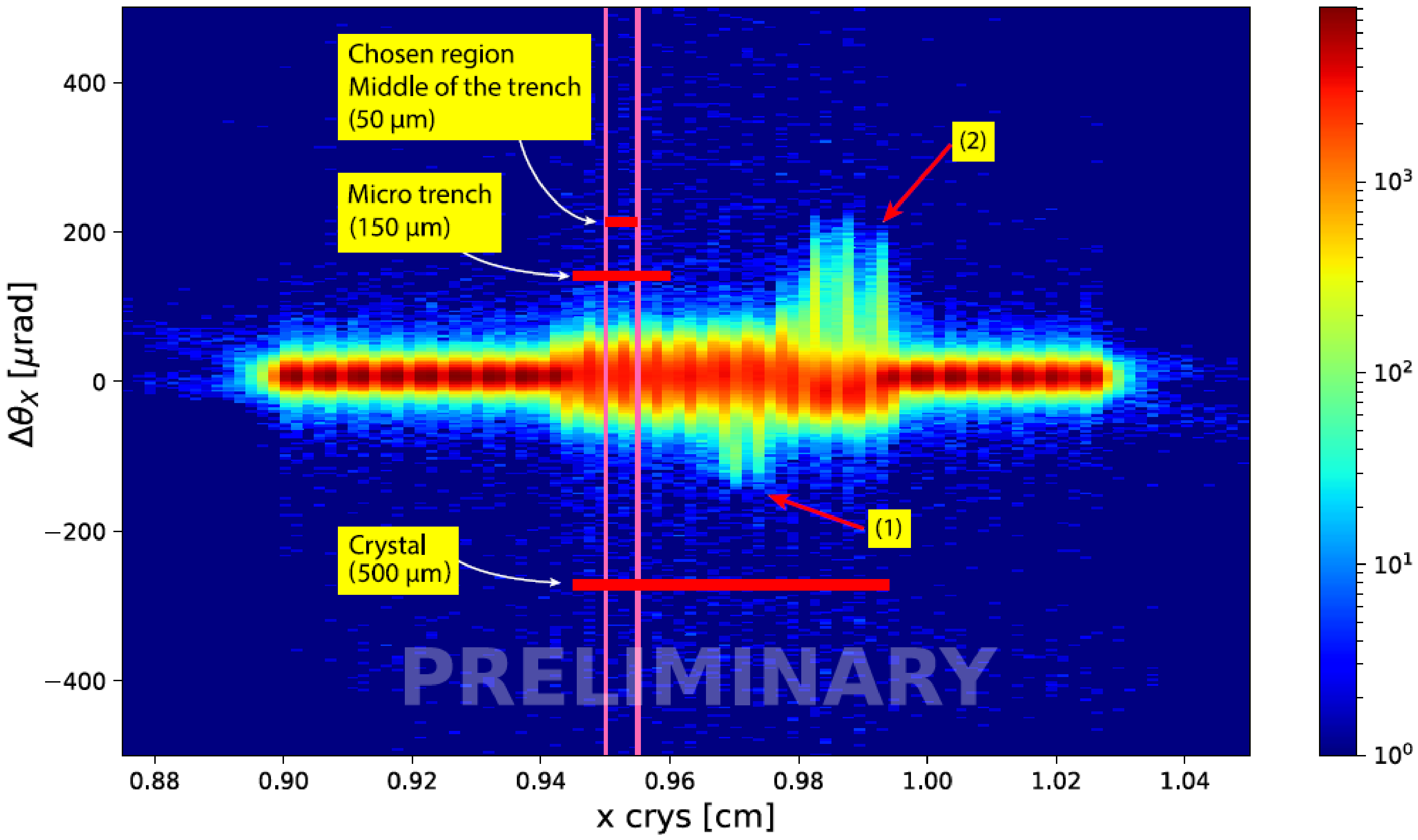








GALORE strange regions

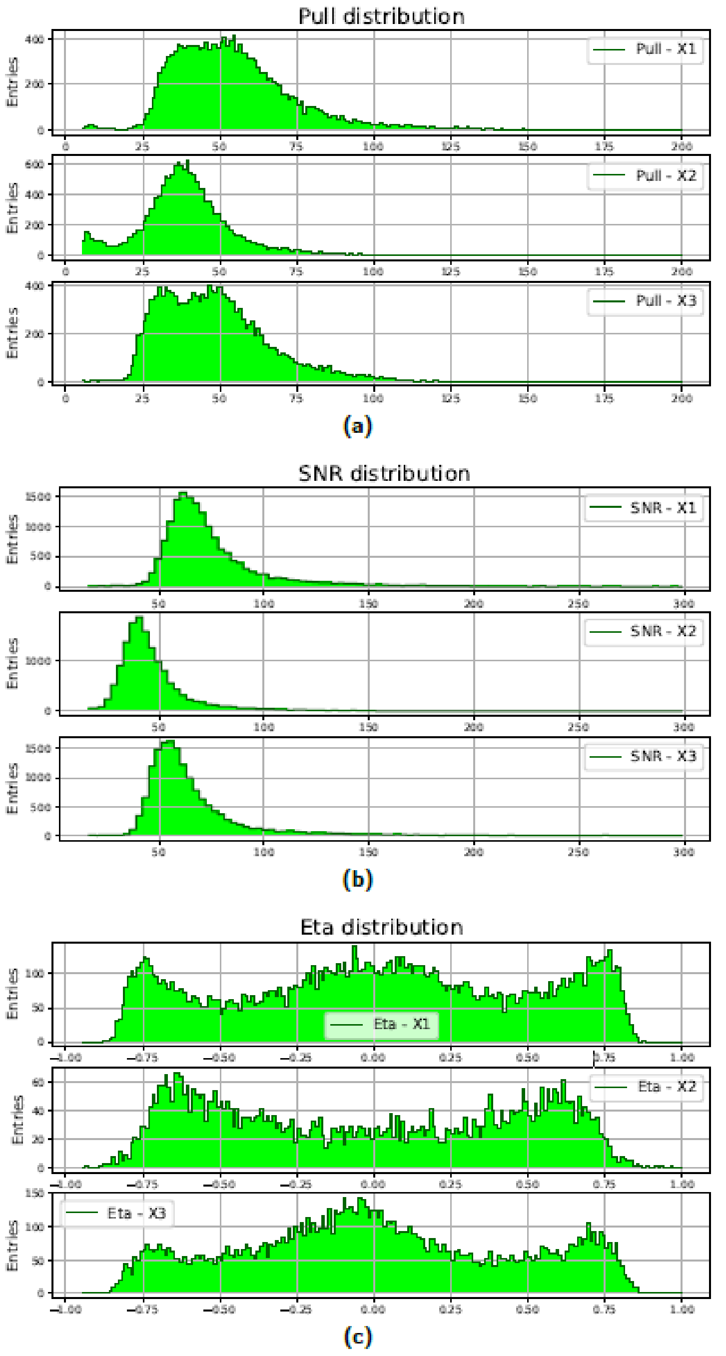


GALORE Beamtest
Performance of the detectors

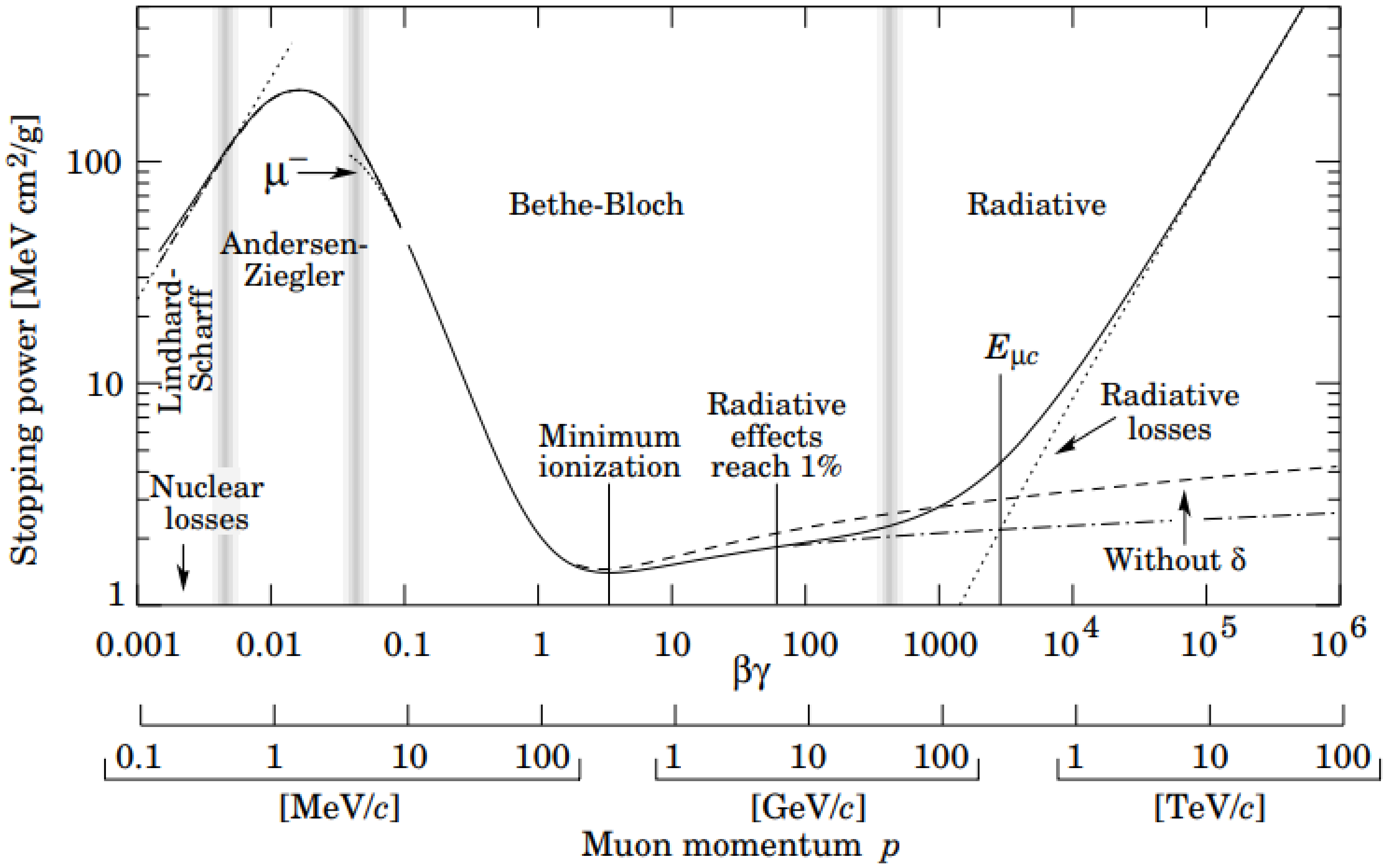
- Pull: ratio between the PH of the channel with the maximum signal and its corresponding noise rms
- Eta: describes the symmetry in the sharing of the charge between nearby strips. Different shapes for single and double side detectors

$$\eta_{\text{right}} = \frac{-\text{PH}_{\text{max}} + \text{PH}_{\text{right}}}{\text{PH}_{\text{max}} + \text{PH}_{\text{right}}}$$

$$\eta_{\text{left}} = \frac{\text{PH}_{\text{max}} - \text{PH}_{\text{left}}}{\text{PH}_{\text{max}} + \text{PH}_{\text{left}}}$$



Bethe-Bloch



Stopping power [MeV cm²/g]
100
10
1
μ⁻
Andersen-
Ziegler
Lindhard-
Scharff
Nuclear
losses
Bethe-Bloch
Radiative
Minimum
ionization
Radiative
effects
reach 1%
$E_{\mu c}$
Radiative
losses
Without δ
0.001
0.01
0.1
1
10
100
1000
10^4
10^5
10^6
βγ
0.1
1
10
100
[MeV/c]
1
10
100
[GeV/c]
1
10
100
[TeV/c]
Muon momentum p