Innovative gamma-ray detectors for environmental and space monitoring

XXXVII cycle – DM1061

PhD final dissertation

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Overview

1. Goal of the project & scientific topic
2. The imaging calorimeter prototype (detector concept, assembling, readout electronics)
3. Characterization of the prototype:
   - in Bari INFN laboratories with Sr90 and CRs
   - at CERN facilities
4. GEANT4 Simulation of the prototype

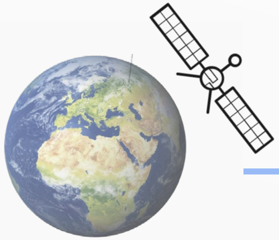
PhD project summary

GOAL: development of innovative satellite-borne or air-borne detectors for low-energy gamma rays (MeV-GeV band)

- Detectors need to meet constraints for space applications
- Imaging calorimeter prototype exploiting the SiPM technology and the coupling between a scintillator crystal and the WLS fibers
  - High segmentation - Reduced material budget - Reduced power consumption

Scientific applications

Detection of gamma rays of astrophysical origin: transient events (Solar Flares, GRBs) and CR interactions with the surface of celestial bodies or the earth's atmosphere



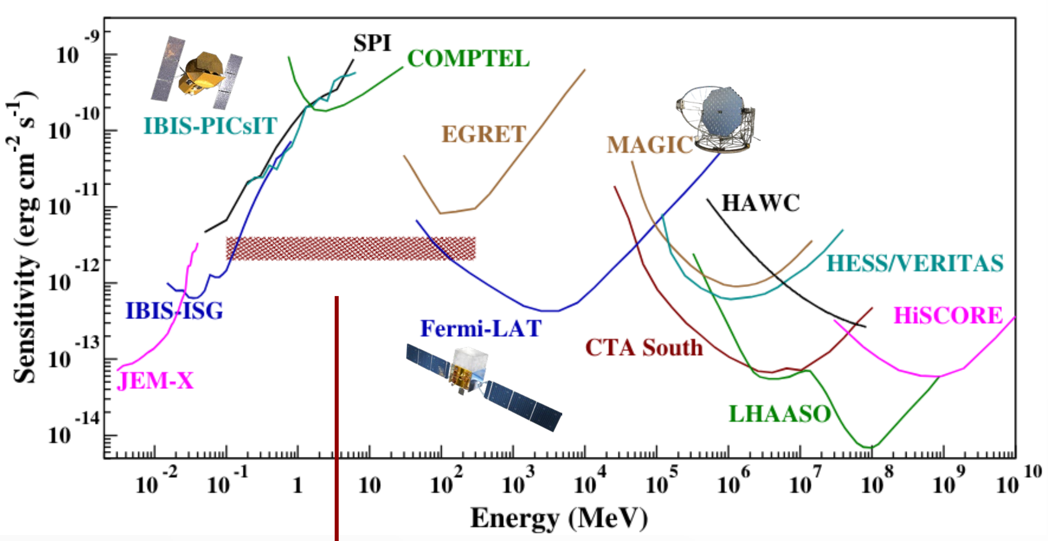
Terrestrial applications

Monitoring of the environmental radioactivity: natural isotopes and artificial products (due to anthropogenic activity, ex: Cs-137, I-131, Co-60)

Science Topic: low-energy gamma rays

- Many astrophysical gamma-ray sources have peak emissivity at energies in the MeV-GeV band
- Satellite experiments are required for detecting gamma rays above the atmosphere

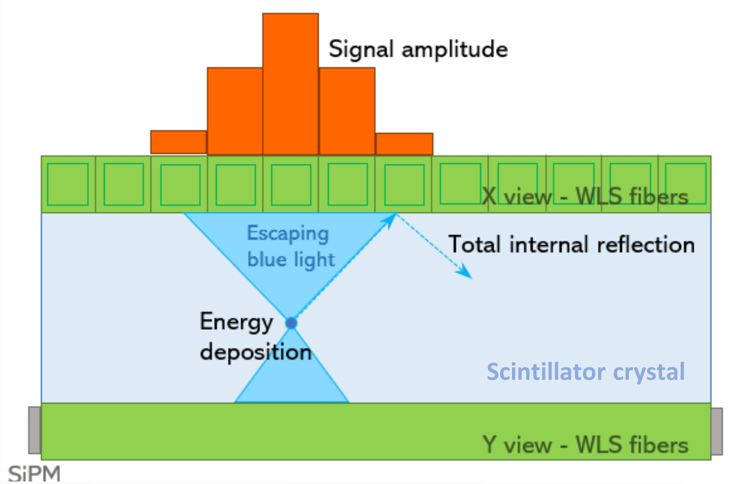
State of the art



Observations in sub-GeV energy band are still poor

- Instrumental limitations have made the exploration of this energy band difficult:
  - Limited capability to evaluate the incoming direction of the photons
  - Large background due to the deactivation of irradiated materials in space
- Recent progress in Silicon detectors and readout microelectronics have re-opened this topic and triggered the development of new detectors

Imaging calorimeter prototype: principle of operation



- An ionizing particle leaves an energy deposit (ΔE) inside the scintillator crystal
- Scintillation light is isotopically produced in the crystal, with a light yield (LY) depending on the material
- WLS fibers within the acceptance cone collect the scintillation photons, shift their wavelengths towards green, and transport them to SiPMs at their ends

$$N_{pe} = LY \times \Delta E \times f_1 \times \varepsilon \times PDE$$

- Crossed fiber planes allow to evaluate (x,y) into the crystal

Scintillator crystal

- high light yield
- matching emission and WLS absorption
- fast decay time
- thickness as a trade off between the absorption length of the incident photon and the range of the electron

WLS fibers

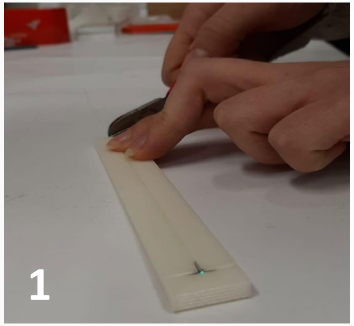
- best optical matching between crystal peak emission and sensor PDE
- fiber size as a trade off between energy resolution and spatial resolution

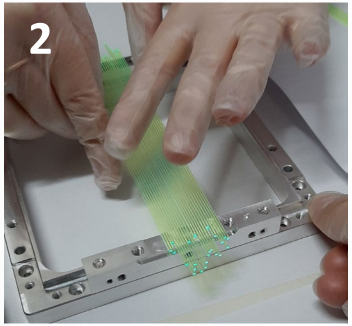
SiPMs

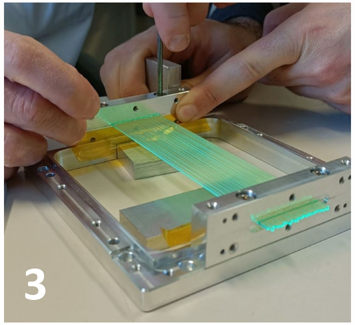
- high gain
- linearity
- micro-cells (side and pitch) determine the number of fibers connected to individual SiPMs

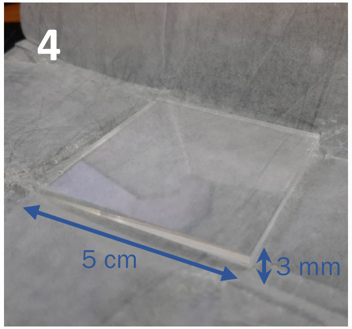
Imaging calorimeter prototype: detector concept

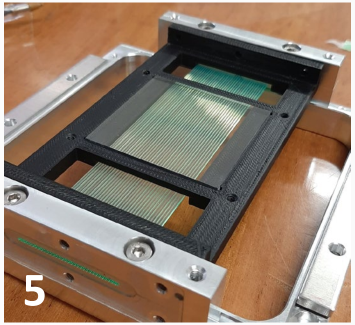
Construction of the prototype





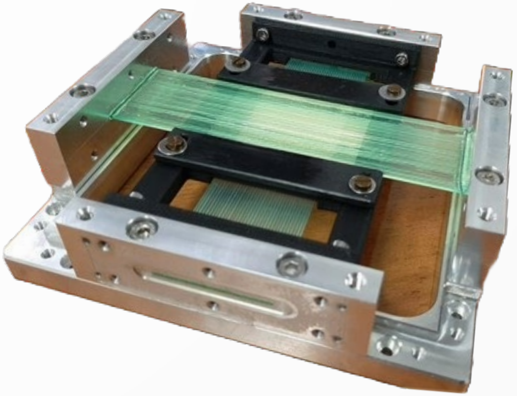






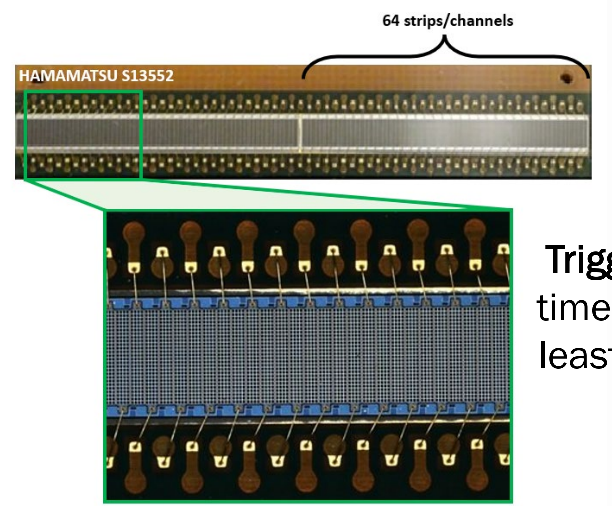
- Modular structure

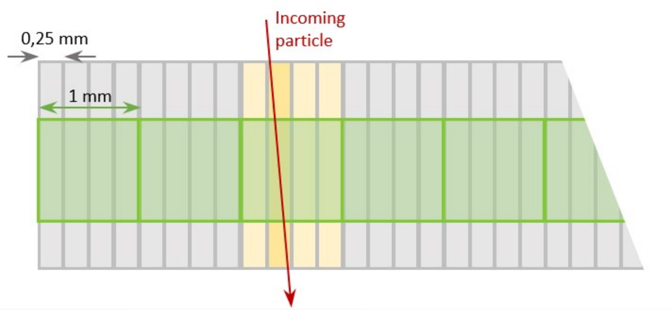
- **Single X-Y module:** 3 mm thick LYSO crystal coupled with two crossed planes of Kuraray Y-11 1mm side square WLS fibers, on its top and bottom faces, read-out by Hamamatsu 128-channels SiPM arrays S13552 at their ends



Read-out system

SiPM channel configuration





PWB interfaces enable different read-out pitches by OR-ing groups of 4 adjacent channels

Trigger: coincidence in a short time window of signals from at least two different channels at opposite sides

Front-end board

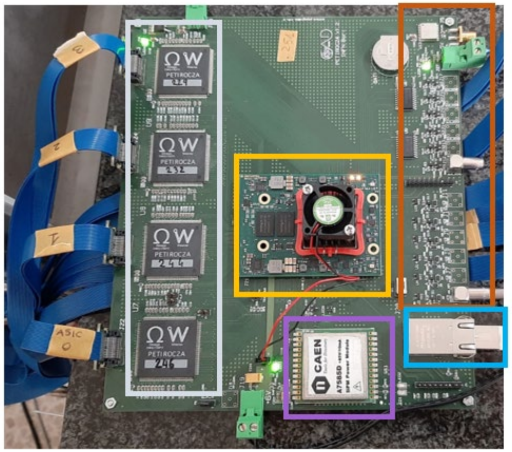
PETIROC 2A (32 channel chip): 32 ADC, TDC and digital outputs for triggering

Kintex-7 FPGA module: data management, trigger, coincidence

CAEN A7585D SiPM voltage module

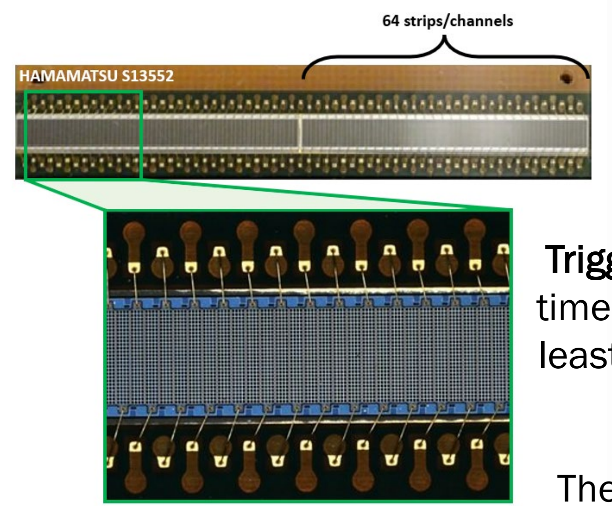
NIM I/O for ext trigger

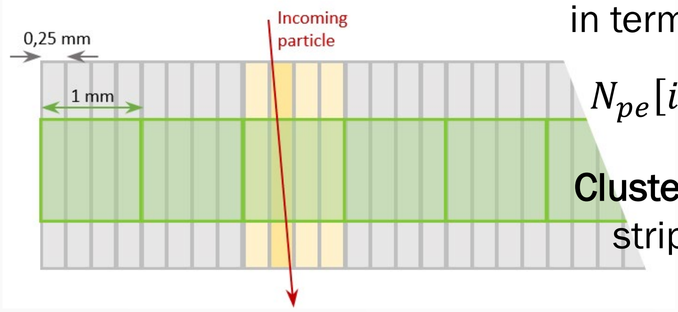
Ethernet



Read-out system

SiPM channel configuration





PWB interfaces enable different read-out pitches by OR-ing groups of 4 adjacent channels

Trigger: coincidence in a short time window of signals from at least two different channels at opposite sides

The charge of each channel in terms of photoelectrons:

$$N_{pe}[i] = \frac{ADC[i] - pede[i]}{gain[i]}$$

Cluster = a group of adjacent strips with a signal at least 3σ above the pedestal

Front-end board

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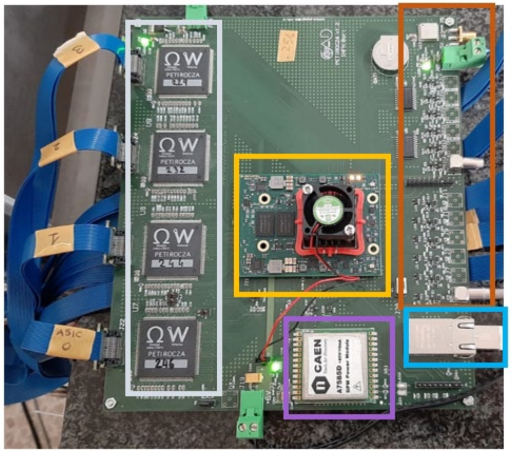
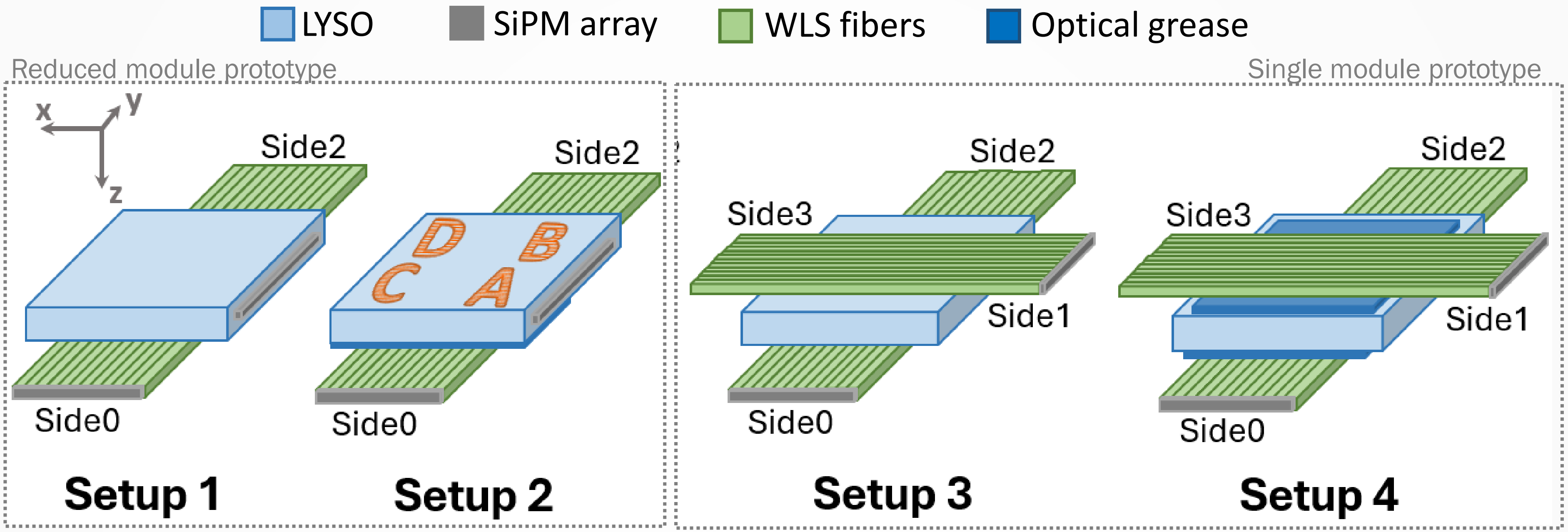


Prototype characterization: measurement setups



Setup 2:
- Single WLS plane
- Grease only covers half the LYSO surface
- Letters indicate the Sr-90 positions.

Setup 3:
- Double WLS planes
- No grease

Setup 4:
- Double WLS planes
- Grease covers top/bottom LYSO surfaces

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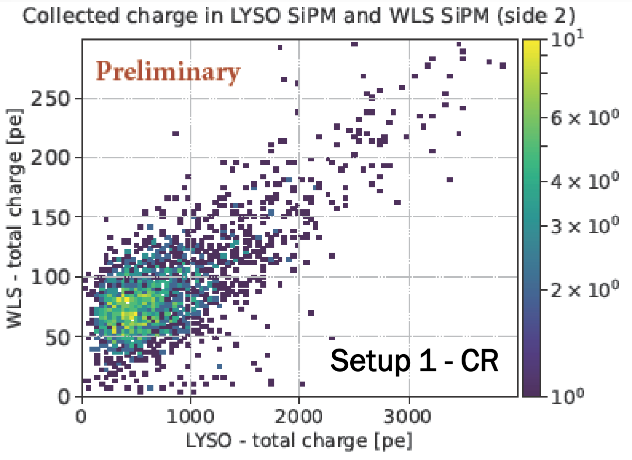
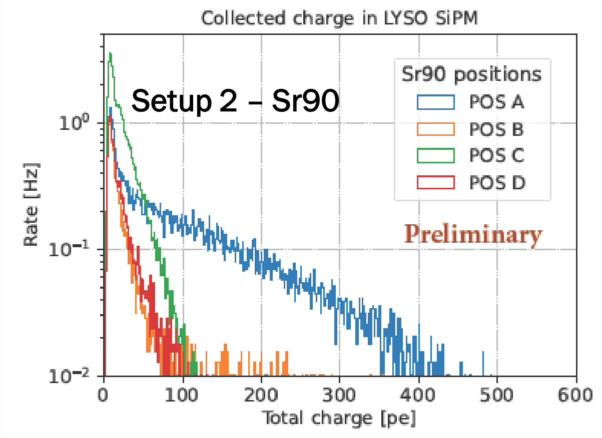
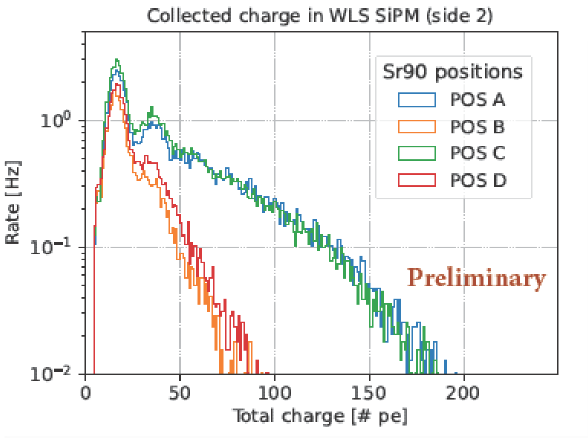
Prototype characterization: light yield results

Reduced module



- WLS and LYSO p.e. are correlated and as expected $WLS_{pe}/LYSO_{pe} \sim 12\ \%$
- However, the values of the collected charges in the SiPMs connected to the LYSO fibers and to the WLS crystal correspond respectively to the 60% and to the 88% of the expected values.





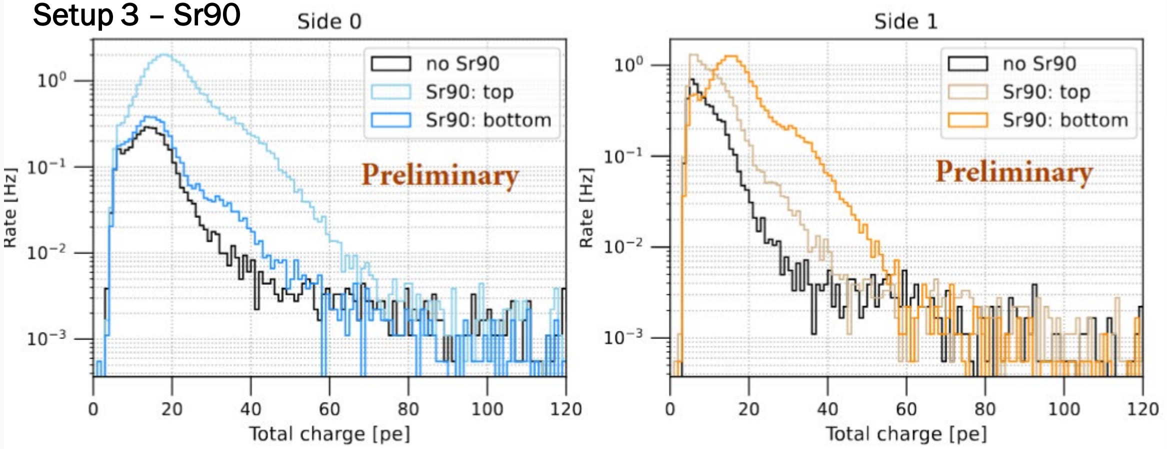
- Direct light contribution into LYSO
- Optical grease improves the light collection by SiPMs

Published in: DOI:10.1016/j.nima.2024.169827

Prototype characterization: light yield results

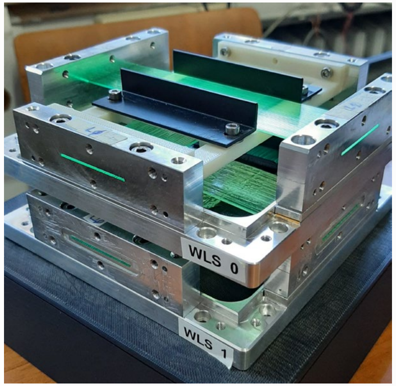
Single module

Setup 3 – Sr90

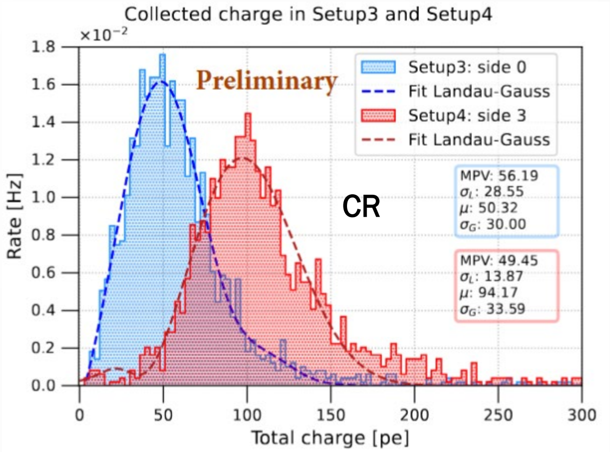


- WLS planes closer to Sr90 collects a higher charge than the other, due to the range of β electrons in the WLS and in the LYSO
- they exhibit two peaks: around 10 p.e. and 20 p.e
- WLS planes far from Sr90 like background
- comparing “symmetric” configurations: side0 collects more charge than side1, due to different couplings between the WLS fiber planes and the crystal surfaces.

Two-module tower

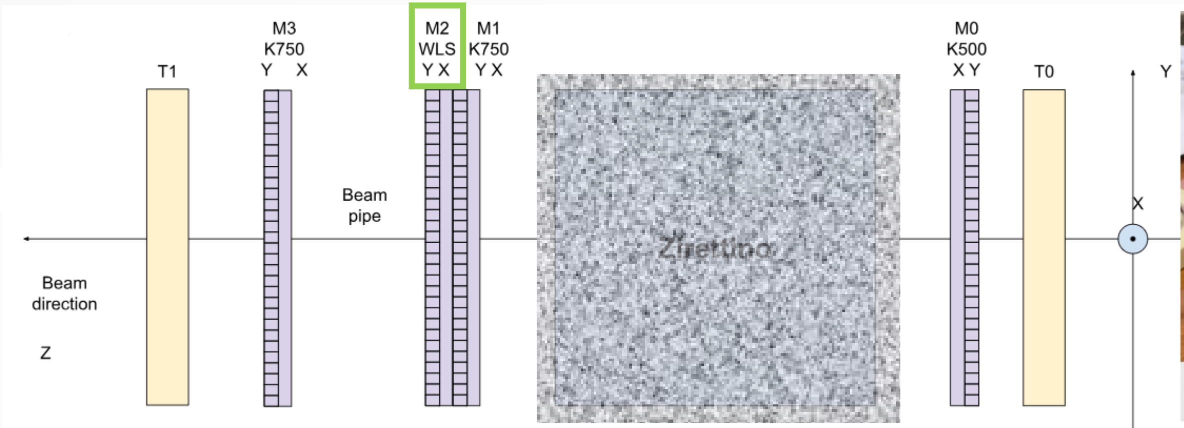


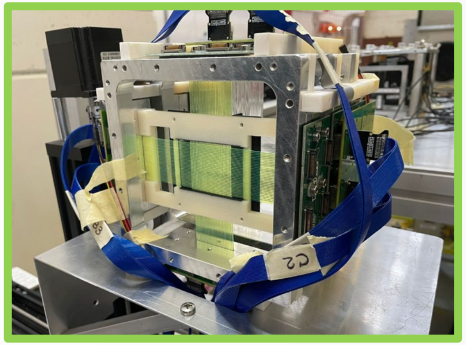
More light collected in Setup4 thanks to the optical grease between the WLS fibers and the LYSO crystal



Beam Test at CERN PS T-10 (2023)

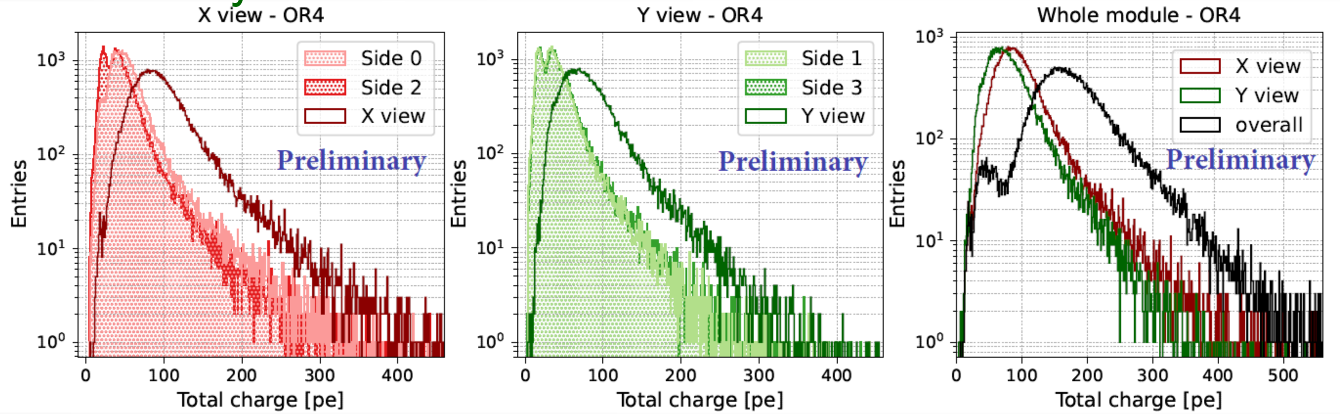
Beam: π^+ 10 GeV/c





T0, T1: 10 cm square tile, 2 fingers (1cm) and 1 veto tile (2cm hole): **external trigger system**

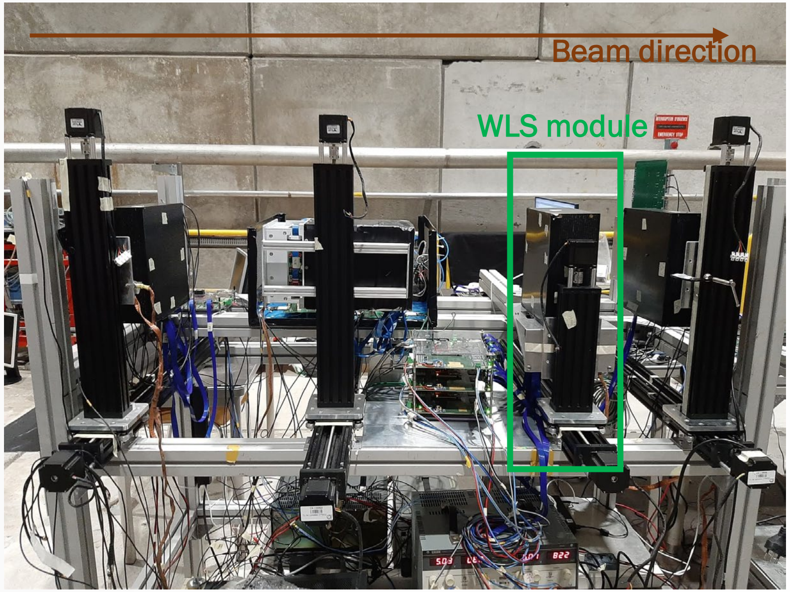
Preliminary results

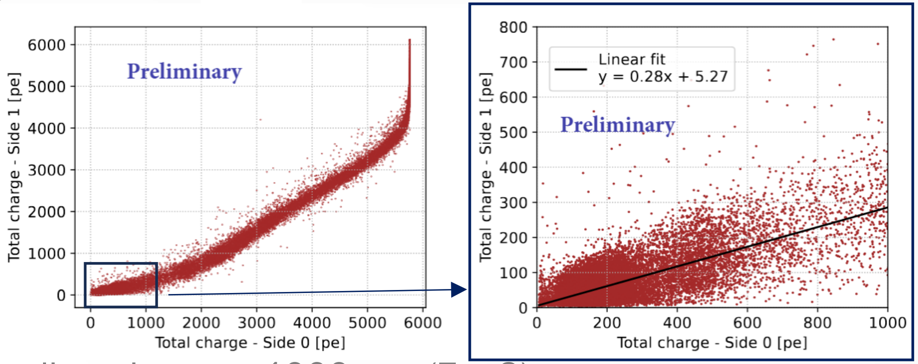


Double-peak structure at 20 p.e. and 40 p.e. in each side
→ expected value: 129 p.e.

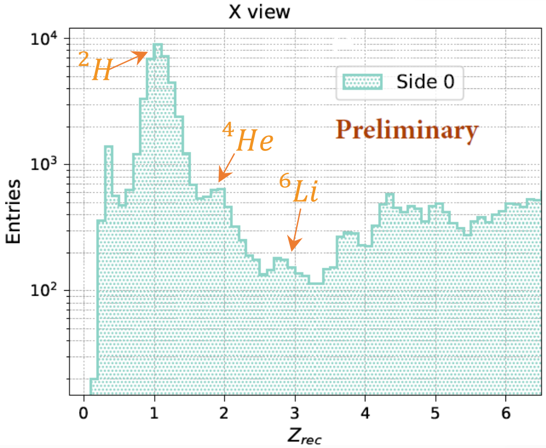
Beam Test at CERN SPS H-8

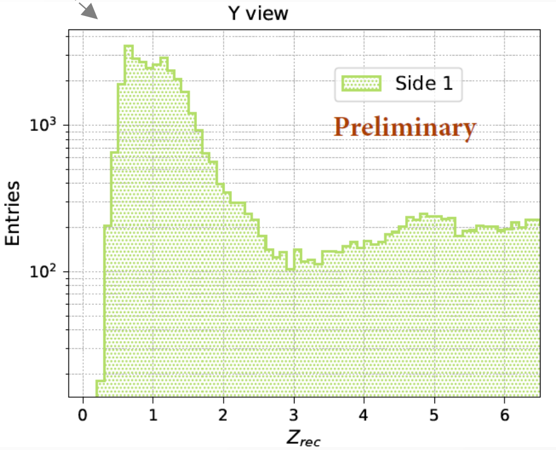
Beam: 150 GeV/c per nucleon





linearity up to 1000 p.e. (Z < 3)





- Charge conversion $Z_{rec} = \sqrt{N_{pe}/N_{first}}$

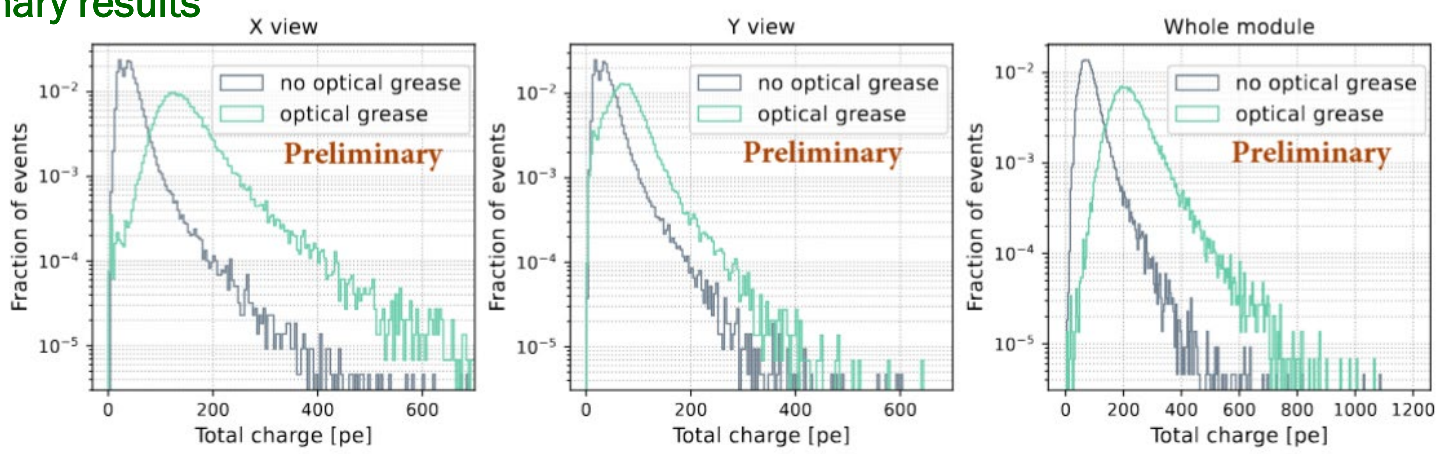
- At higher Z, the linearity is loss, and the peaks are less evident
- For Y view: study of the X/Y view correlation → the peak corresponding to Z = 1 seems to be overwhelmed by the noise peak at Z < 1

Beam Test at CERN PS T-10 (2024)

Beam: π^+ 10 GeV/c

- Differences from the beam test at T-10 of 2023:
  - WLS single module readout by only one side of the X and Y view
  - Between LYSO crystal and WLS fibers a thin layer of optical grease was spread
- The 2023 data in the following plots are referred to the SiPMs on the same side as in 2024.

Preliminary results

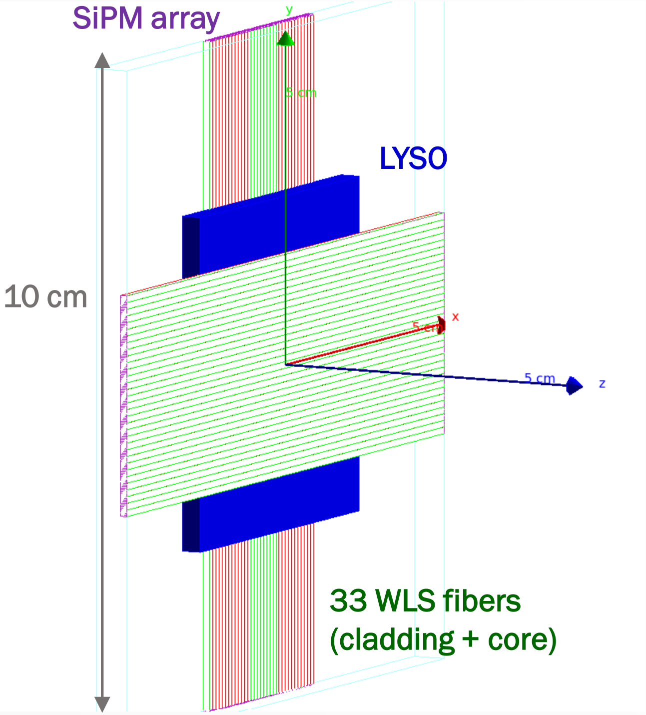


optical grease improves light collection

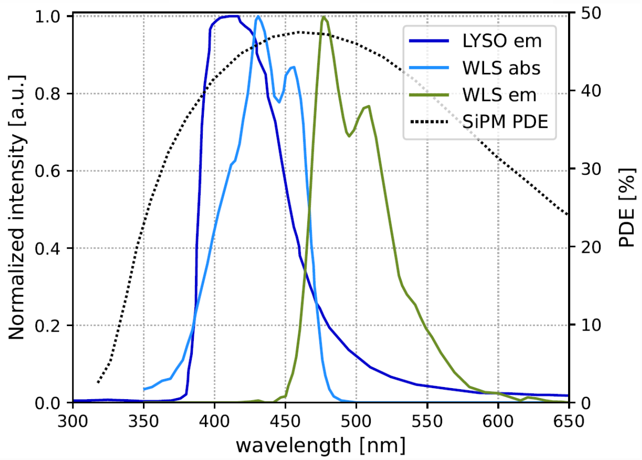
- two peaks in 2023 at 20 p.e. and 40 p.e. → two peaks in 2024 at 20 p.e. and 125 p.e. (expected ~ 300 p.e.)
- 1st peak: scintillation light produced by π in the WLS; 2nd peak: light produced in the LYSO crystal
- Y view less efficient than X view

Simulation study

- Geant4 simulation with optical photons for detector performance studies
- Primary particle generated in a circular region of 1 mm radius
  - e^- of linear energy between 0,5 and 2,2 MeV
  - monoenergetic π^+ of 10 GeV



Operational work window



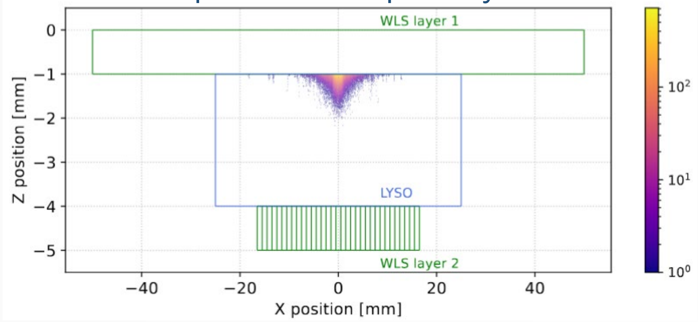
LYSO	
Refractive index	1,82
Density [g/cm³]	7,25
Light yield [ph/keV]	30
Time decay [ns]	42

WLS (PMMA + Polystirene)	
Cladding refractive index	1,49
Core refractive Index	1,59
Time delay [ns]	7,1

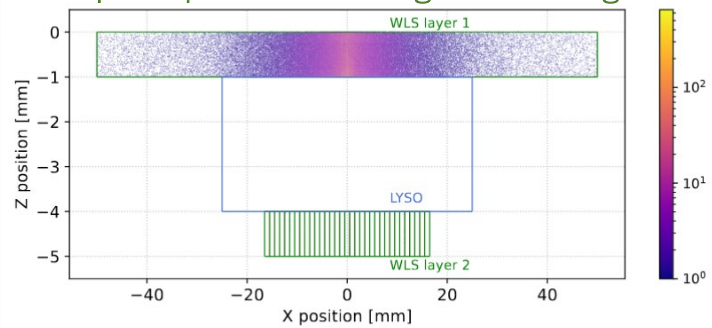
SiPM array	
Refractive index	1,55
PDE	λ dependent

Simulation results: electrons

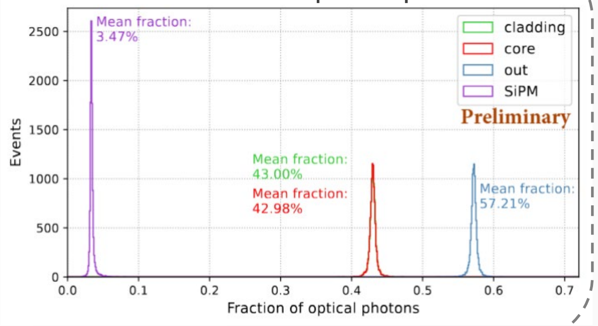
Interaction points of the primary in the LYSO



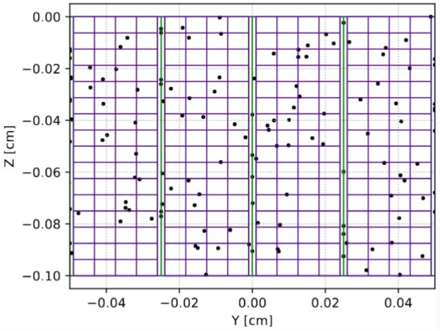
Optical photons entering the claddings

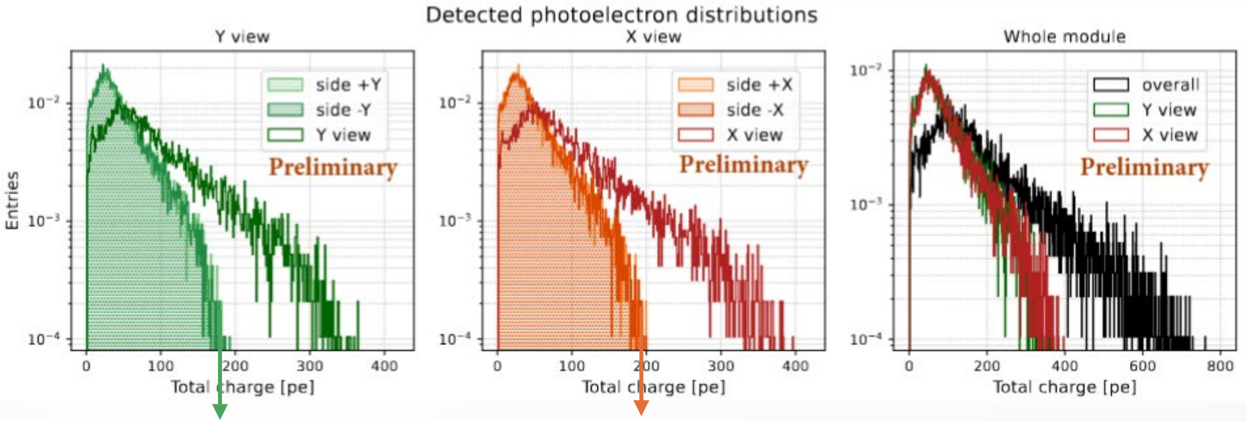


Fractions of optical photons



- N_{pe} computed from optical photons extracting a p.e. (extraction probability given by the PDE)
- Hit microcells of a strip are counted only once (saturation effect)

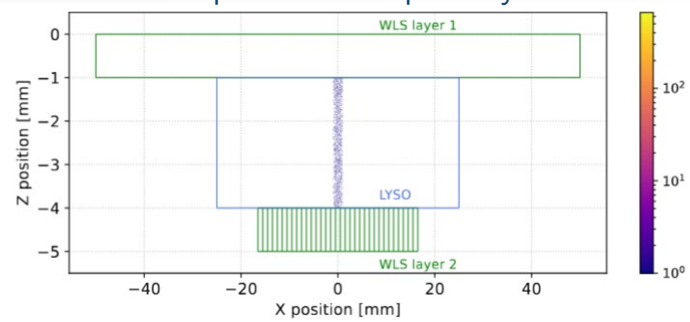




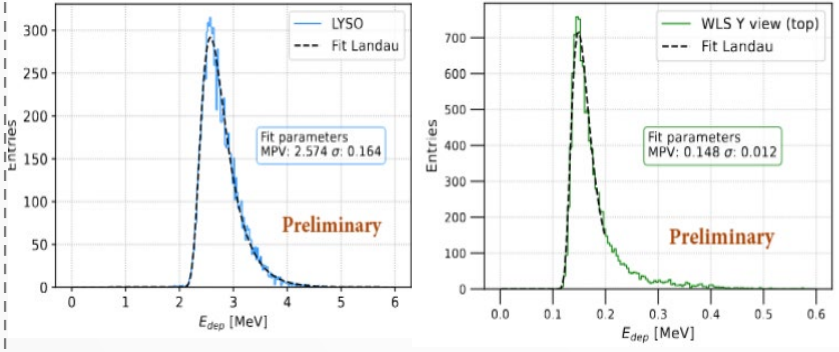
Peak at ~20 p.e. consistent with the experimental results

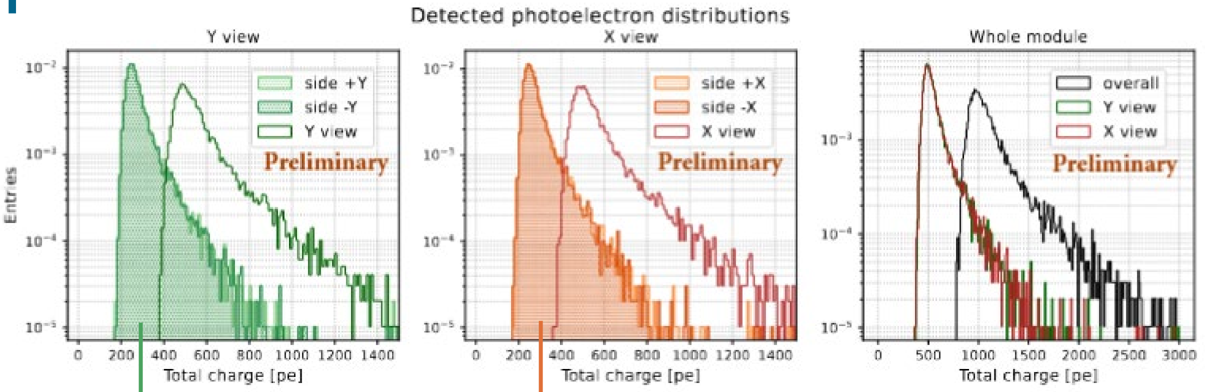
Simulation results: pions

Interaction points of the primary in the LYSO

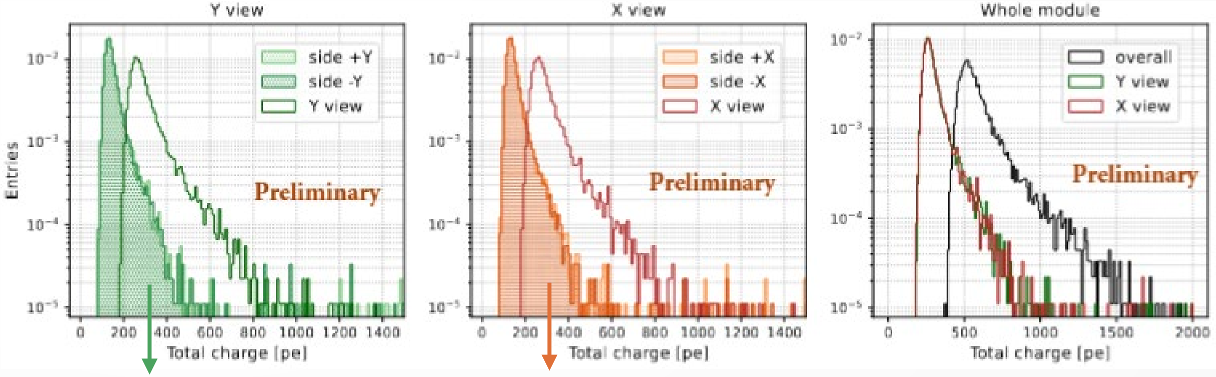


Total energy deposited in LYSO and WLS Y view





peak is found at ~ 250 p.e.: a factor 2 with respect to the experimental results of the beam test T-10 2024



peak is 125 p.e simulating a LYSO crystal with a light yield of 15 ph/keV

Conclusions (1/2)

1. R&D of an innovative detector for low-energy gamma rays, based on a **scintillator crystal** coupled with **WLS fibers** and exploiting the **SiPM technology**
2. Different detector prototypes tested in the INFN Bari laboratories with a Sr-90 and CR, for **light yield studies**:
   i. correlation between the LYSO and WLS charges (~ 60% and 88% of the expected values)
   ii. more light is found in the setup with the optical grease, as expected, thanks to the optimal matching of refractive indices
3. Single module tested in 2023 at CERN-PS T10 beam line with 10 GeV/c π^+: charge distributions exhibited a **two-peak structure**, at 20 and 40 p.e., quite below the expected number of photoelectrons

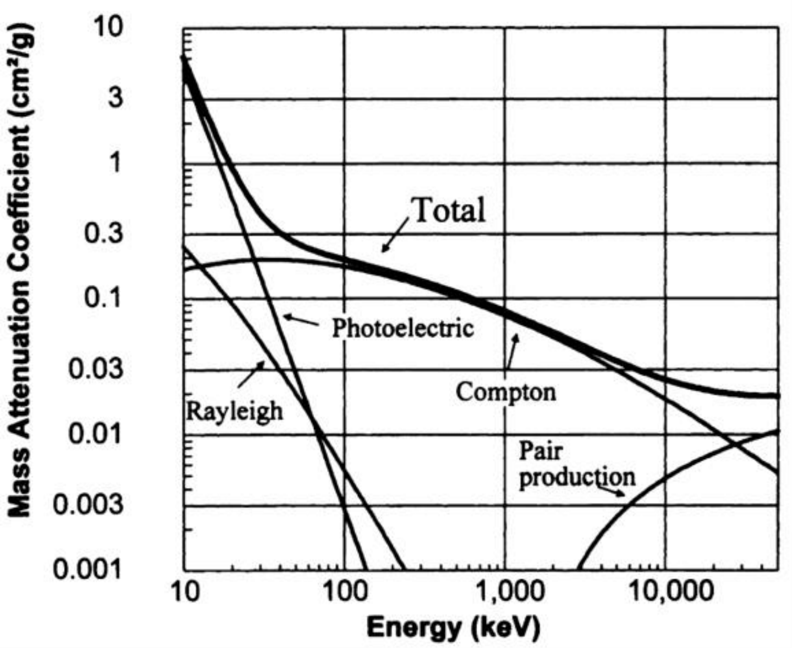
Conclusions (2/2)

4. Single module tested at CERN-SPS H8 line with ions: peak structure associated to the **lighter nuclei**
5. Single module with optical grease tested in 2024 at CERN-T10 beam line with 10 GeV/c π^+: two-peak structure at 20 and 125 p.e.. in the layer upstream the crystal, increased w.r.t. the module without optical grease, but below the theoretical expectations.
6. GEANT4 **simulation**:
    1. simulated data reproduce experimental results obtained with Sr90 in laboratory, but only for the SiPM connected to the WLS fiber layer closer to the source;
    2. simulated data with primary pions reproduce the experimental results only reducing by a factor 2 the light yield of the LYSO crystal
7. Future developments: different crystals (GAGG, CsI), tests on a drone.

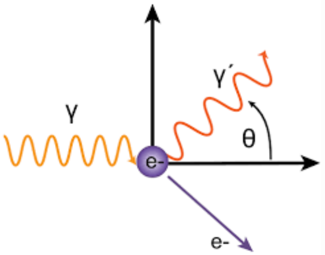
THANKS FOR THE ATTENTION

Backup

Low-energy gamma ray interaction



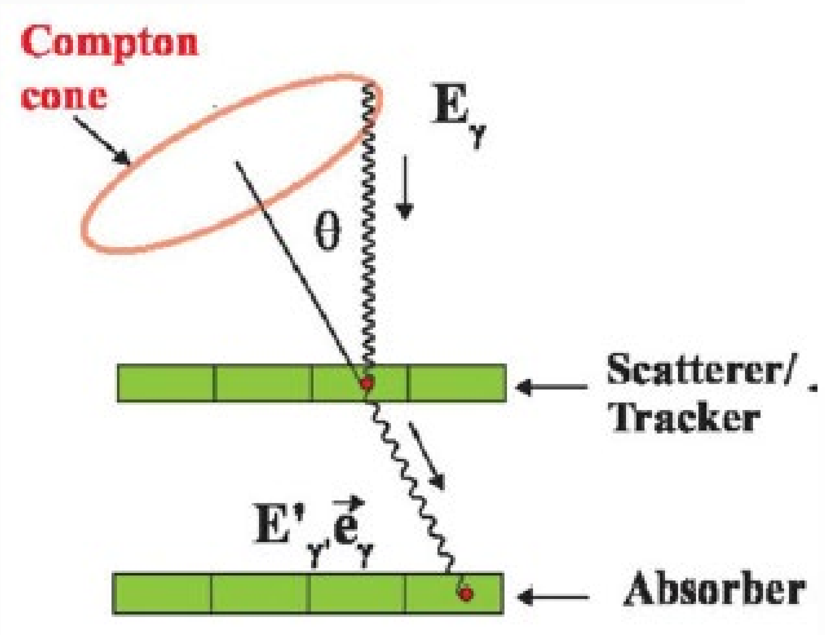
The dominant process of gamma-matter interaction is Compton scattering

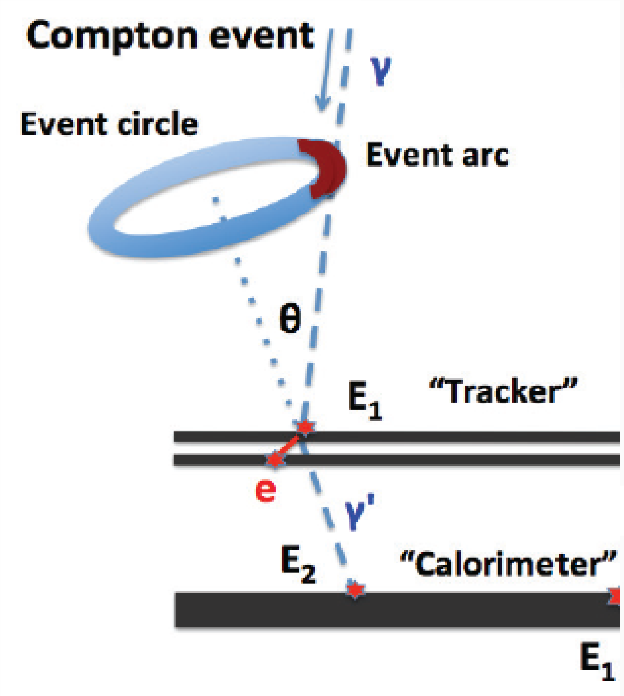


$$\frac{1}{h\nu'} - \frac{1}{h\nu} = \frac{(1-\cos\vartheta)}{m_e c^2}$$

It is needed the measurement of the energies and directions of the photons and the recoil electron
→ the detector has to ensure optimal energy and angular resolution

Compton detection technique

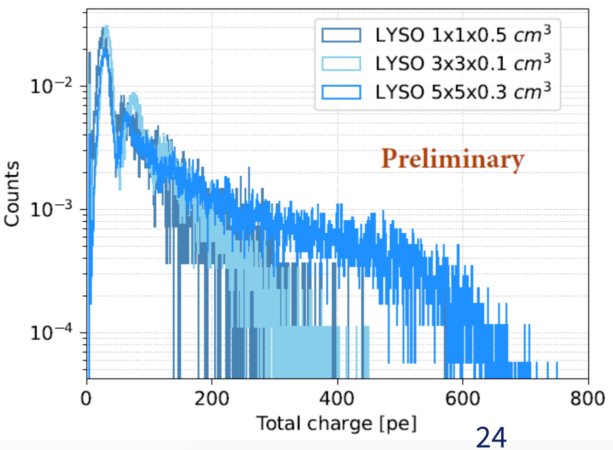




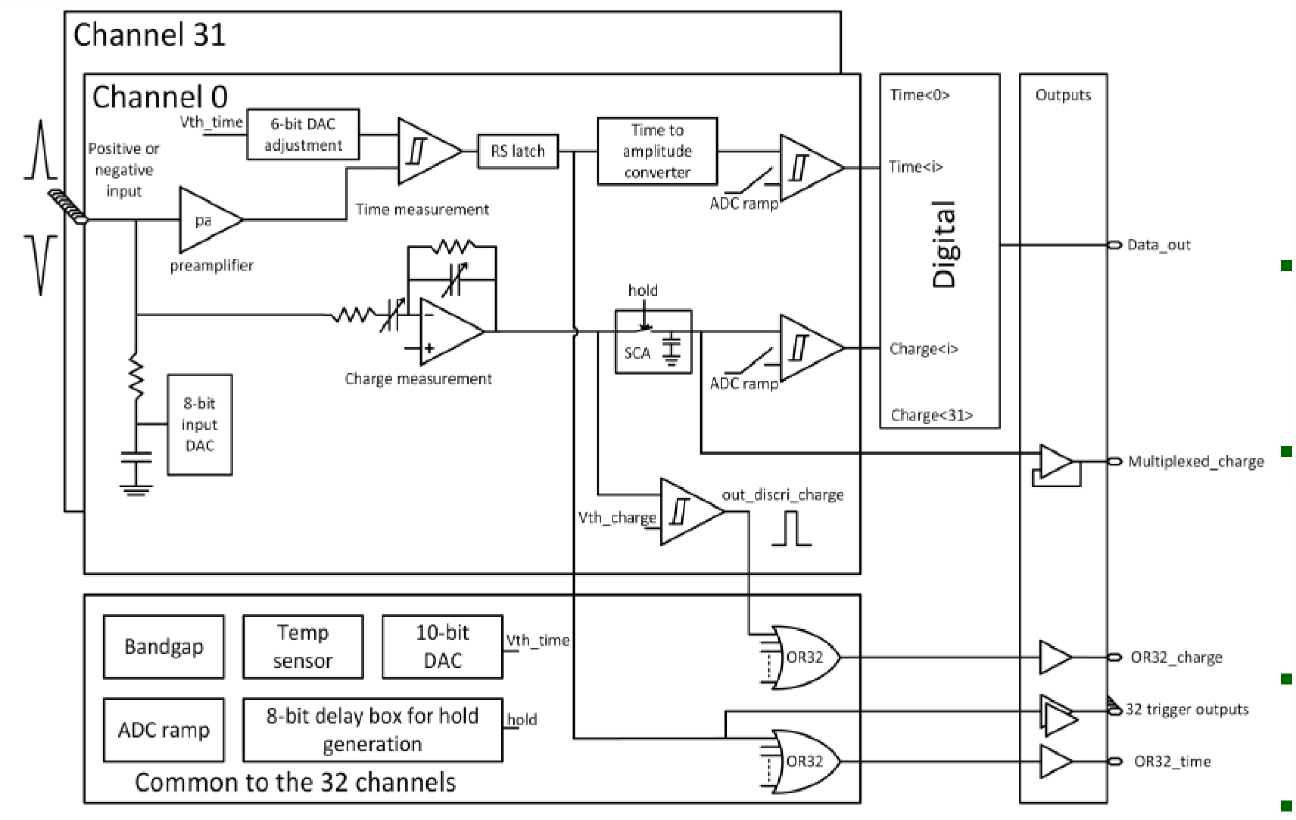
Scintillator crystal characteristics

Material	Emission peak [nm]	Light Yield [ph/MeV]	Density [g/cm^3]	Refr. index^a	X_0 [cm]	FWHM^b [%]	Decay time [ns]	Hygro-scopic
NaI(Tl)	415	38-55 k	3.67	1.85	2.6	7	230	yes
CsI(Na)	420	38-44 k	4.51	1.84	1.86	7-8	630	slightly
CsI(Tl)	550	52-65 k	4.51	1.79	1.86	7-8	600-3400	yes
BGO	480	8-10 k	7.13	2.15	1.13	> 9	300	no
GAGG(Ce)	520	22-60 k	6.63	1.9	1.54	5.1	50-100	no
LYSO(Ce)	420	30-33 k	7.1-7.2	1.82	1.15	8-10	40-45	no
$LaBr_3$(Ce)	380	63 k	5.29	1.9	1.88	2.7	16	yes
CaF_2(Eu)	435	19-30 k	3.18	1.47	-	3.8-4	940	yes

^{a}Index of refraction at the wavelength of maximum emission,
^{b}Energy resolutions quoted at 661.7 keV

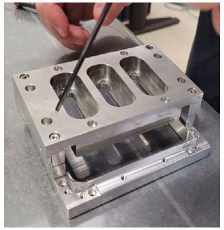


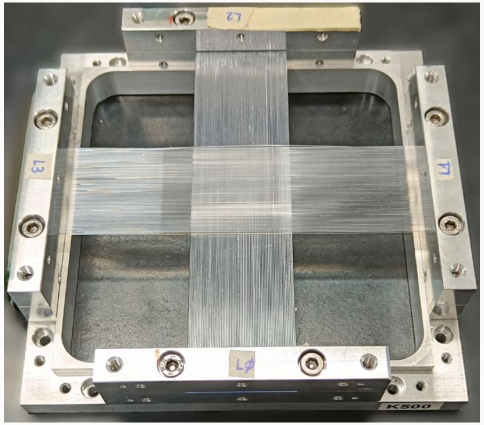
Petiroc 2A ASIC architecture

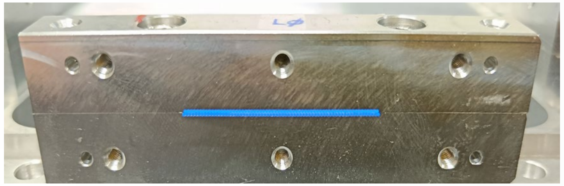


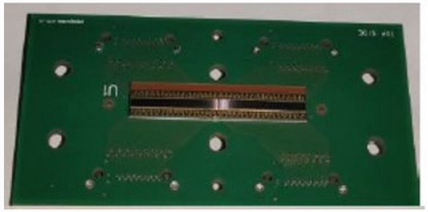
- 32-channels ASIC
- PA for internal trigger and timing
  - 10-bits global DAC threshold + 6-bits individual DAC threshold
  - 32 individual trigger outputs
  - OR-32 trigger output
- ADC for charge measurements -10 bits
  - 4-bits for the CR-RC shaping time
  - OR-32 charge trigger
- TDC to measure the arrival time
  - 9 bits for coarse time -25 ns resolution
  - 10 bits for fine time -37 ps resolution
- DIGITAL read-out
  - 12 μs conversion time
- Power: 192 mW
- TRL: 6

Fiber Tracker prototype

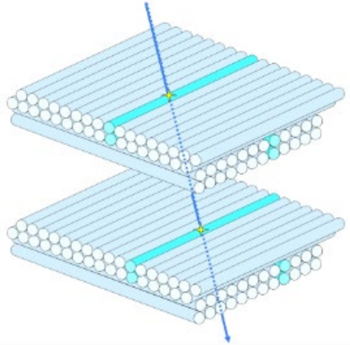








- Detector: 3 X-Y modules
- Each X-Y module consisting of two view planes
- Each view: two staggered layers of round scintillating fibers
  - *Kuraray SCSF-78MJ 500 μm*
  - *Kuraray SCSF-78MJ 750 μm*
- Each view readout by SiPM array Hamamatsu S13552
  - *128-channel*
  - *250 μm strip pitch*

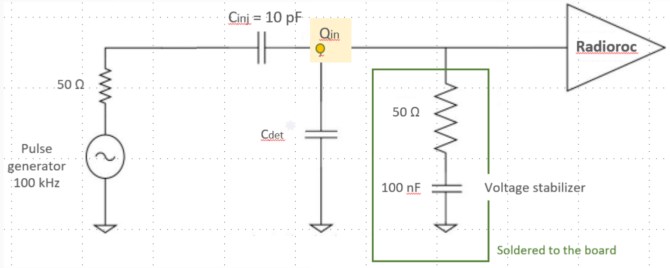


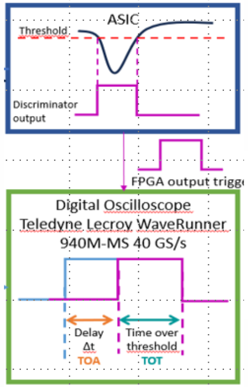
- A charged particle crossing a plane will release an energy deposit in at least a pair of adjacent fibers in the top and bottom layers
- Scintillation photons will be then collected by at least a pair of adjacent SiPM strips

Internship at Omega Microelectronics

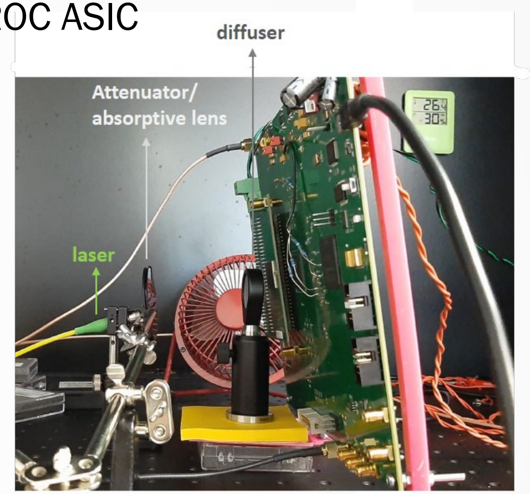
6-month internship:

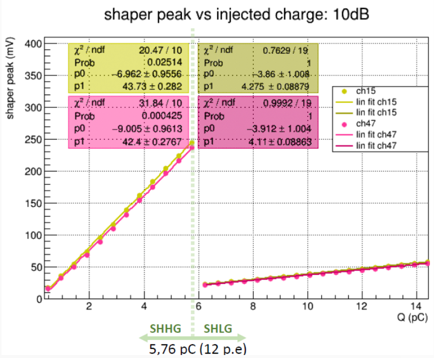
- Characterization of the RADIOROC ASIC with three different detector capacitances
- Study of the performance of SiPM in terms of charge and time resolution with RADIOROC ASIC

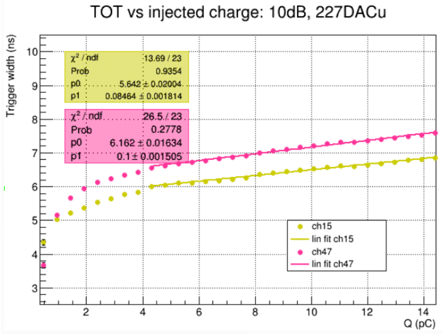


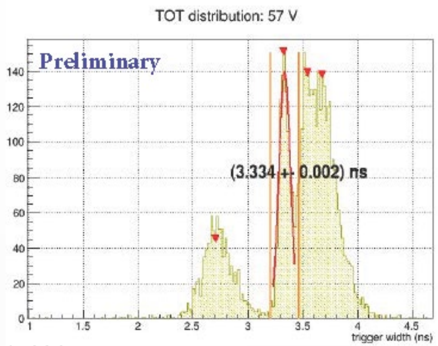


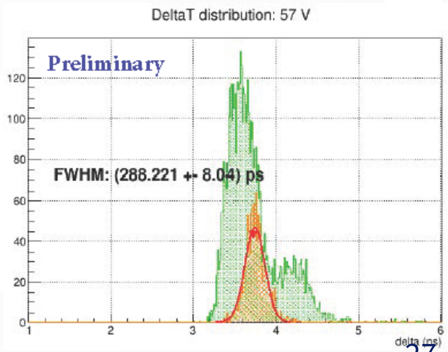
	HAM S13361-2050NE-08	HAM S13360-3050CS
Sensitive area (mm^2)	2 x 2	3 x 3
Pixel pitch (µm)	50	50
Gain	1,7 x 10^6	1,7 x 10^6
Terminal Capacitance (pF)	140	320



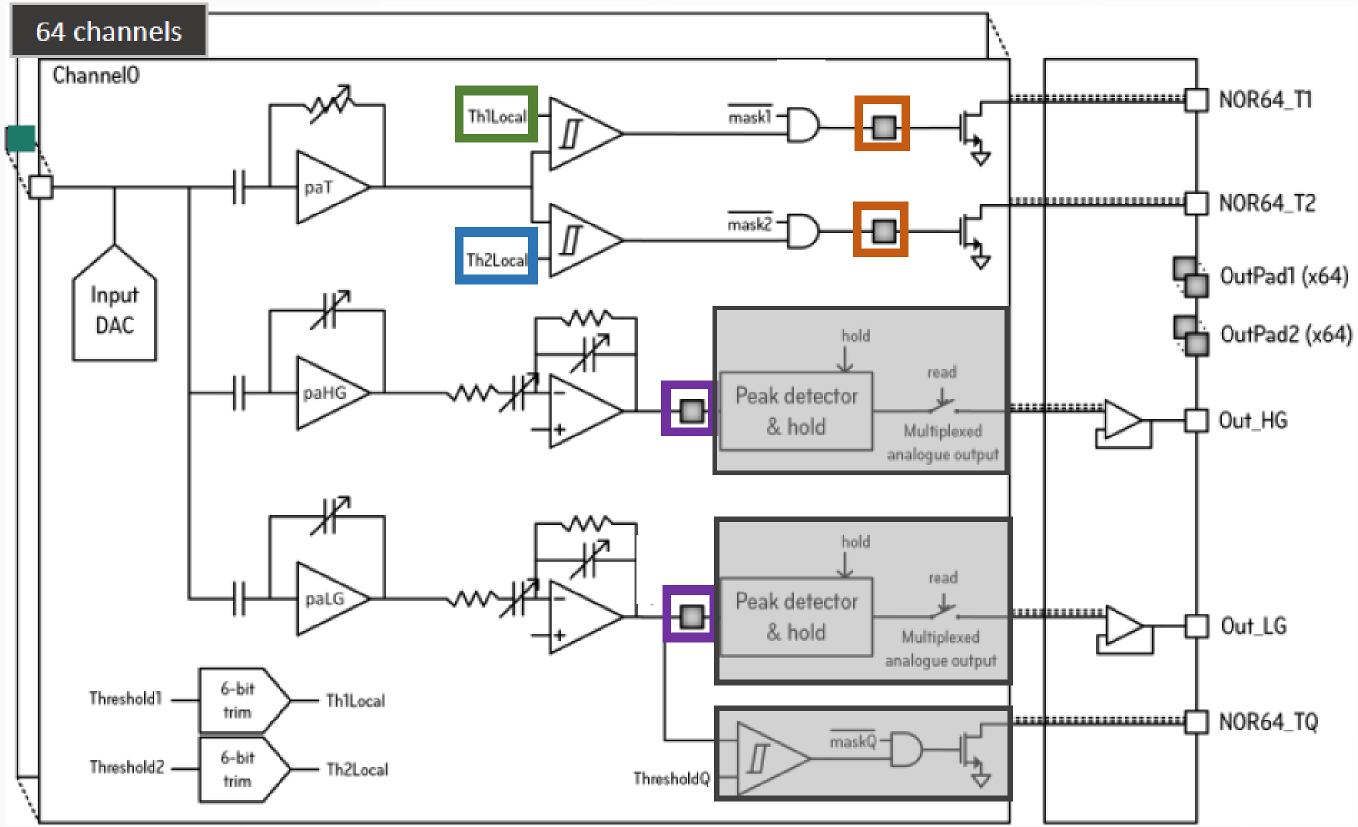








Radioroc ASIC architecture



Time low threshold DAC1: 1 – 5 p.e.

Time high threshold DAC2: 5 – 10 p.e.

Analog charge preamplifier/shaper output

Digital time preamplifier output (trigger)

Not working yet

- Power: 310 mW