INFN BARI
Istituto Nazionale di Fisica Nucleare
Sezione di Bari

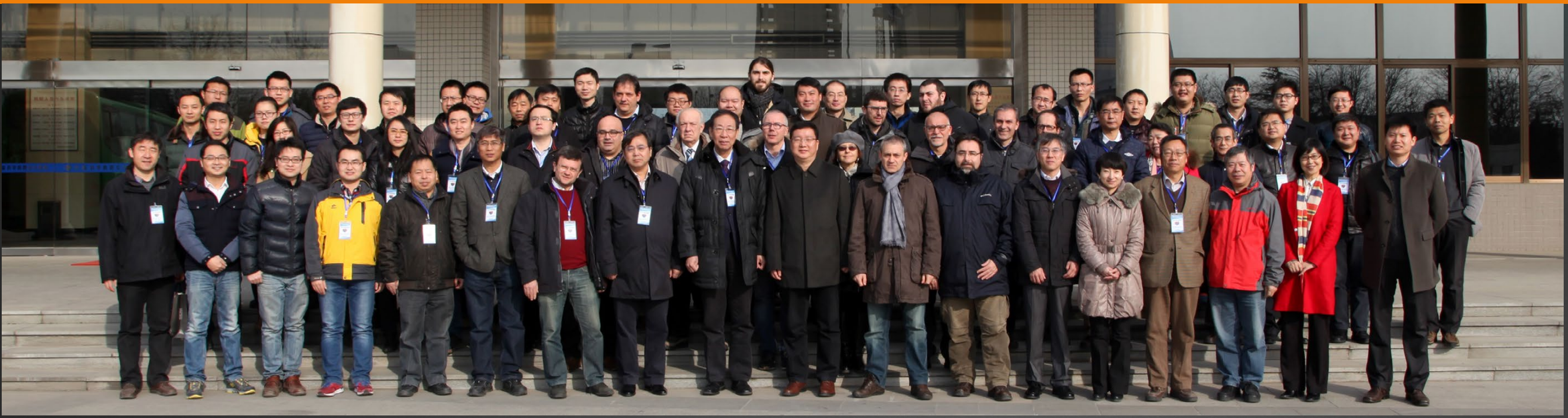
Particle identification capability of Plastic scintillator tiles equipped with SiPMs for the High Energy cosmic-Radiation Detection (HERD) facility

F.GARGANO ON BEHALF OF THE **HERD** COLLABORATION

INFN-BARI

SiPM workshop: from fundamental research to industrial applications

COLLABORATION



CHINA

- **Institute of High Energy Physics, CAS, Beijing**
- Xi'an Institute of Optical and Precision Mechanics, China
- Purple Mountain Observatory, CAS, Nanjing
- University of Science and Technology of China, Hefei

ITALY

- INFN Bari and University of Bari
- INFN Firenze and University of Firenze
- INFN Perugia and University of Perugia
- INFN Pisa and University of Pisa
- INFN Lecce and University of Salento
- INFN Laboratori Nazionali del Gran Sasso and GSSI Gran Sasso Science Institute

SPAIN

- CIEMAT - Madrid
- ICCUB - Barcellona

SWITZERLAND

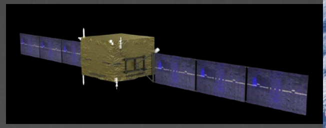
- University of Geneva

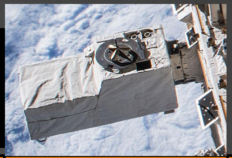
The **High Energy cosmic-Radiation Detection** (HERD) facility is a China-led international space mission that will start operation around 2026.

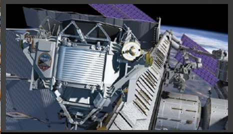
The experiment is based on a **3D, homogeneous, isotropic and finely-segmented calorimeter** that fulfills the following requirements and goals

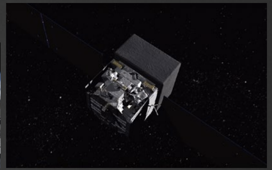
Main requirements			
	γ	e	p, nuclei
Energy Range	0.5 GeV 100 TeV	10 GeV 100 TeV	30 GeV 3 PeV
Energy resolution	1% @ 200 GeV	1% @ 200 GeV	20% @ 100 GeV -1 PeV
Effective Geometric Factor	>1 m^2sr @ 200 GeV	>3 m^2sr @ 200 GeV	>2 m^2sr @ 100 TeV

Main Scientific goals
Direct measurement of cosmic rays flux and composition up to the knee region
Gamma-ray monitoring and full sky survey
Indirect dark matter search (e^++e^-, γ,...)





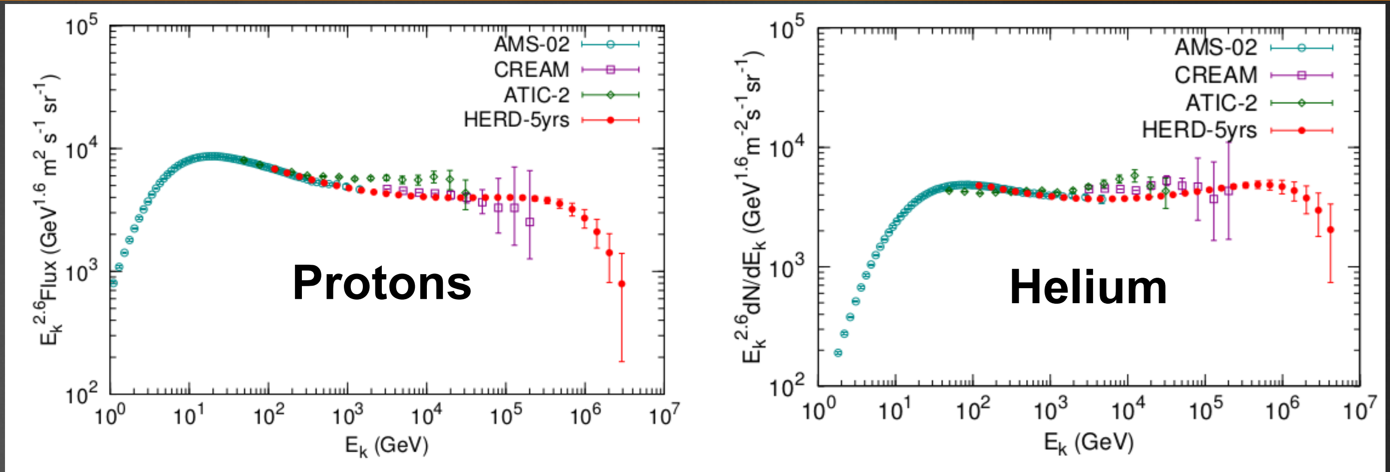




	HERD	DAMPE	CALET	AMS-02	Fermi LAT
e/γ Energy res.@100 GeV (%)	<1	<1.5	2	3	10
e/γ Angular res.@100 GeV (deg.)	< 0.1	<0.2	0.2	0.3	0.1
e/p discrimination	$>10^6$	$>10^5$	10^5	10^5 - 10^6	10^3
Calorimeter thickness (X_0)	55	32	27	17	8.6
Geometrical accep. (m^2sr)	>3	0.3	0.12	0.09	1

Physics goals

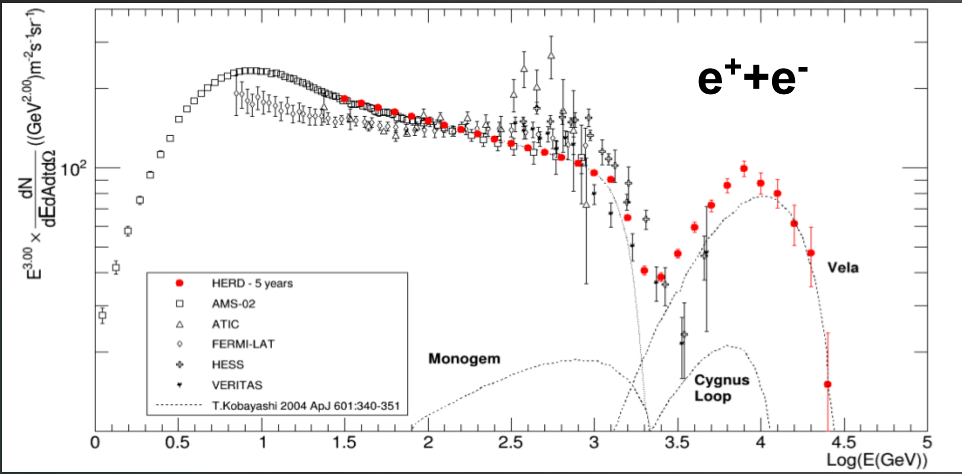
Expected charged particles fluxes in 5 years



HERD will measure the flux of nuclei:

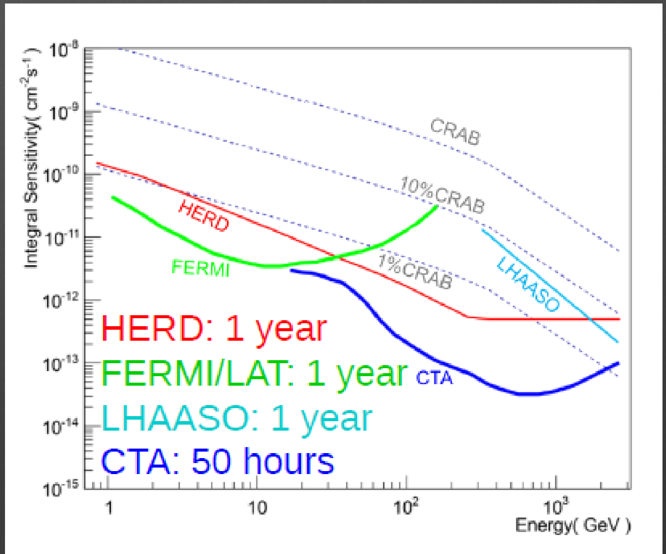
- p and He up to a few PeV
- nuclei up to a few hundreds of TeV/n

First direct measurement of p and He knees will provide a strong evidence for the knee structure as due to acceleration limit



HERD will measure the e^+ e^- flux up to several tens of TeV

- spectral cutoff at high energy,
- local SNR sources of very high energy e^-
- anisotropy measurement



Expected γ sensitivity

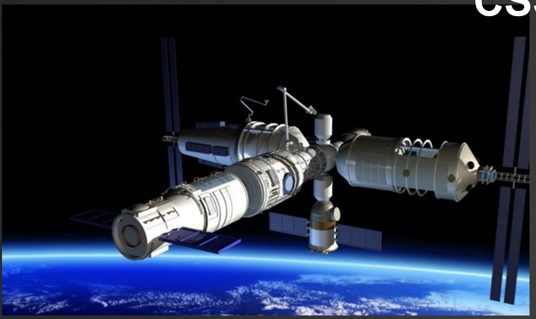
Sky survey @ 5σ level

Targets of Gamma-Ray Sky Survey:

- search for dark matter signatures
- study of galactic and extragalactic γ sources
- study of galactic and extragalactic γ diffuse emission detection of high energy γ Burst

Multi-messenger astronomy

Possible synergy with other experiments designed for γ (CTA), ν (KM3, IceCube), GW (Ligo, Virgo)

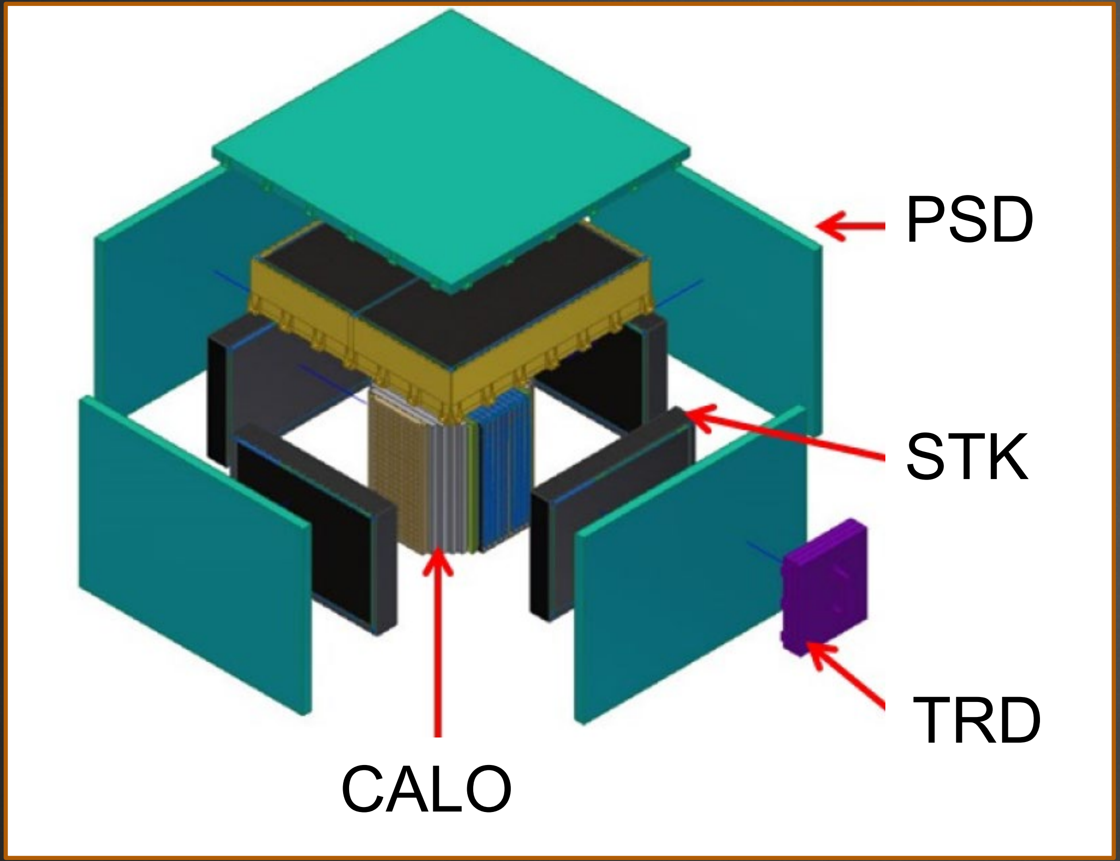


CSS expected to be completed in 2022

Life time	> 10y
Orbit	Circular LEO
Altitude	340-450 km
Inclination	42°

HERD expected to be installed around 2026

Life time	> 10y
FOV	+/- 70°
Power	< 1.5 kW
Mass	< 4 t

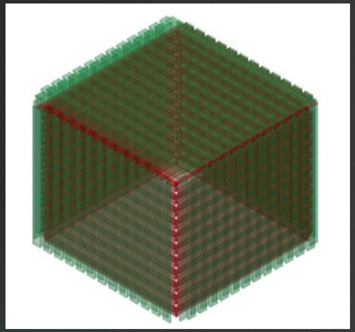


CALO	Energy Reconstruction e/p Discrimination
STK	Trajectory Reconstruction Charge Identification
PSD	Charge Reconstruction γ Identification
TRD	Calibration of CALO response for TeV proton

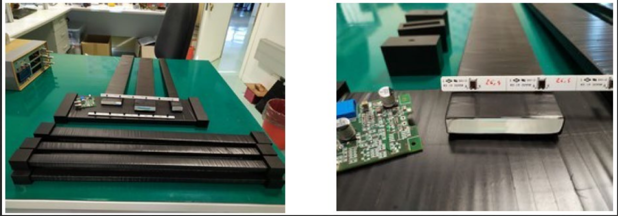
HERD Plastic Scintillator Detector (PSD)

PSD provide γ **identification** (VETO of charged particles) and **nuclei identification** (energy loss $\propto Z^2$)

Back-scattering can greatly degrade the performances



In China (IHEP) and Italy (GSSI and Lecce) there are ongoing activities on this option

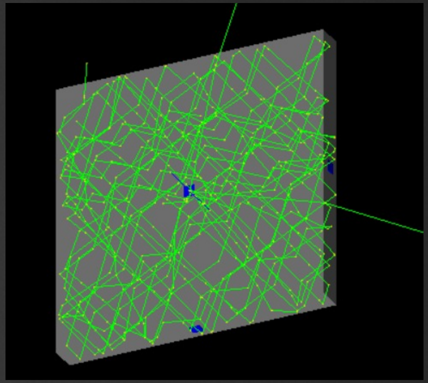


Bar - option

- Long bars 160x3x1 cm^3
- Each layer made by two staggered sub layer to increase hermeticity
- Read-out with 4 SiPM (two for each end)
- PRO
  - Less number of readout channel
- CONS
  - Higher Back-scattering problem

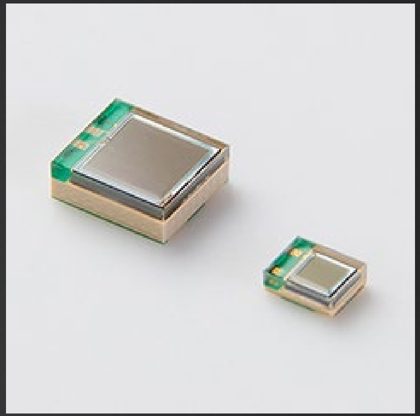
Tile - option

- Small square tile 10x10x1 cm^3
- Two layer of tiles to increase nuclei identification power
- Each tile is readout by 4 SiPM (one for each side)
- PRO
  - Reduce back-scattering problem
- CONS
  - Higher number of readout channel



In (Bari and Pavia) there are ongoing activities on this option

I will present some results for this option



SiPMs suitable to replace PMT

- low voltage
- compact
    - Good for space missions
- better sensitivity to low light yields

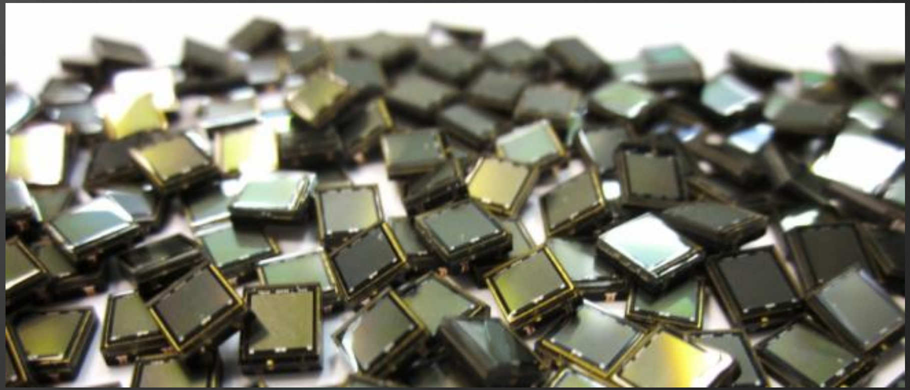
Plastic scintillator + SiPMs are being tested in recent years for future missions.

Requirements:

Overall High efficiency and low dark noise for charged particles rejection (>0.9999)

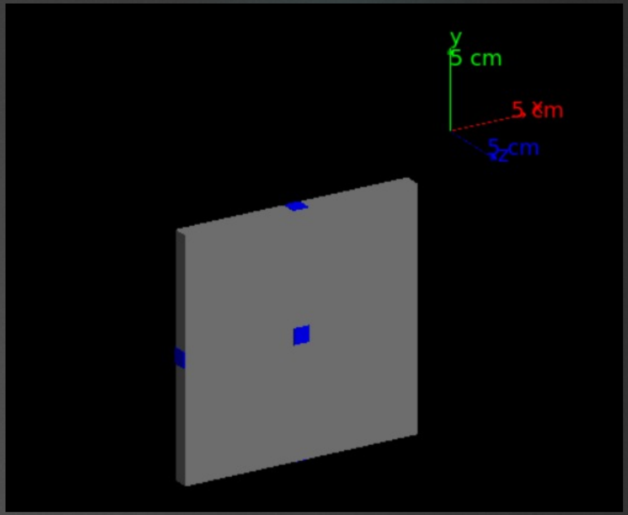
Good energy resolution for better charge particle detection

High dynamic range for high Z identification

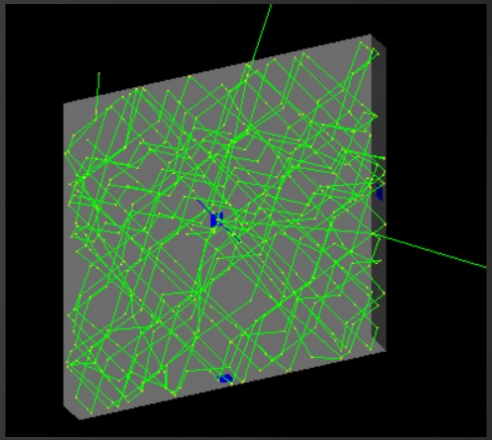


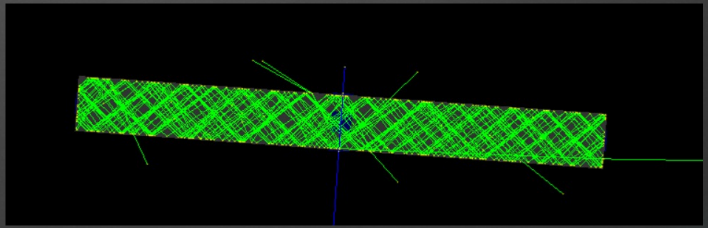
SIMULATION

- We have developed a simulation that tracks every optical photon generated by scintillation in a tile. The code is based on GEANT4.
- We have simulated a tile 10x10x1 cm^3
- The tile is equipped with 6 SiPM 4x4 mm^2 placed on the four sides and on the top and bottom face
- In this simulation we can change a lot of parameters such as
  - Tile size
  - Number and position of SiPMs
  - Light Yield and attenuation length of the scintillator
  - Birks parameters
  - Physical parameters of the wrapping

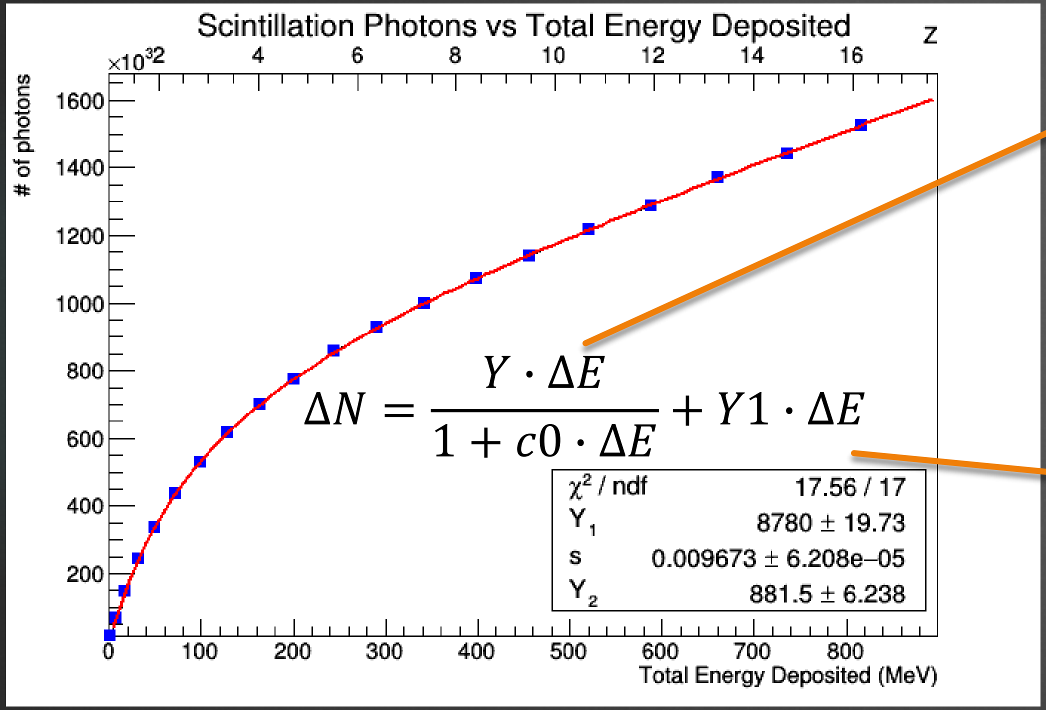


1/100 photon is drawn

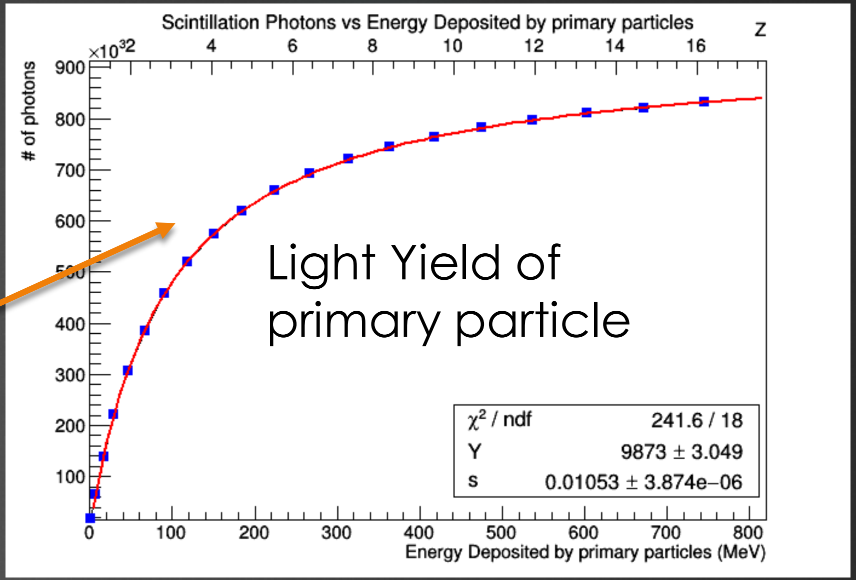


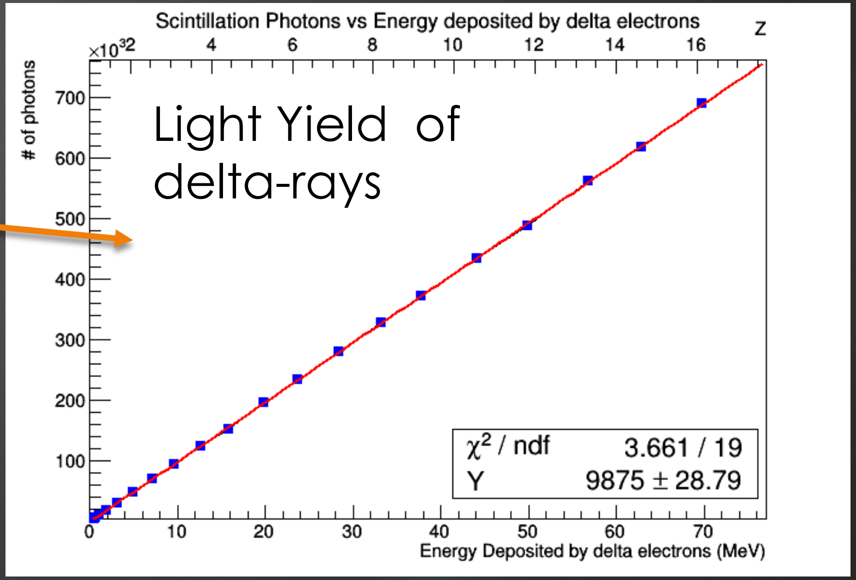


The simulation code takes into account the Birks saturation effect



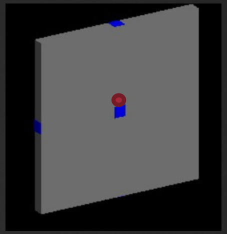
$$\Delta N = \frac{Y \cdot \Delta E}{1 + c0 \cdot \Delta E} + Y1 \cdot \Delta E$$



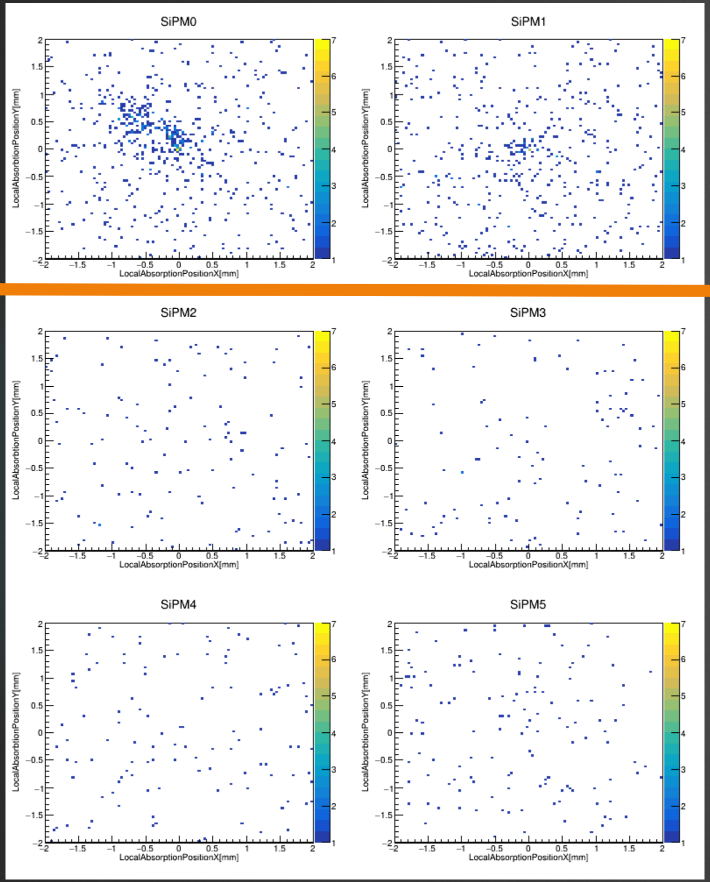


SIMULATION – SiPM OCCUPANCY

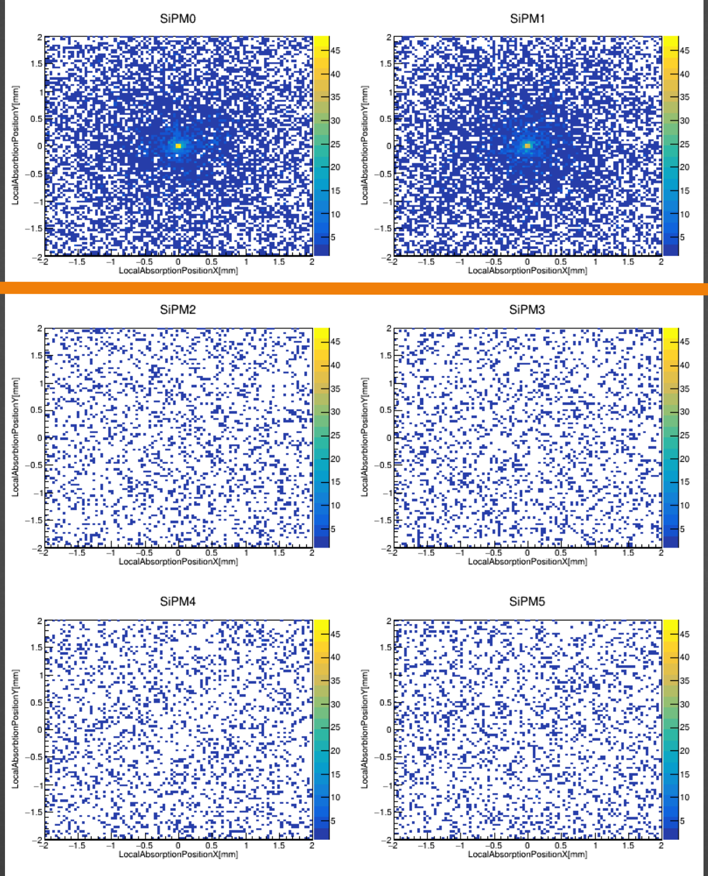
- We have simulated particles crossing the tile in the center (TiO2 diffuse reflector)



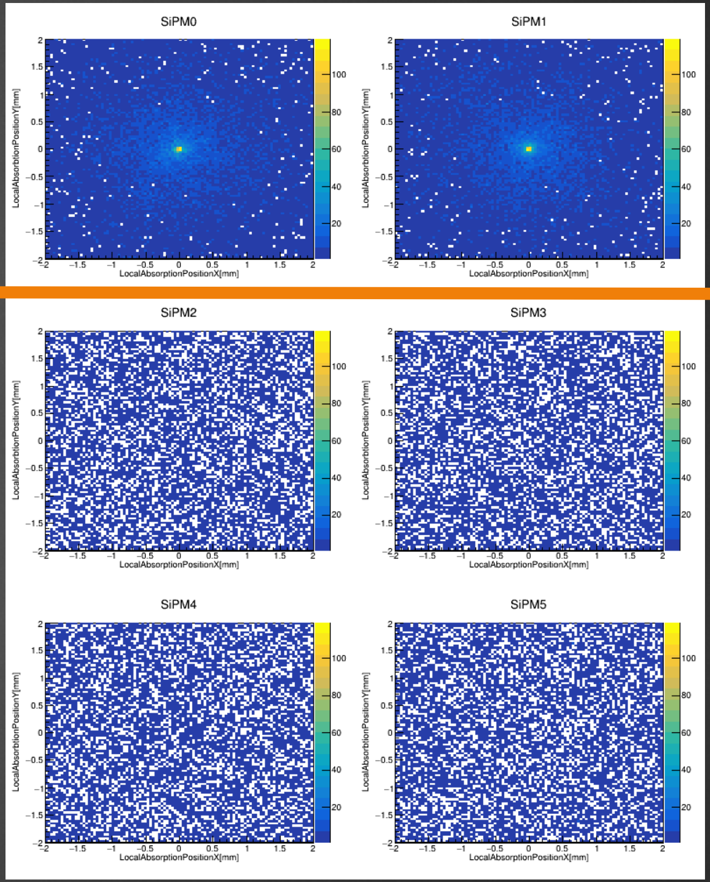
Proton



Carbon



Iron



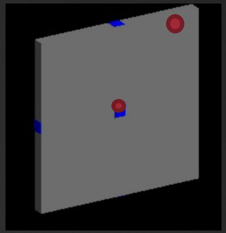
TOP
Direct + Reflected light

SIDE
Reflected light

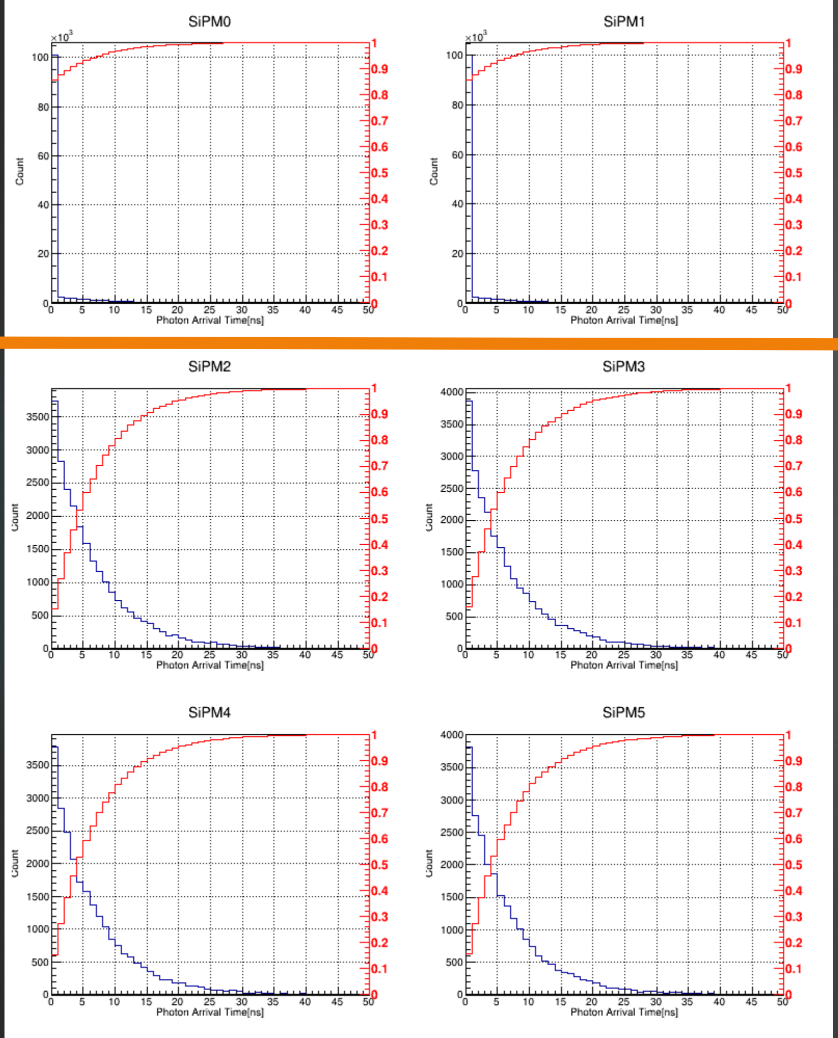
	Proton TOP	Proton SIDE	Carbon TOP	Carbon SIDE	Iron TOP	Iron SIDE
Ph	600	120	10000	2300	48000	11000
Cell	550	120	5800	2000	9500	6500

SIMUALTION - TIMING

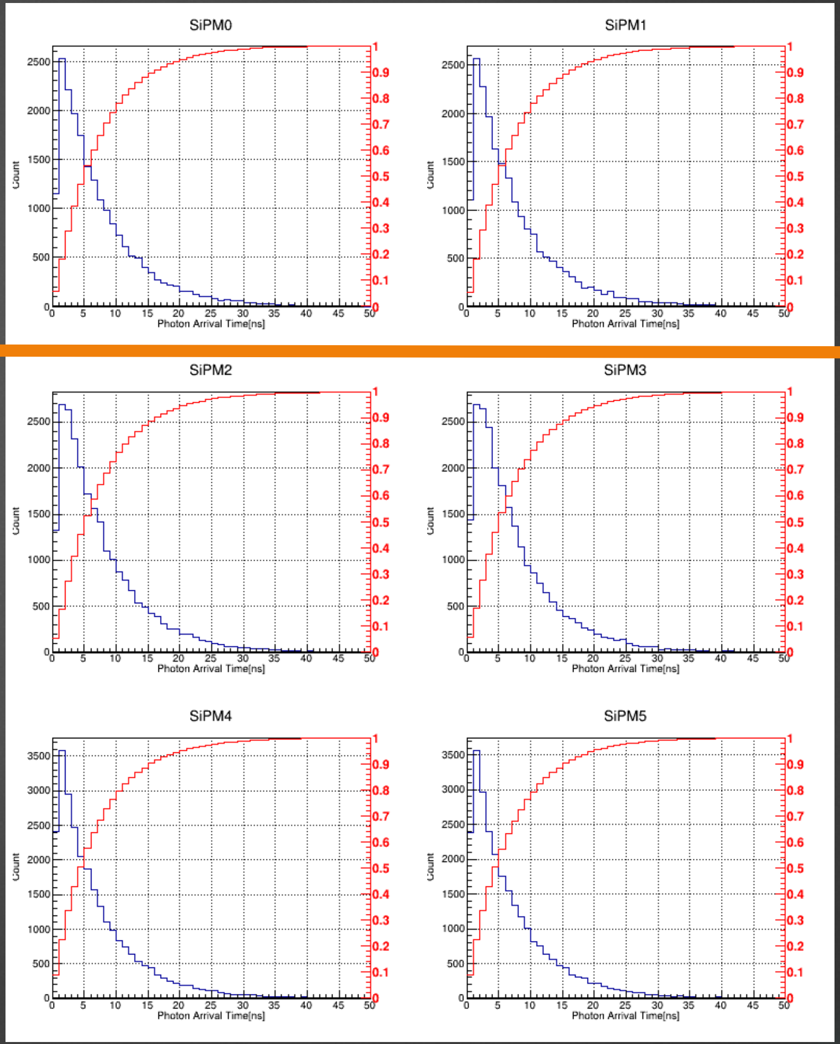
Protons crossing the tile in the center and in a corner (TiO2 diffuse reflector)



CENTRAL POS



CORNER POS



TOP

Effect of prompt direct light in central position

SIDE

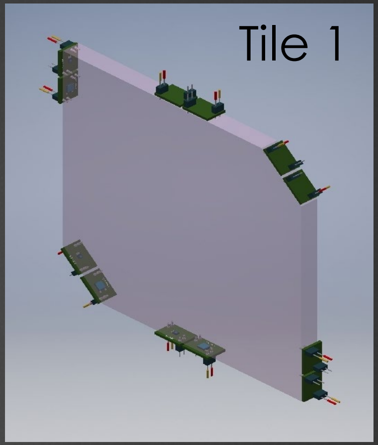
50% of photons are collected in 5ns

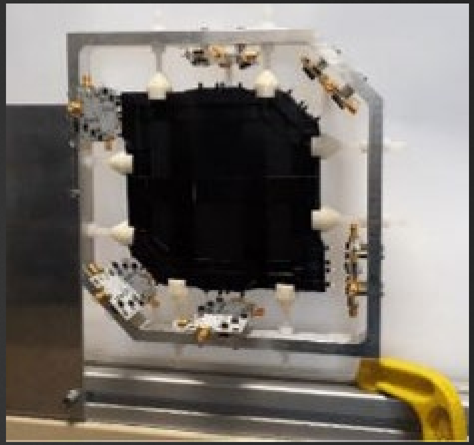
80% of photons are collected in 10ns

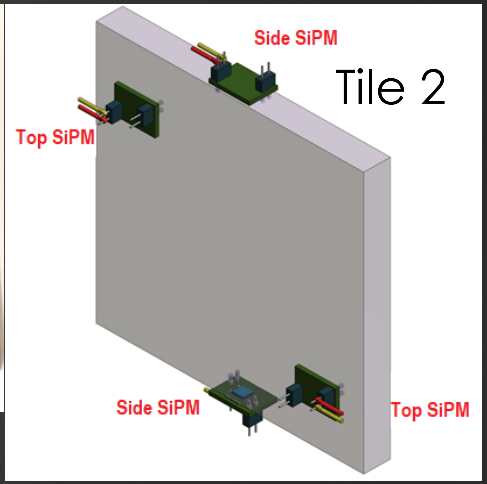
The collection time does not change with particle type

TILE PROTOTYPES

- We have built two tile prototypes to test the performances
- Tile 1(BC-404)
  - Squared shape with a side of 15 cm and thickness of 1 cm.
  - Two angles were cut at 2.5 cm from the corner.
  - 12 ADVANSID NUV SiPMs (40μm cell; Gain 10^5):
    n.6 1x1 mm^2 (Small)
    n.6 4x4 mm^2 (Large)
- Tile 2 (BC-404)
  - Squared shape with a side of 10 cm and thickness of 1 cm.
  - n.4 4x4 mm^2 ADVANSID NUV SiPMs (40μm cell; Gain 10^5)
- Readout electronics from ADVANSID
  - Transimpedance amplifier with low and high gain (x5) output
  - RC filter for tail cancellation
- DAQ: CAEN QDC V792







Tile 1

PS - T10: 5 GeV particles (e/pi)

Scintillator irradiated in different positions → dependence of collected light on beam position

SPS – H8: 20 GeV particles (e/pi)

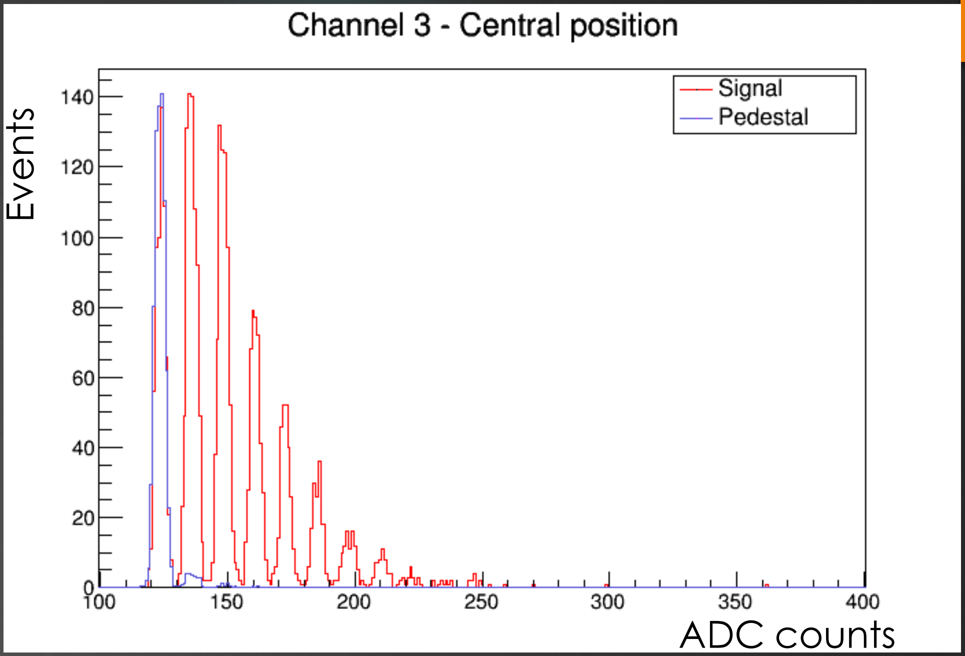
Scintillator irradiated only in the central position → efficiency studies

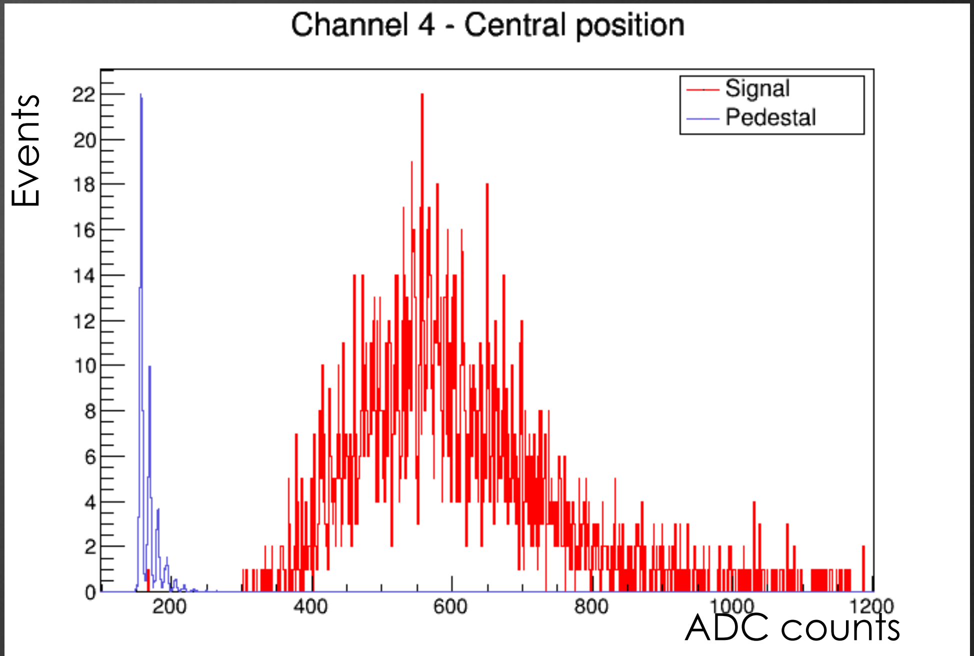
Tile 2

SPS – H4: beam line with a beam of selected momentum of 330 GeV/Z, coming from a primary beam of lead, with energy 150 GeV/A, impinging onto a Beryllium target.

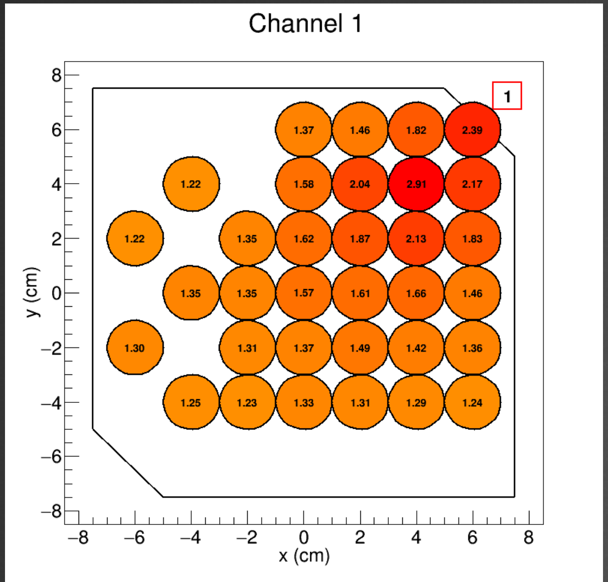
Scintillator irradiated in the central position → capability to discriminate ion charges

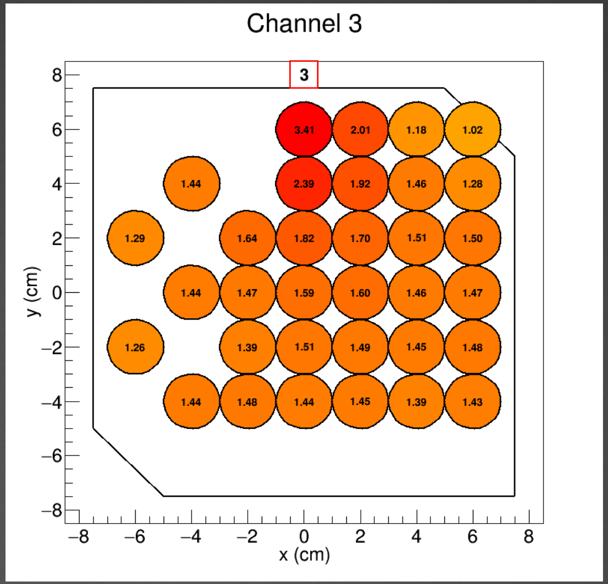
- **Small SiPMs** (1x1mm^2 area):
  - Charge distributions fitted with multi-gaussian functions
  - Areas of individual peaks fitted with Poisson distributions
  - Calibration with dark counts
- **Large SiPMs** (4x4mm^2 area):
  - Individual peaks still visible in charge distributions, but difficult to fit due to low statistics
  - Rebinning of histograms and fit with a Landau distribution folded with a gaussian
  - Calibration with dark counts

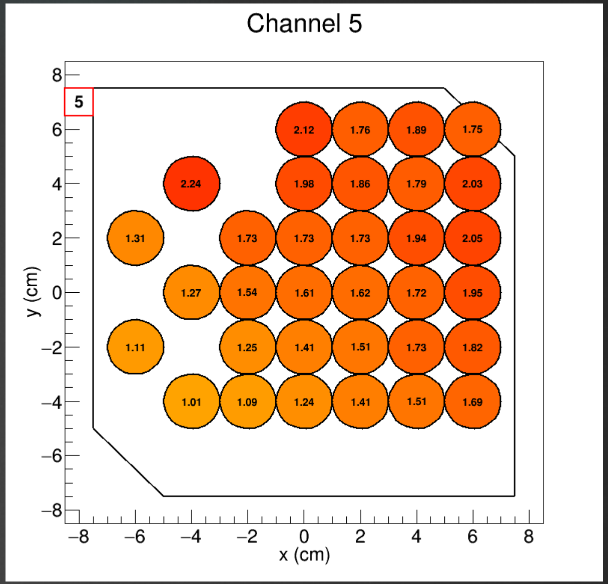


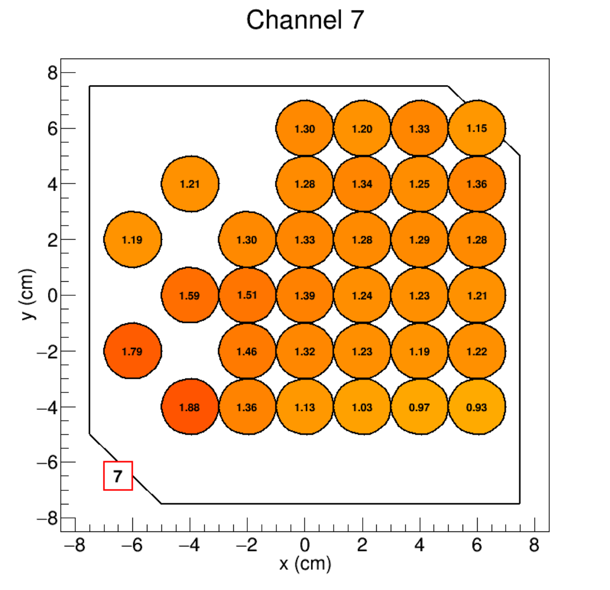


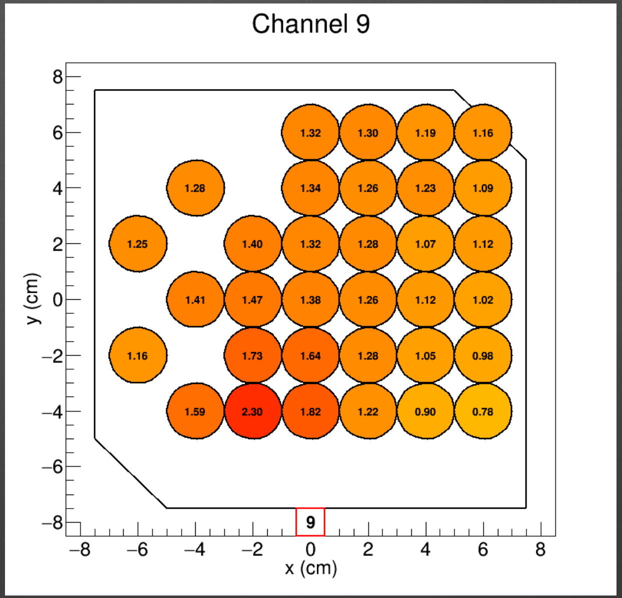
Small SiPMs


Channel 1
1
1.37 1.46 1.82 2.39
1.22 1.58 2.04 2.91 2.17
1.22 1.35 1.62 1.87 2.13 1.83
1.35 1.35 1.57 1.61 1.66 1.46
1.30 1.31 1.37 1.49 1.42 1.36
1.25 1.23 1.33 1.31 1.29 1.24
y (cm)
x (cm)


Channel 3
3
3.41 2.01 1.18 1.02
1.44 2.39 1.92 1.46 1.28
1.29 1.64 1.82 1.70 1.51 1.50
1.44 1.47 1.59 1.60 1.46 1.47
1.26 1.39 1.51 1.49 1.45 1.48
1.44 1.48 1.44 1.45 1.39 1.43
y (cm)
x (cm)


Channel 5
5
2.12 1.76 1.89 1.75
2.24 1.98 1.86 1.79 2.03
1.31 1.73 1.73 1.73 1.94 2.05
1.27 1.54 1.61 1.62 1.72 1.95
1.11 1.25 1.41 1.51 1.73 1.82
1.01 1.09 1.24 1.41 1.51 1.69
y (cm)
x (cm)


Channel 7
1.30 1.20 1.33 1.15
1.21 1.28 1.34 1.25 1.36
1.19 1.30 1.33 1.28 1.29 1.28
1.59 1.51 1.39 1.24 1.23 1.21
1.79 1.46 1.32 1.23 1.19 1.22
1.88 1.36 1.13 1.03 0.97 0.93
7
y (cm)
x (cm)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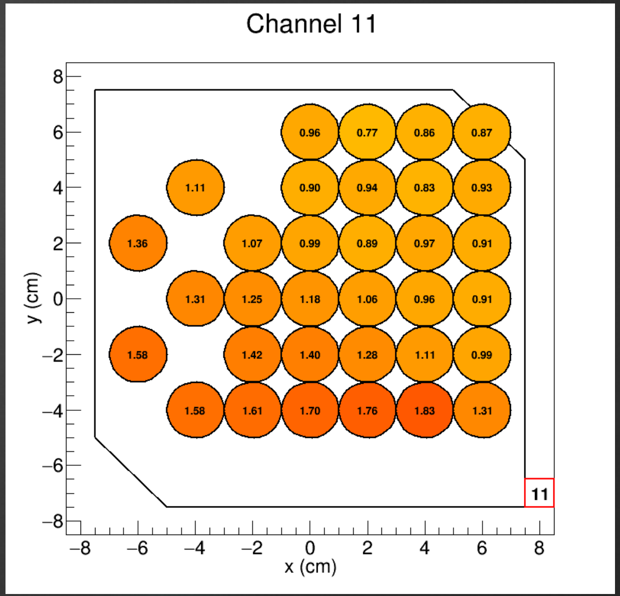
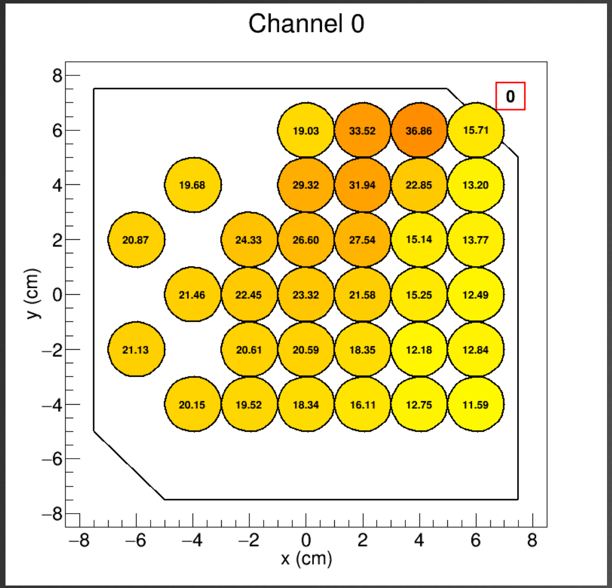
1.32 1.30 1.19 1.16
1.28 1.34 1.26 1.23 1.09
1.25 1.40 1.32 1.28 1.07 1.12
1.41 1.47 1.38 1.26 1.12 1.02
1.16 1.73 1.64 1.28 1.05 0.98
1.59 2.30 1.82 1.22 0.90 0.78
9
y (cm)
x (cm)


Channel 11
0.96 0.77 0.86 0.87
1.11 0.90 0.94 0.83 0.93
1.36 1.07 0.99 0.89 0.97 0.91
1.31 1.25 1.18 1.06 0.96 0.91
1.58 1.42 1.40 1.28 1.11 0.99
1.58 1.61 1.70 1.76 1.83 1.31
11
y (cm)
x (cm)

Large SiPMs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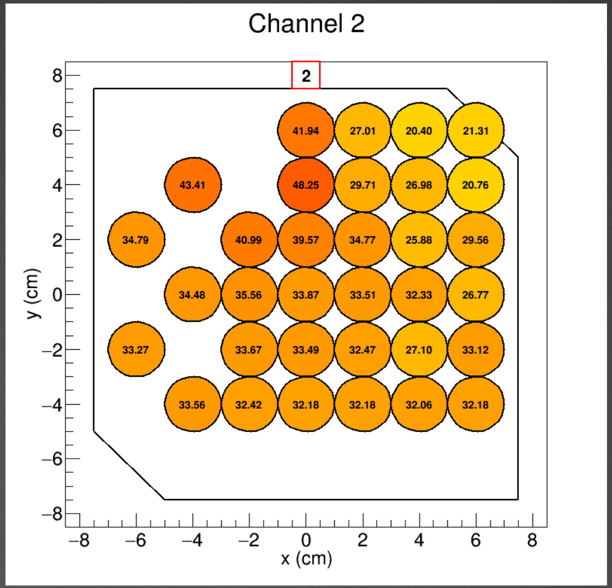
0
19.03 33.52 36.86 15.71
19.68 29.32 31.94 22.85 13.20
20.87 24.33 26.60 27.54 15.14 13.77
21.46 22.45 23.32 21.58 15.25 12.49
21.13 20.61 20.59 18.35 12.18 12.84
20.15 19.52 18.34 16.11 12.75 11.59
y (cm)
x (cm)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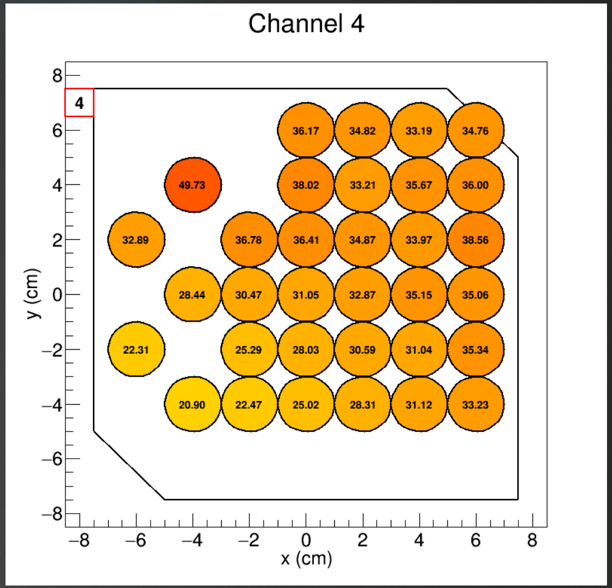
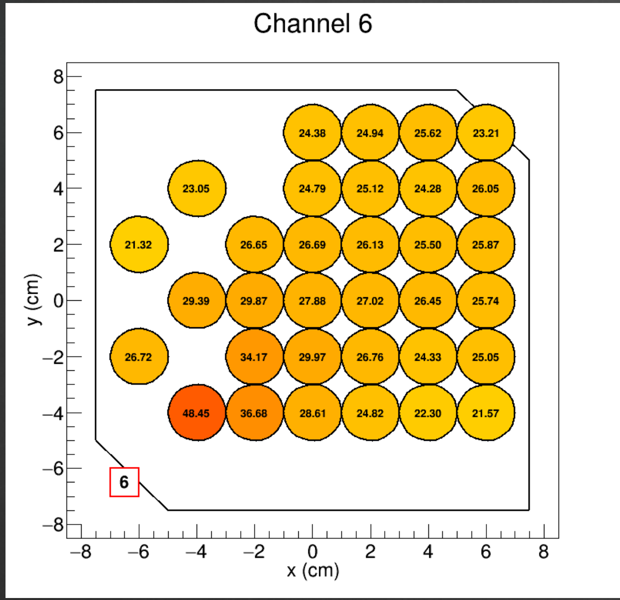
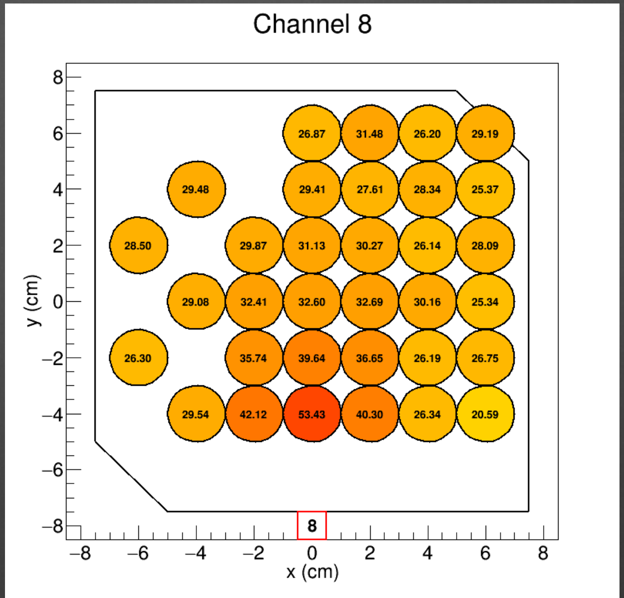
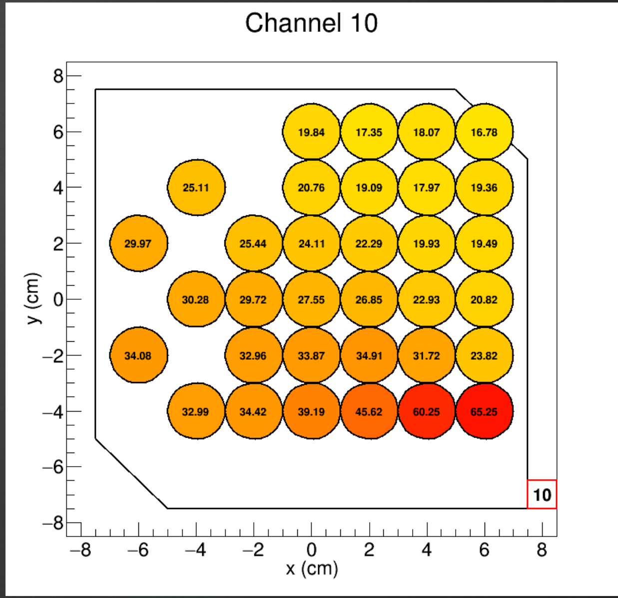
43.41 48.25 29.71 26.98 20.76
34.79 40.99 39.57 34.77 25.88 29.56
34.48 35.56 33.87 33.51 32.33 26.77
33.27 33.67 33.49 32.47 27.10 33.12
33.56 32.42 32.18 32.18 32.06 32.18
y (cm)
x (cm)

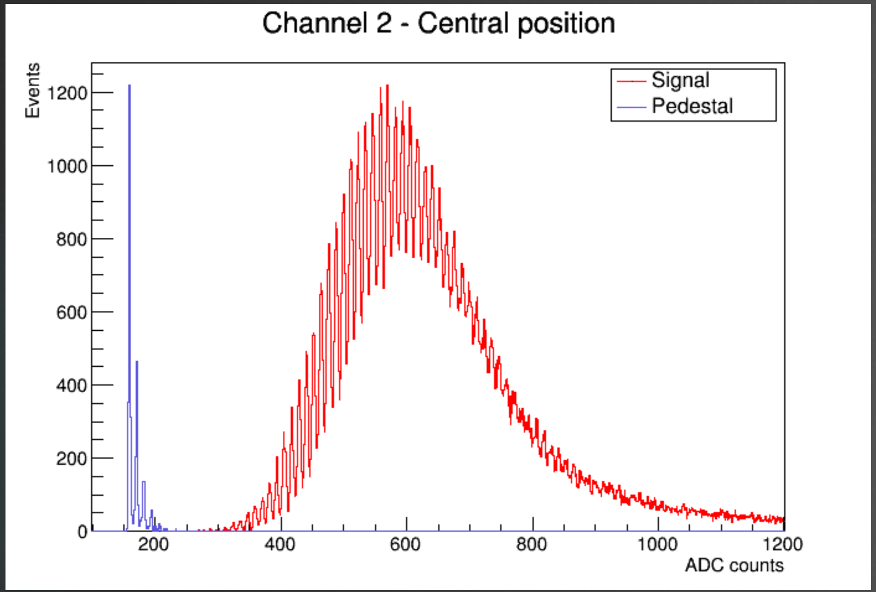

Channel 4
4
36.17 34.82 33.19 34.76
49.73 38.02 33.21 35.67 36.00
32.89 36.78 36.41 34.87 33.97 38.56
28.44 30.47 31.05 32.87 35.15 35.06
22.31 25.29 28.03 30.59 31.04 35.34
20.90 22.47 25.02 28.31 31.12 33.23
y (cm)
x (cm)

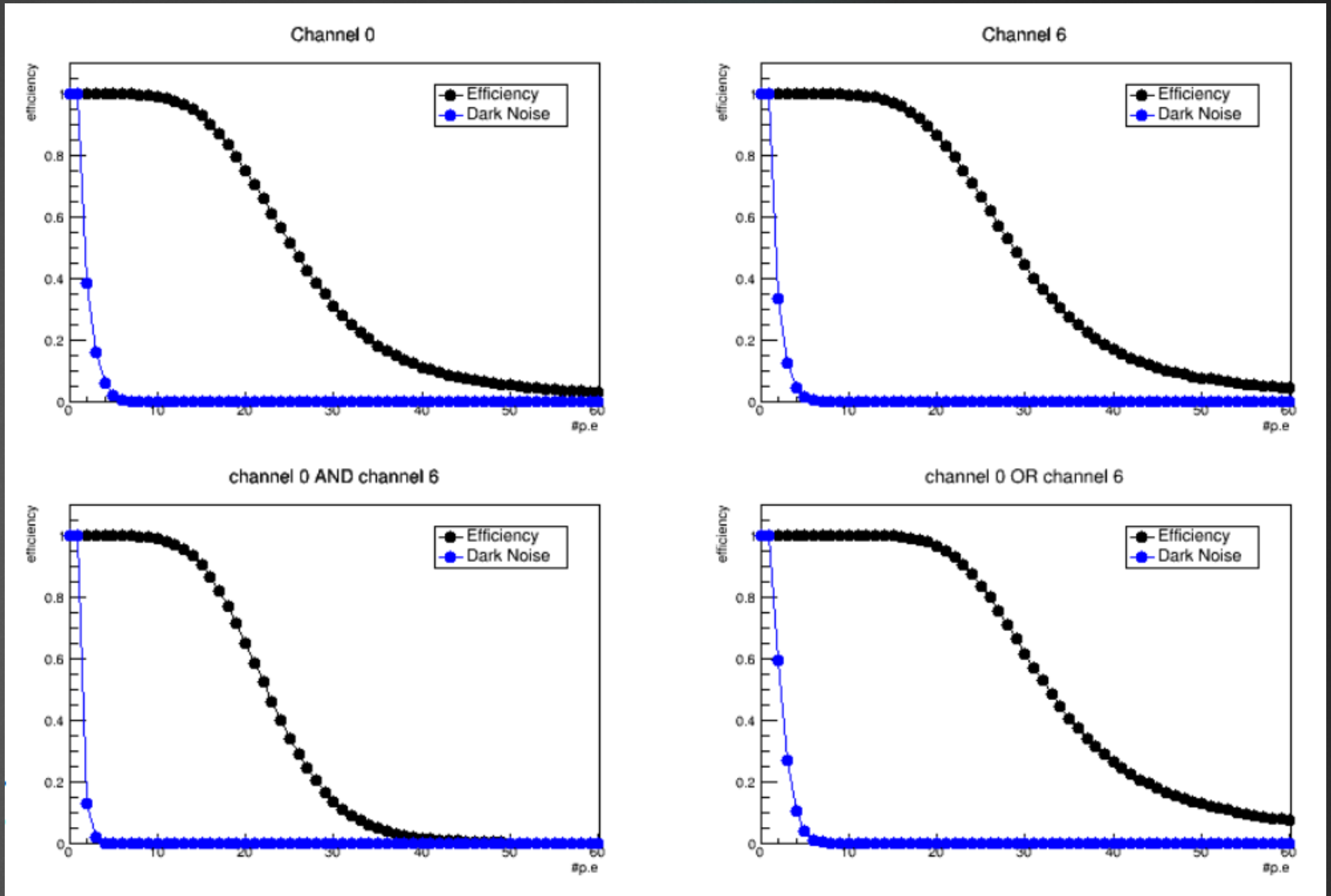

Channel 6
24.38 24.94 25.62 23.21
23.05 24.79 25.12 24.28 26.05
21.32 26.65 26.69 26.13 25.50 25.87
29.39 29.87 27.88 27.02 26.45 25.74
26.72 34.17 29.97 26.76 24.33 25.05
48.45 36.68 28.61 24.82 22.30 21.57
6
y (cm)
x (cm)


Channel 8
26.87 31.48 26.20 29.19
29.48 29.41 27.61 28.34 25.37
28.50 29.87 31.13 30.27 26.14 28.09
29.08 32.41 32.60 32.69 30.16 25.34
26.30 35.74 39.64 36.65 26.19 26.75
29.54 42.12 53.43 40.30 26.34 20.59
8
y (cm)
x (cm)


Channel 10
19.84 17.35 18.07 16.78
25.11 20.76 19.09 17.97 19.36
29.97 25.44 24.11 22.29 19.93 19.49
30.28 29.72 27.55 26.85 22.93 20.82
34.08 32.96 33.87 34.91 31.72 23.82
32.99 34.42 39.19 45.62 60.25 65.25
10
y (cm)
x (cm)

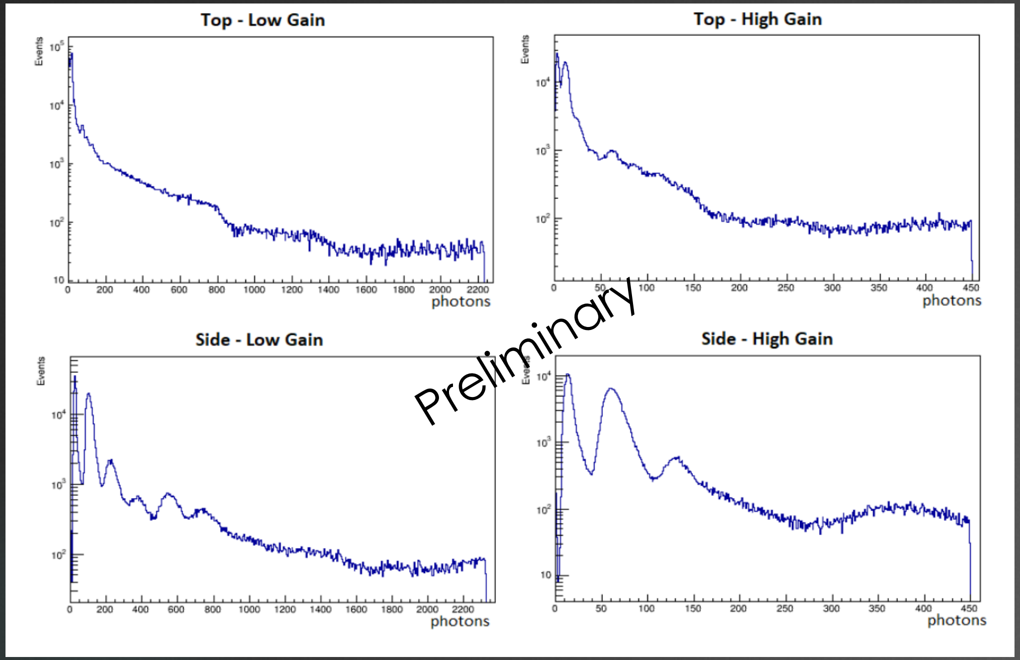
Efficiency and dark noise evaluated as function of p.e. in single, AND and OR configuration

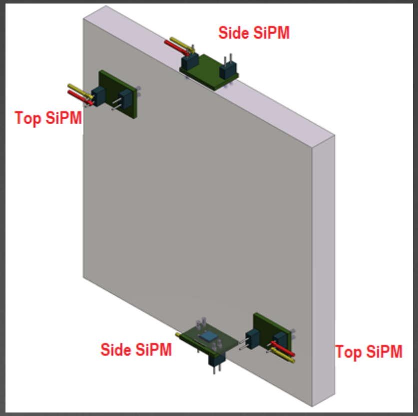




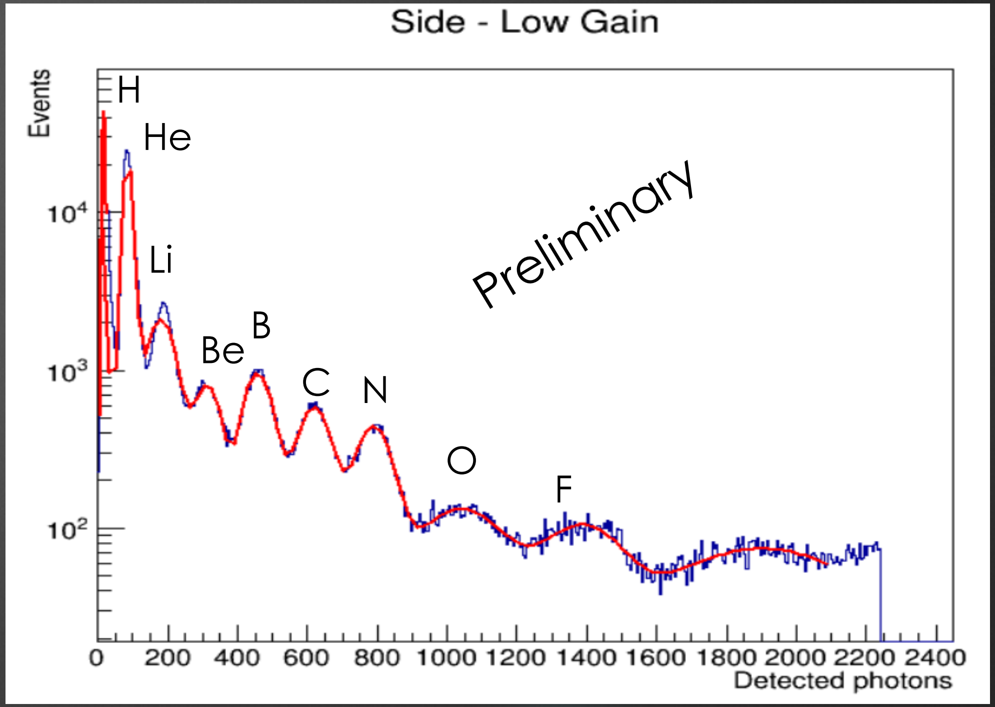
	Ch 0		Ch 6		AND		OR	
Thr	***Eff.***	***Cont.***	***Eff.***	***Cont.***	***Eff.***	***Cont.***	***Eff.***	***Cont.***
3 p.e.	0.99997	0.16229	0.99997	0.12812	0.99997	0.02079	1.00000	0.26962
5 p.e.	0.99984	0.00913	0.99984	0.00554	0.99981	0.00001	1.00000	0.01463
10 p.e.	0.99224	0.00014	0.99224	0.00006	0.99012	< 0.00001	0.99998	0.00020

TILE 2 Test@SPS with ions





Side SiPM with low gain show the best performances



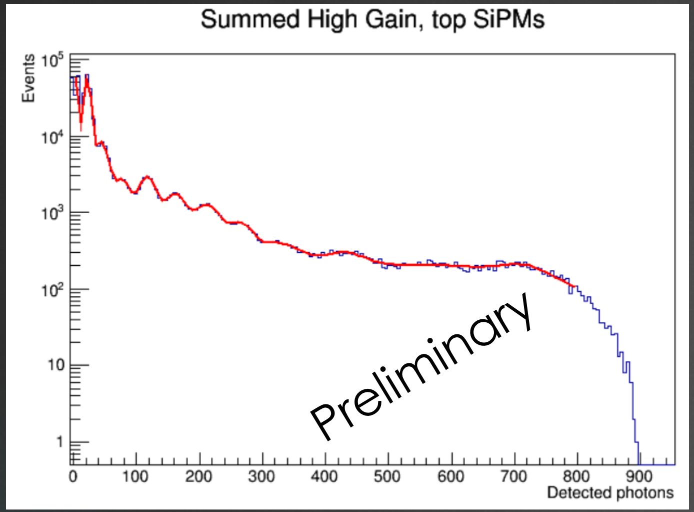
Top SiPMs collect less light than Side SiPMs

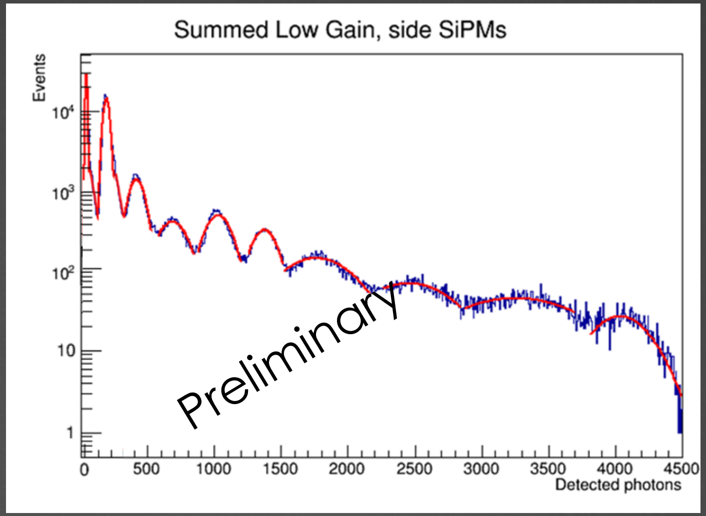
Side SiPMs: the high gain amplification appears to be inappropriate, since the readout chain allows resolution up to Z = 3

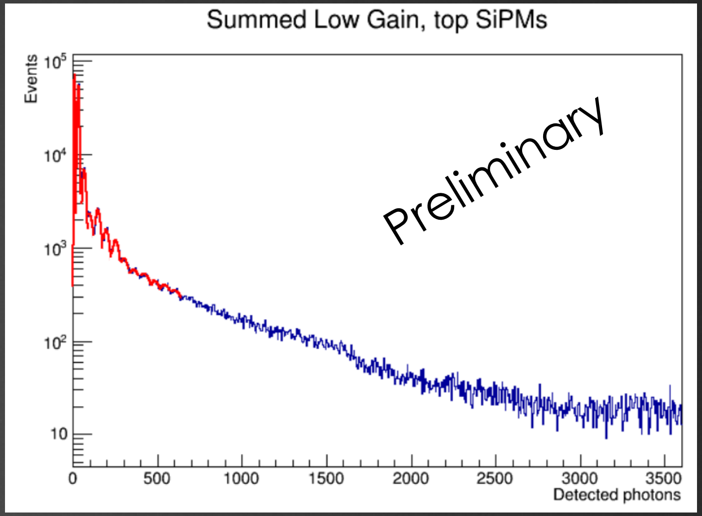
Top SiPMs: the high gain channels are able to resolve more peaks than the Low gain ones

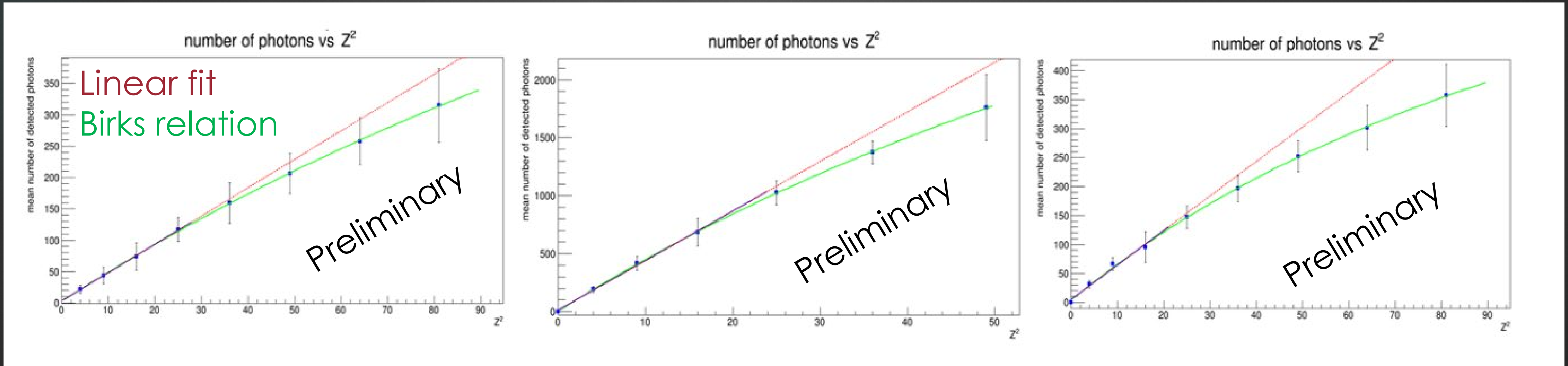
TILE 2 Test@SPS with ions

- Some improvement achieved if we sum together the signals from SiPMs









Lesson learned

- Tile 1
  - Small SiPM collects very few photons
  - Response is almost uniform in the tile (30-40 p.e. for large SiPMs), with peaks in the points closer to the SiPMs
  - Efficiency reached with this configuration is very high, fulfilling the requirements of anti-coincidence systems in cosmic ray satellites.
- Tile 2
  - nuclei detection and identification up to Z=8 with single channel
  - Summing up the equivalent channels → clear improvement in the signal
  - The readout used in these tests limited the dynamics → must be improved.

- In conclusion, this study shows that SiPM technology can be used instead of the classical PMTs in space experiment both to reject charged particles and to identify ions.
- A lot of work is still needed to design proper readout electronics, to study the timing performances, to study the effect of dark noise and cross talk on resolution and to increase the overall performances

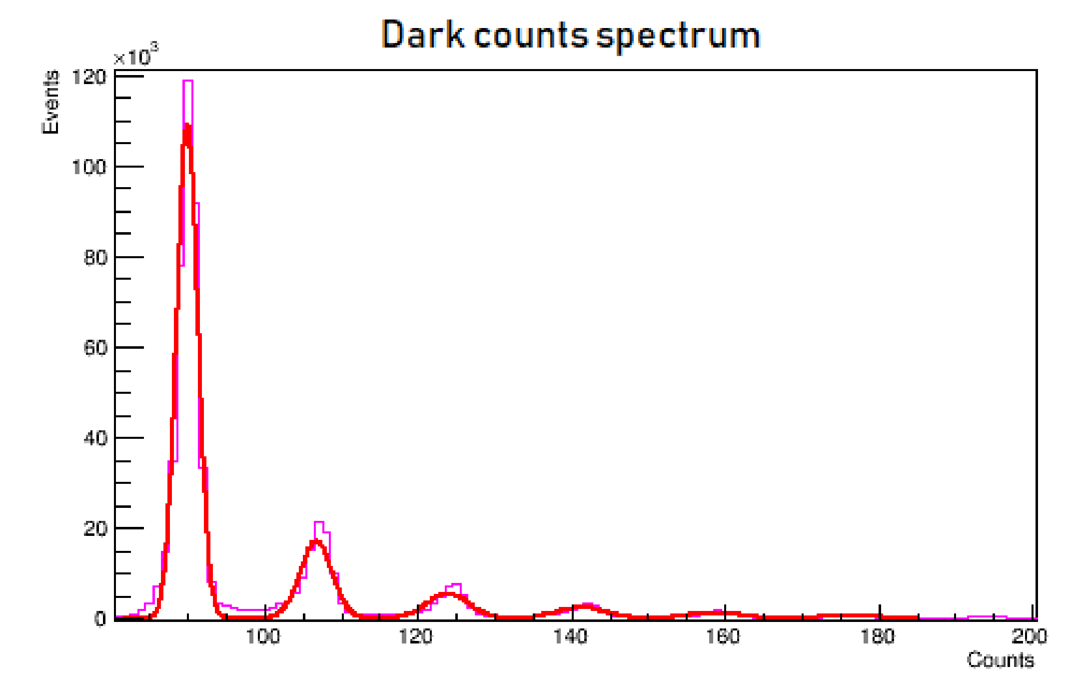
THANKS!!

Back up slides

TILE 2 Test@SPS with ions - Resolutions

Channel Resolution	Resolution of He peak (σ/peak position)
Low gain, Side	0.1601 ± 0.0005
Summed low gain, Side	0.1296 ± 0.0004
Summed high gain, Side	0.1355 ± 0.0006
Summed low gain, Top	0.2042 ± 0.0008
Summed high gain, Top	0.2813 ± 0.0008

- Signals collected and calibrated for each SiPM using the dark count distributions measured in runs without particles.
- Gain evaluated from the distance between two adjacent p.e. peaks once the pedestal has been subtracted.



To calibrate the signal distribution, we subtracted the pedestal from the raw data, and divided by the gain, allowing the conversion of ADC counts to detected photons.

To identify the nuclei with a system different from the tile under test the signals from S0 and Sh were used.

The red line is obtained by fitting the peaks with gaussian functions up to the nineteenth peak.