Silicon Photomultiplier based dual readout fibre Calorimeter: firsts results and the pathway beyond the proof-of-concept

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On behalf of the RD52 collaboration and RD-FA INFN collaboration

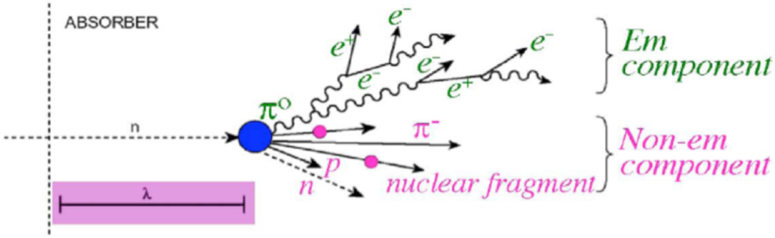
1) Università degli Studi dell'Insubria (COMO) and INFN (Milano)

Outline

- Dual Readout Calorimetry
- Summary of the test beam results
- What next

Hadron showers development

- The hadronic showers are made of two components:
  - Electromagnetic component:
    - from neutral meson (π0, η) decays
  - Non electromagnetic component:
    - charge hadrons π±, K± (20%)
    - nuclear fragments, p (25%)
    - n, soft γ's (15%)
    - break-up of nuclei (invisible energy) (40%)



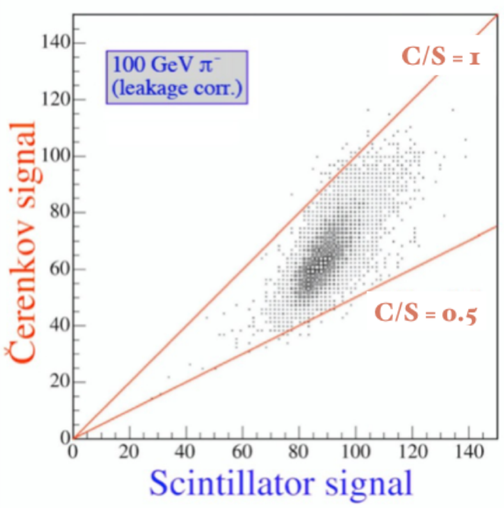
- The main fluctuations in the event-to-event calorimeter response are due to:
  - Large non-gaussian fluctuations in energy sharing em/non-em
  - Large, non-gaussian fluctuations in "invisible" energy losses
  - Increase of em component with energy

- The calorimetric performance at collider experiments has always been spoiled by the problem of non-compensation, arising from the dual nature of hadronic showers

Dual-readout calorimetry

- The concept is to measure the fem component event by event. This eliminates the fem fluctuation effect on calorimeter performance

- The measurement is performed using two different sampling processes:
  - Cherenkov light, produced by the relativistic particles, dominating in the e.m. shower component
  - Scintillation light produced by the total deposited energy



$$C = E\left[f_{em} + \frac{1}{(e/h)_C}(1-f_{em})\right]$$

$$S = E\left[f_{em} + \frac{1}{(e/h)_S}(1-f_{em})\right]$$

e.g. if: (e/h) = 1.3(S) vs 4.7(C)

$$\frac{C}{S} = \frac{f_{em} + 0.21(1-f_{em})}{f_{em} + 0.77(1-f_{em})}$$

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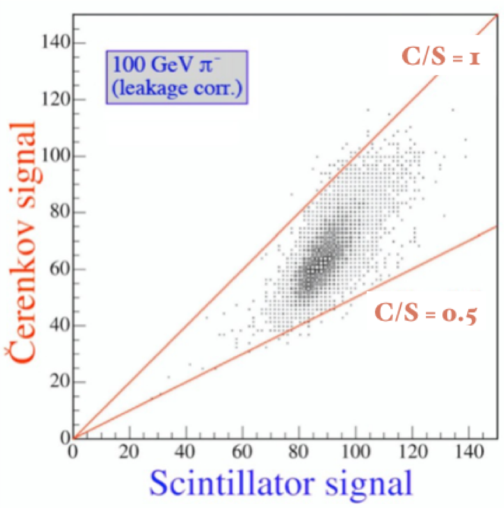

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$$\frac{C}{S} = \frac{f_{em} + 0.21(1-f_{em})}{f_{em} + 0.77(1-f_{em})}$$

$$\boxed{E = \frac{S - \chi C}{1 - \chi}}$$

Universally valid!

with: $\chi = \dfrac{1-(h/e)_S}{1-(h/e)_C}$

χ is independent of both:

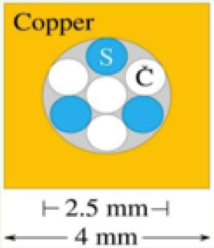
- Energy
- Type of hadron

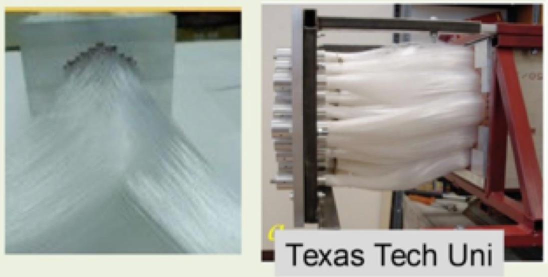
The history of Dual Readout Fiber Calorimeter

15 years of R&D qualified the dual-readout calorimetric technique

2003
DREAM

Copper
2m long, 16.2 cm wide
19 towers, 2 PMT each
Sampling fraction: 2%

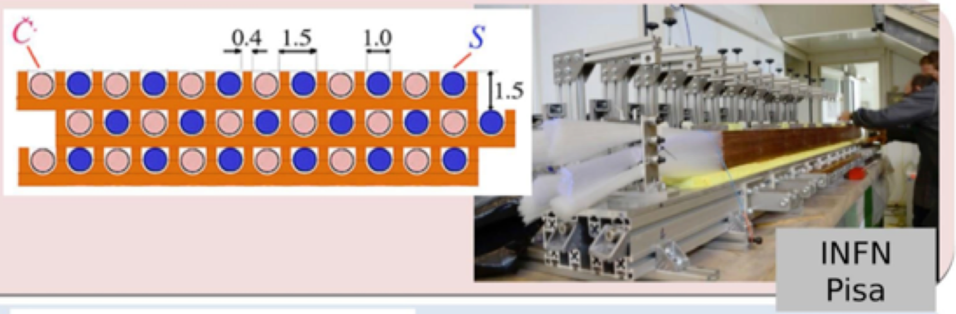




2012
RD52

Copper, 2 modules

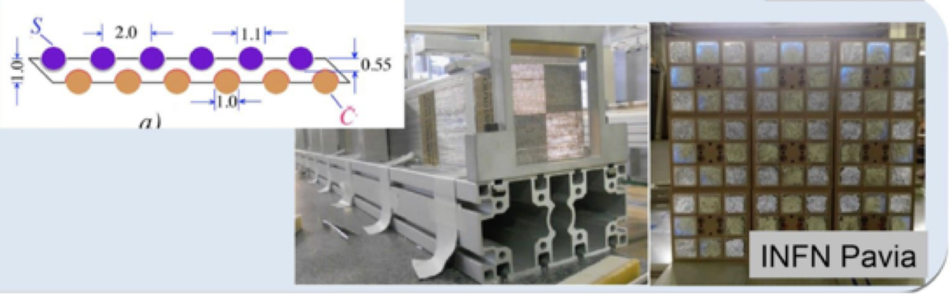
Each module: 9.3 * 9.3 * 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: 4.5%, 10 λ_{int}



2012
RD52

Lead, 9 modules

Each module: 9.3 * 9.3 * 250 cm^3
Fibers: 1024 S + 1024 C, 8 PMT
Sampling fraction: 5%, 10 λ_{int}



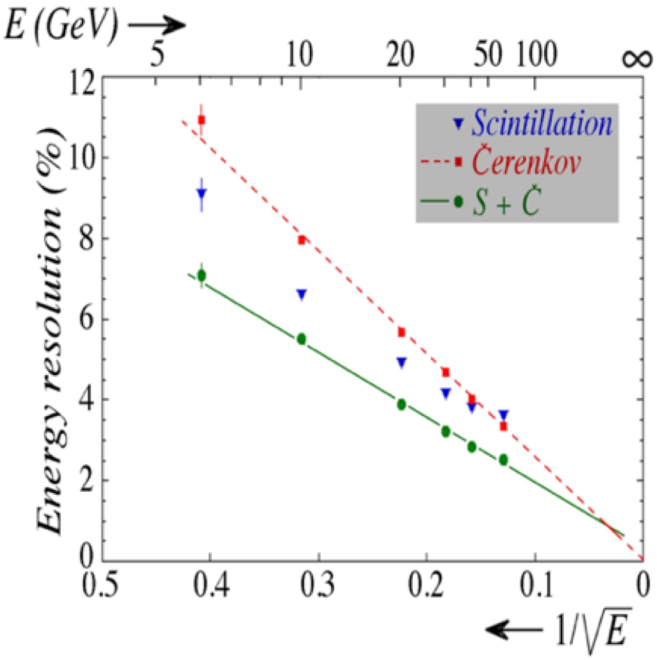
S. Lee, M. Livan, R. Wigmans, *Dual-Readout Calorimetry*, Rev. Mod. Phys. 90 (2018) 025002.

Energy resolution

- Electromagnetic resolution:

$$\frac{\sigma_{EM}}{E} = \frac{11\%}{\sqrt{E}} \oplus 1\%$$

Copper module
NIM A735, 130-144 (2014)

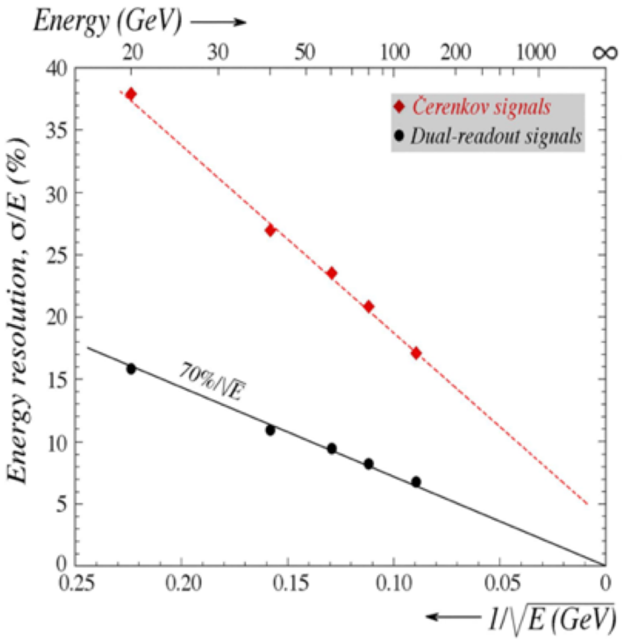


- Hadronic resolution:

$$\frac{\sigma_{HAD}}{E} = \frac{70\%}{\sqrt{E}}$$

Lateral Leakage

Lead module
NIM A537, 537-561 (2014)



Particle Identification

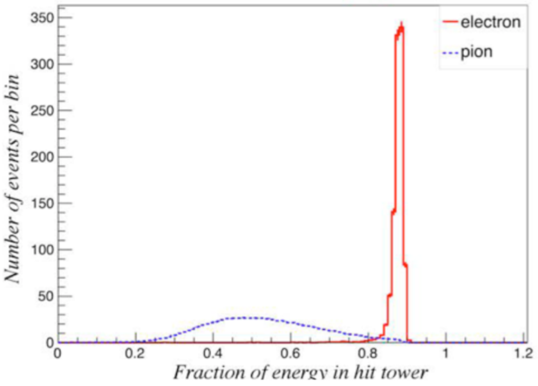
- Different methods allow hadron/electron separation:

RD52 lead calorimeter:
60 GeV e^-/π^-

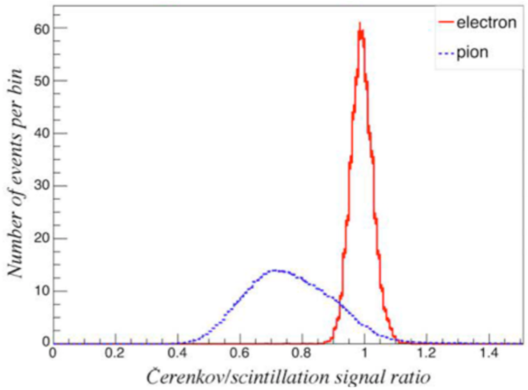
A multivariate analysis reached a particle ID capability of:

**$\varepsilon(e^-) = 99.8\%$
@ $R(\pi^-) \sim 500$**

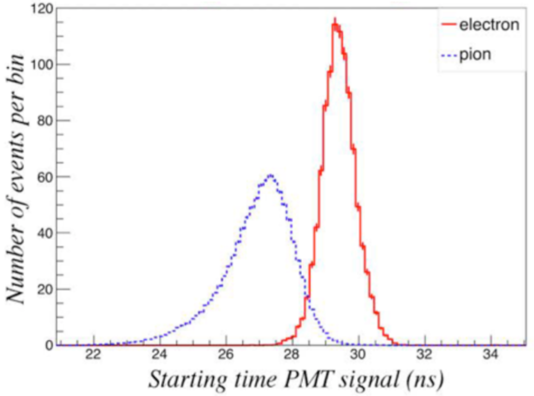
Lateral shower profile



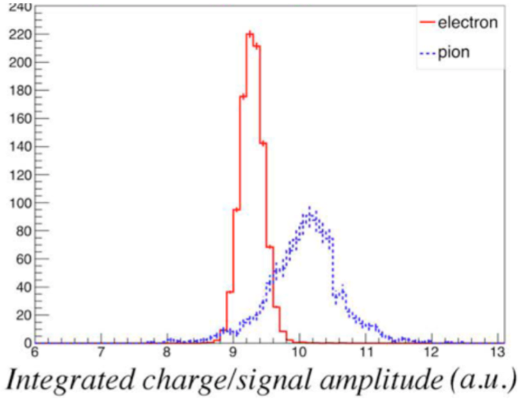
Difference C/S signal



Starting time



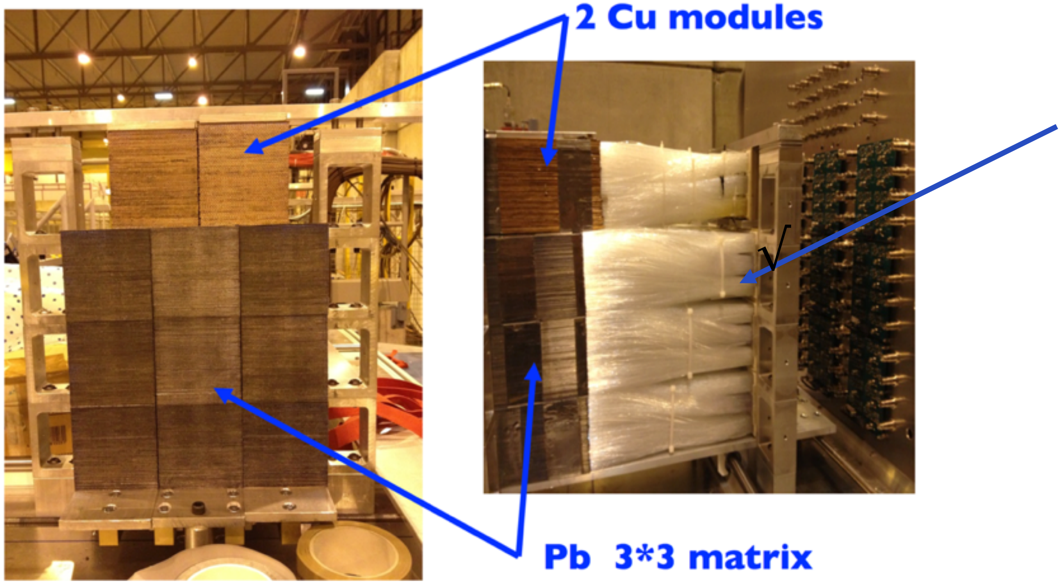
Signal charge/amplitude ratio



NIM A735, 210 (2014)

Is this the end?

The generic R&D phase has demonstrated that the dual-readout technique fulfil the requirements for future high energy lepton colliders (i.e. CEPC, FCC-ee, ILC) where resolutions of the order of $\frac{16\%}{\sqrt{E}}$ (EM) and $\frac{50\%}{\sqrt{E}}$ (Had) are required



2 Cu modules

Pb 3*3 matrix

Bundle of fibers (≈ 30 cm long) to bring the light towards the PMTs

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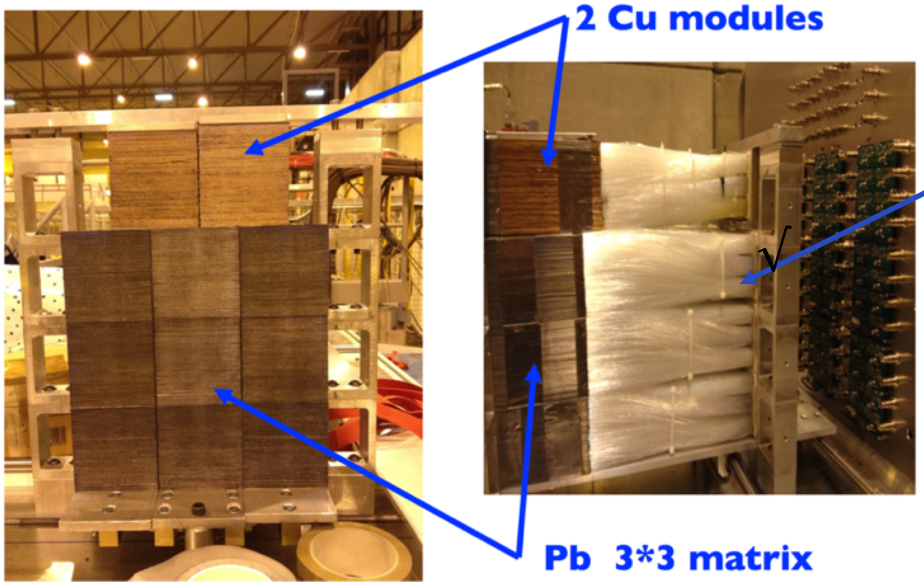
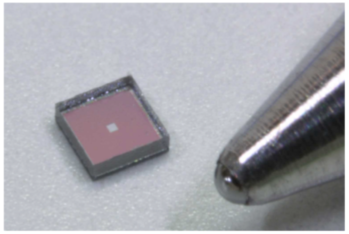


Bundle of fibers (≈ 30 cm long) to bring the light towards the PMTs

Is the Silicon Photomultiplier (SiPM) a possible solution?



Now is the time to demonstrate that this technique can be integrated into a geometry for collider experiments

PMT VS SiPM

- Advantages:
  - Compact readout:
    - no fibres sticking out (antennas)
  - Possible longitudinal segmentation
  - Operation in a magnetic field
  - Higher photon detection efficiency (PDE):
    - Cherenkov photoelectrons are the limiting factor to the hadronic calorimeter resolution

- Potential disadvantages:
  - Signal saturation and Dynamic range
  - Optical crosstalk between Cherenkov and scintillating signals
  - Some instrumental effects:
    - Temperature gain variation, dark count rate, etc.

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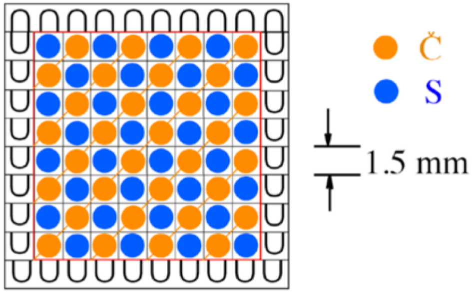
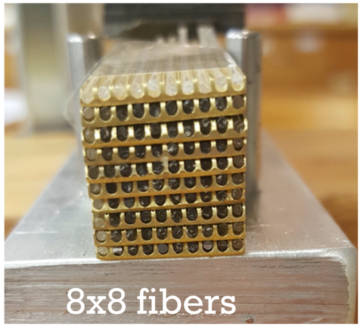
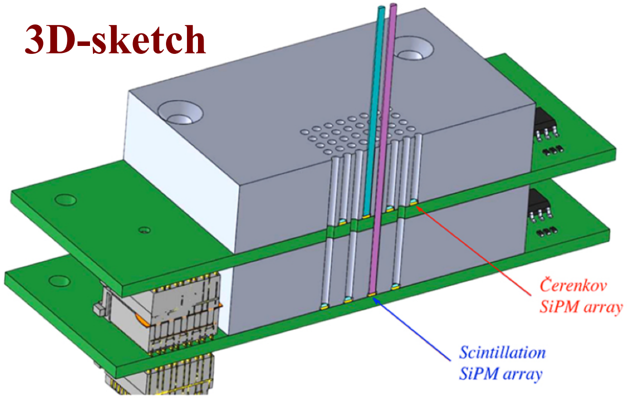
The module under test





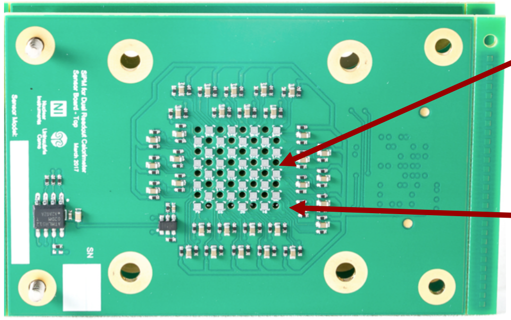
The module (112 cm long, X_0 = 29 mm) is built from stacked brass layers, housing 1mm diameter clear & scintillating fibres with a pitch of 1.5 mm (R_M = 31 mm)

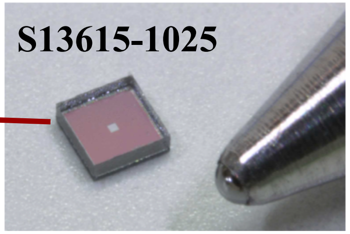
3D-sketch



Top layer (Front view)

Through – holes

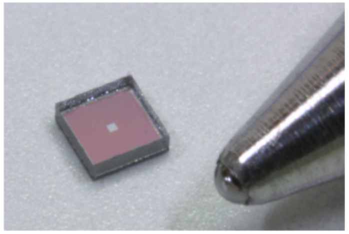




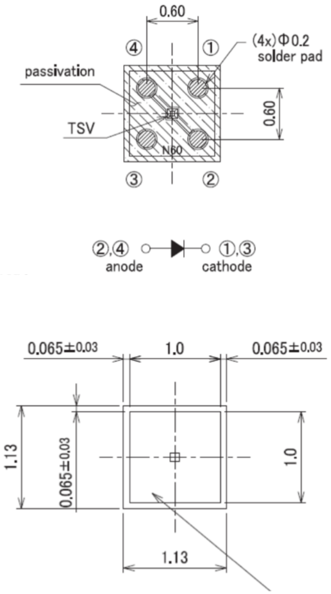
- The light propagated in each fiber is sensed by individual SiPMs
- The SiPMs collecting Cerenkov / scintillating light are placed on separate boards to avoid that Cherenkov light is contaminated by scintillating light. The latter is expected to be ≈ 50 time more intense

The chosen SiPM

The sensor in use has 25 μm cell pitch (S13615-1025)

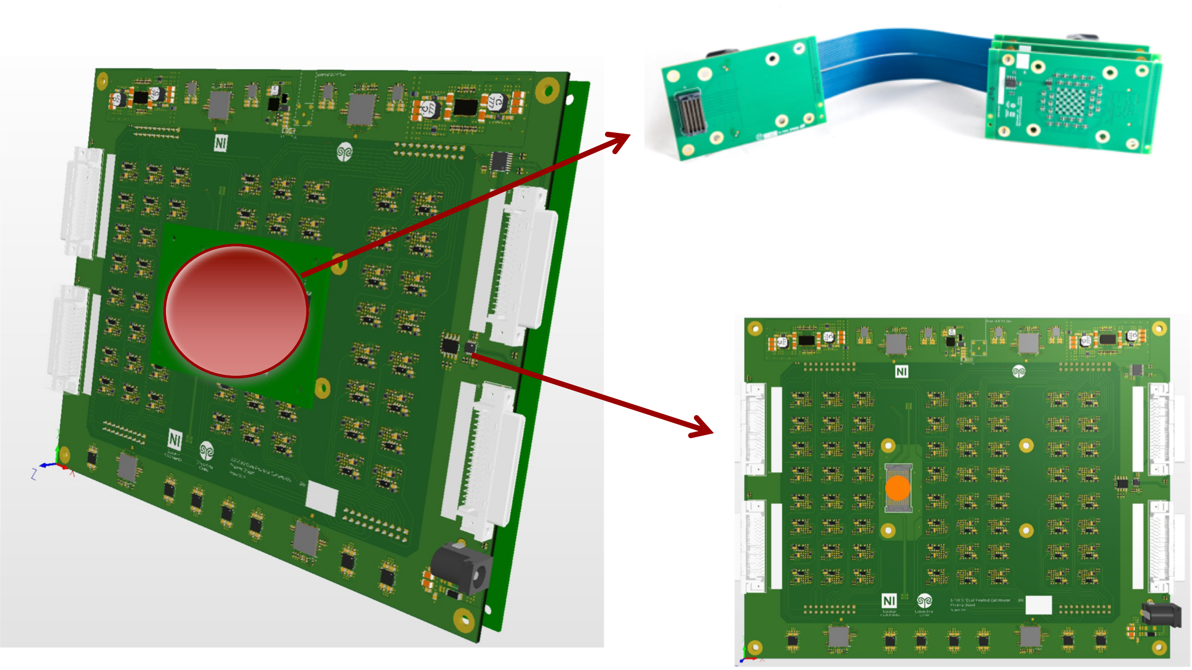


Parameters	S13615 -1025	S13615 -1050	Unit
Effective photosensitive area	1.0x1.0		mm^2
Pixel pitch	25	50	μm
Number of pixels / channel	1584	396	-
Geometrical fill factor	47	74	%



Parameters		Symbol	S13615 -1025	S13615 -1050	Unit
Spectral response range		λ	320 to 900		nm
Peak sensitivity wavelength		λp	450		nm
Photon detection efficiency at λp[*3]		PDE	25	40	%
Breakdown voltage		V_{BR}	53 ±5		V
Recommended operating voltage[*4]		V_{op}	V_{BR} + 5	V_{BR} + 3	V
Dark Count	Typ.	-	50		kcps
	Max.		150		
Crosstalk probability	Typ.	-	1	3	%
Terminal capacitance		Ct	40		pF
Gain[*5]		M	7.0x10^5	1.7x10^6	-

FEE Board and DaQ



2 - Layer daughter board with extended cable

- Individual bias voltage with fine adjustment (3V - range) for the 64 SiPMs
- Temperature measurement for gain compensation

Mother board

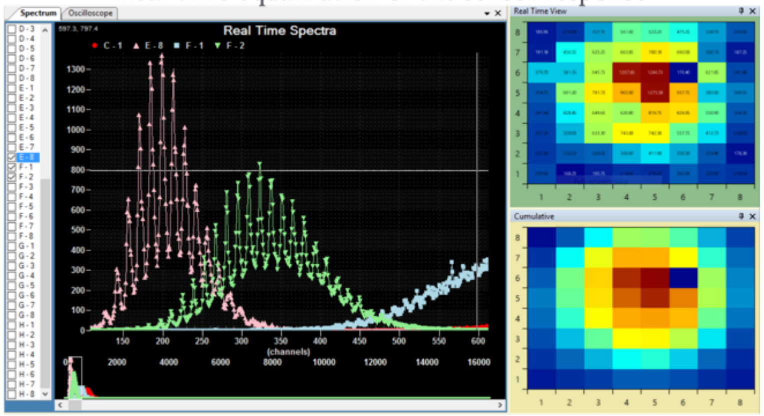
- 64 DC-coupled amplifiers with $1\mu s$ shaping time to match the digitization sampling rate
- Signals routing to the digitisation system

Nuclear Instruments

- Two MADA boards (32 channel digitizer each)
- Sampling rate 80MSpS/14-bit ADC
- FPGA based charge integration algorithm with on-line baseline subtraction

System qualification

Real-time equalization of the sensor response



On-line system

- SiPM response to LED
- All SiPMs have been equalized in bias voltage to have the same gain (peak-peak distance)
- Sensor measurements confirmed the expected spurious effects (i.e. DCR, X_{talk})

System qualification

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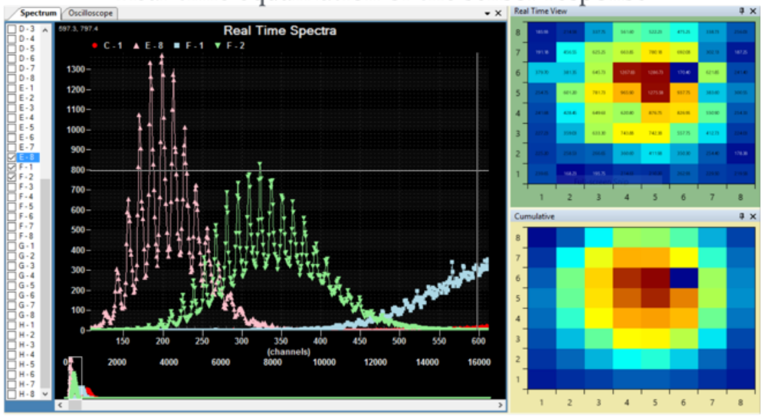

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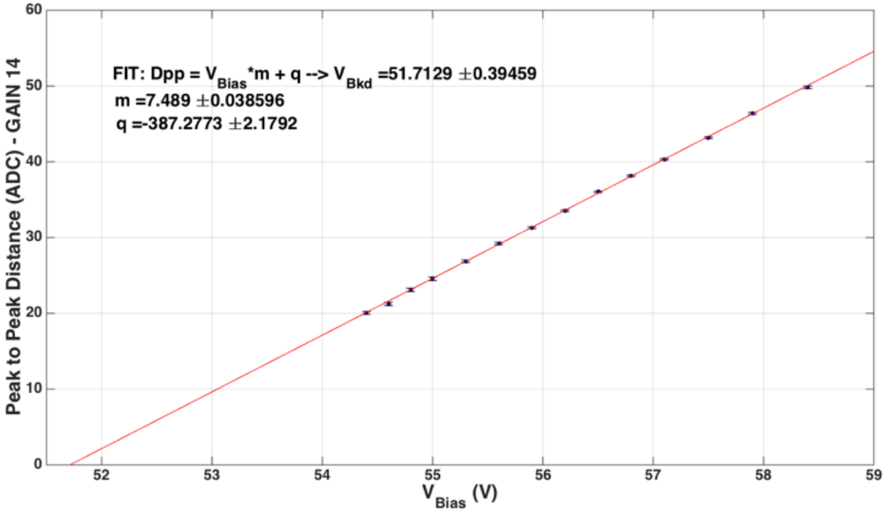
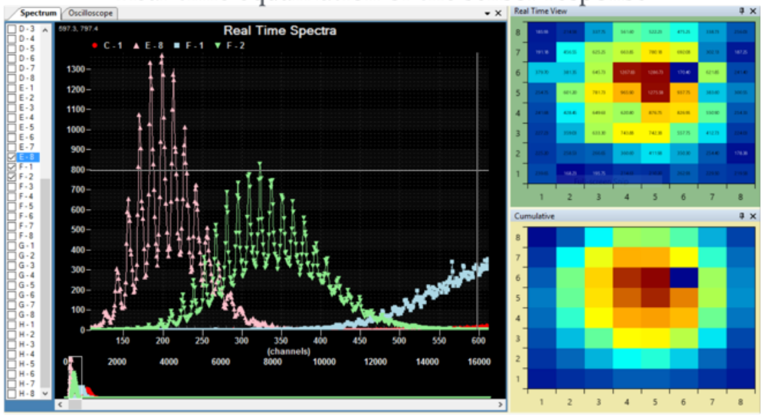


Peak - Peak distance VS Bias

- Allows to measure the breakdown voltage for each SiPM
- It is used to adjust for temperature Gain variation

System qualification

Real-time equalization of the sensor response



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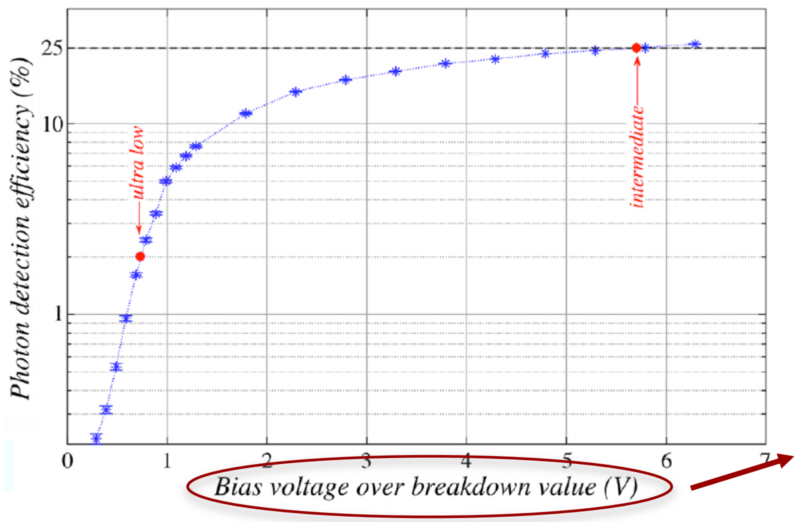


PDE (Photo-detection efficiency)

Starting from the absolute value quoted in the data sheet (25 %), the relative number of detected photons is measured as a function of bias voltage over the breakdown

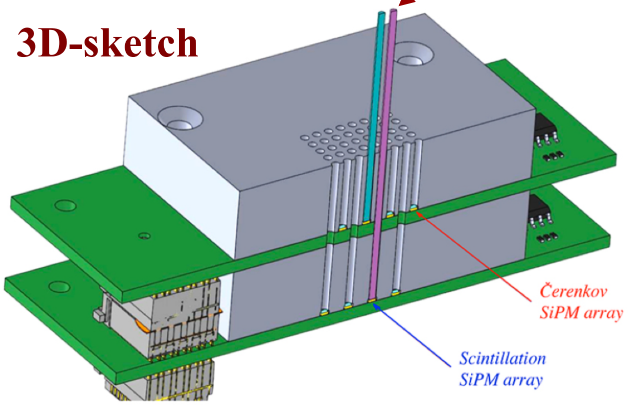
$$PDE(\lambda, T, \Delta V) = QE(\lambda, T) * G_f * P_{ph-e}(T, \Delta V)$$

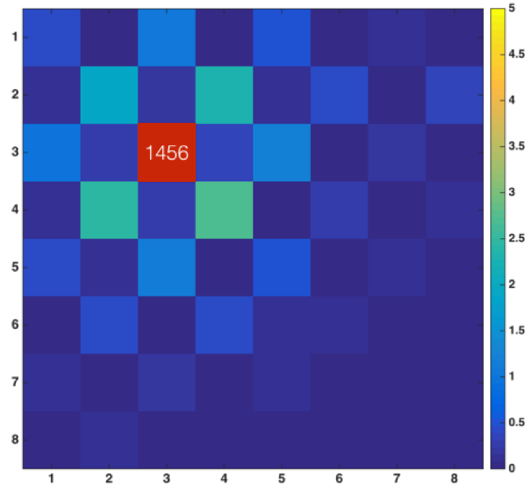
- $QE(\lambda, T)$ = Quantum efficiency
- G_f = geometrical fill factor
- $P_{ph-e}(T, \Delta V)$ = Probability of primary Ph-e to trigger the avalanche

Fibers cross-talk measurement

Light from LED conveyed in one fiber

3D-sketch

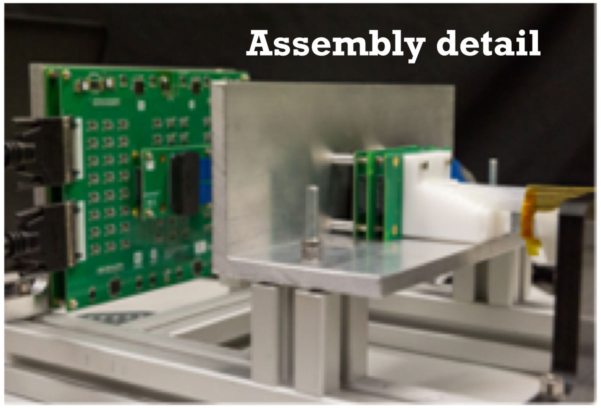


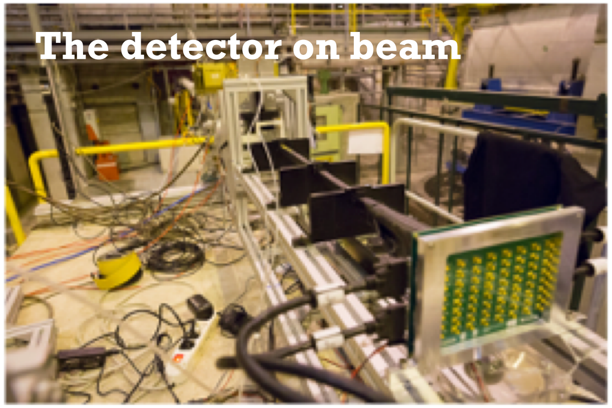

z max truncated to 5 fired cells

- LED light conveyed into one scintillating fiber
- All SiPMs in the matrix are readout
- It is expected that all SiPMs should register no signal except for spurious (Dark Count) events that accidentally start an avalanche in the integration window
- It was measured that:
  - Few Ph-e are contaminating the SiPMs on the same layer (≈ 1 %)
  - The contamination in the second layer is < 0.3 %

The contamination between layers is important due to the large difference in intensity for scintillating / Cerenkov light

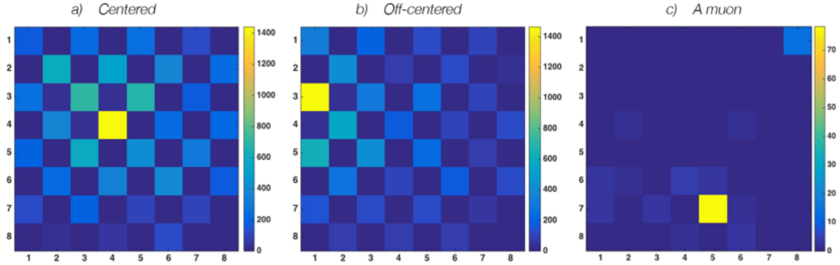
2017 Test Beam





M. Antonello, et al,
NIM-A 899 (2018) 52

Event Display



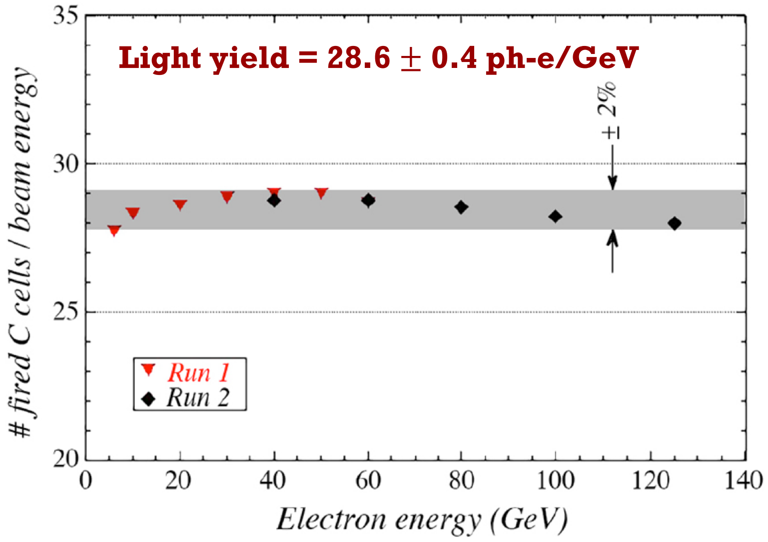
Test beam setup

- T_1, T_2, T_H: scintillators used in the trigger
- Delay Wire Chamber (DWG): selects events in the central region
- Preshower detector: identifies e-
- Muon counter: identifies μ

Measurements

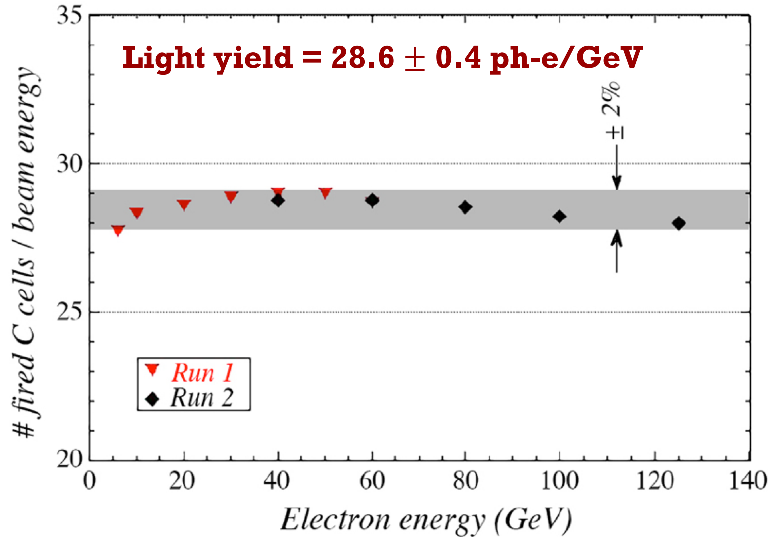
- Response to electron beam at different beam energies
- Response to muons

Cerenkov light yield



- Detector operated at nominal bias voltage (PDE = 25%)
- Temperature stability correction:
  - < 0.5°C during a single run (negligible)
  - < 2°C during the full scan (considered)

Cerenkov light yield



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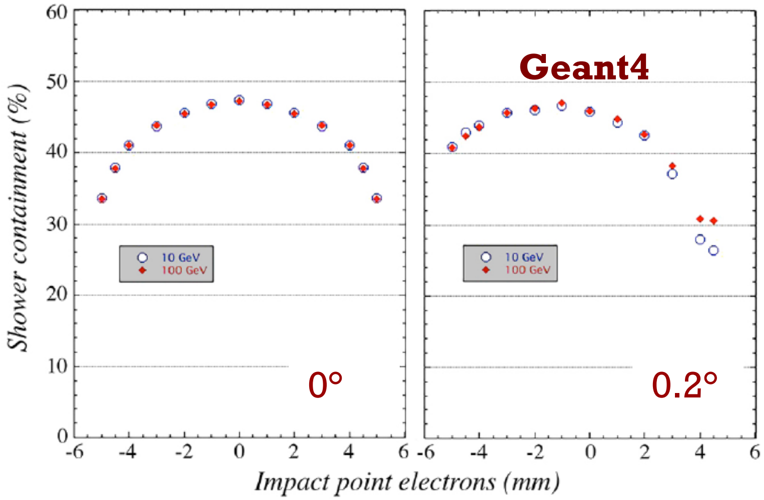


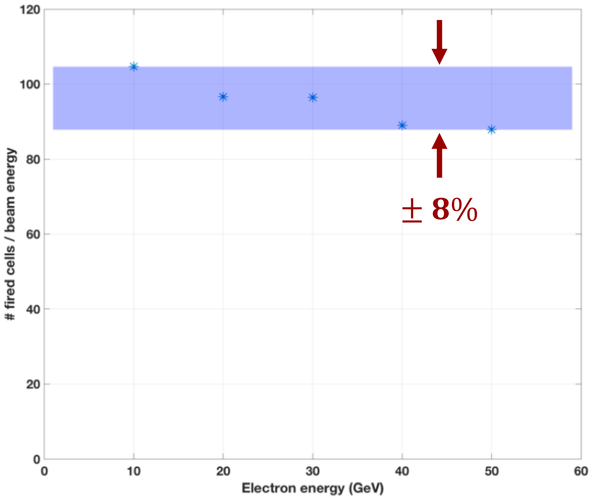
Energy containment predicted by simulation is 45%

- It is independent from beam energy
- It is almost constant when a geometrical cut of 3mm in the center is applied in the selection

A full contained electron shower is expected to have a Light yield* = 54 ± 5 ph-e/GeV

*** Number corrected for the measured scintillating contamination**

Scintillating light yield



- Detector operated at 0.5V over breakdown (PDE ≈ 2%)
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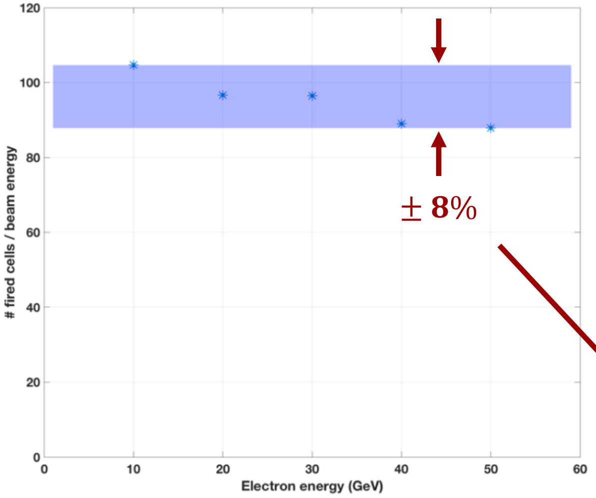
- PDE correction for temperature variation

Scintillating light yield



± 8%

- Detector operated at 0.5V over breakdown (PDE ≈ 2%)
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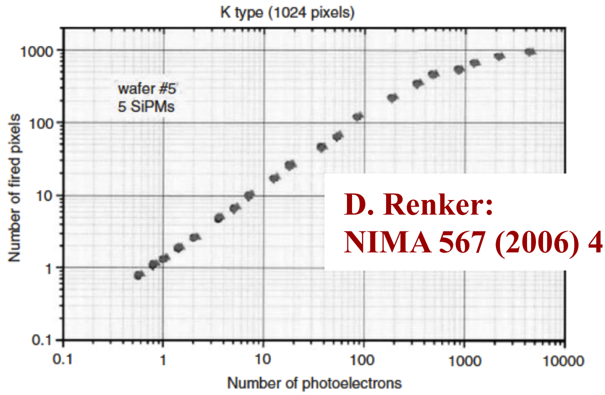
- PDE correction for temperature variation

Even if with low bias voltage the SiPMs are not saturating, they are working in a strongly non linear regime: a correction is required

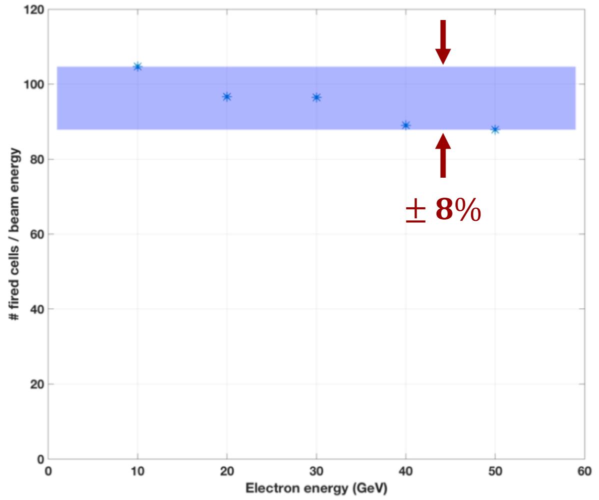
$$N_{fired} = N_{total} \times \left[1 - e^{-\frac{N_{photons} \times PDE}{N_{total}}} \right]$$



D. Renker:
NIMA 567 (2006) 48–56

Valid as a first approximation: the light uniformly illuminate the SiPMs, all photons come at the same time and spurious effects are negligible

Scintillating light yield



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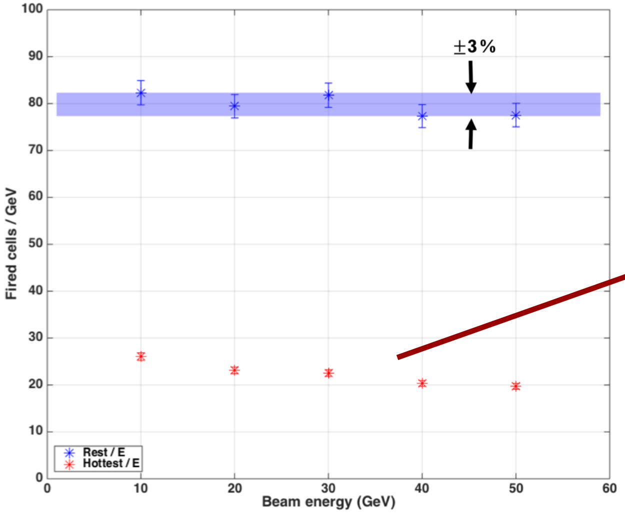
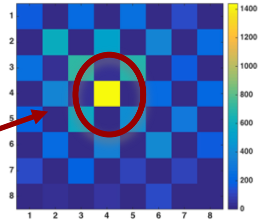




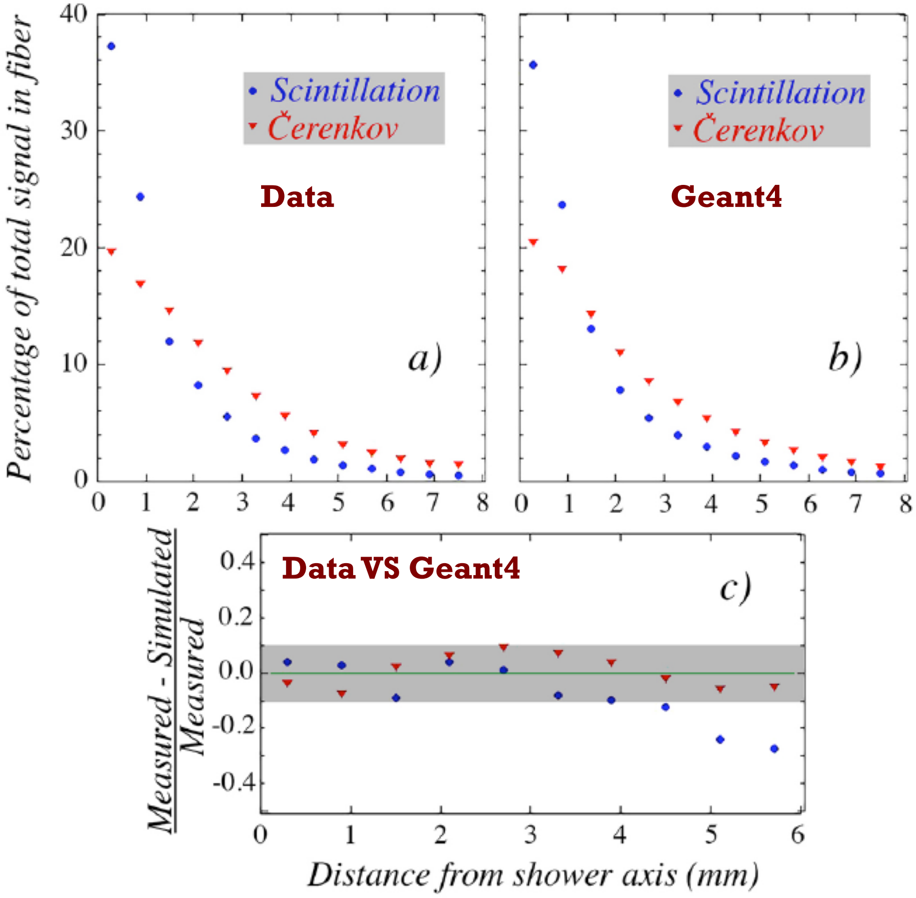
Once the correction is applied, even if it is not perfect, the linearity is largely improved

A full contained electron shower is expected to have a Light yield* = 3200 ph-e/GeV

*** The light yield is scaled to the typical SiPM PDE (25%)**

Lateral shower profile

In addition, this segmentation allowed to measure the electromagnetic lateral shower profile with an unprecedented granularity

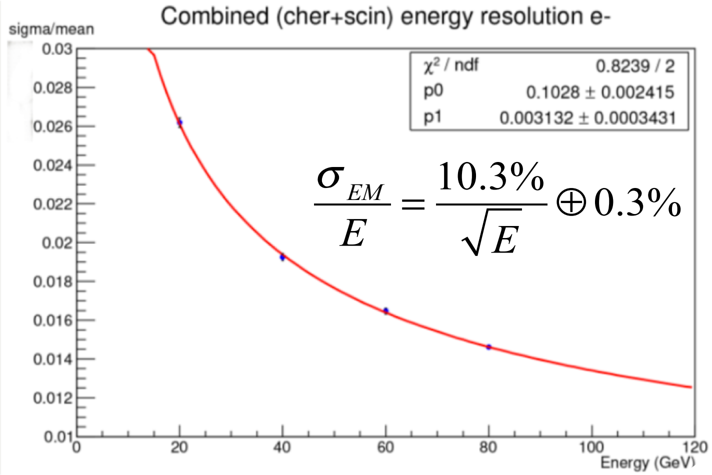


$$\bar{x} = \frac{\sum_i x_i E_i}{\sum_i E_i}, \qquad \bar{y} = \frac{\sum_i y_i E_i}{\sum_i E_i}$$

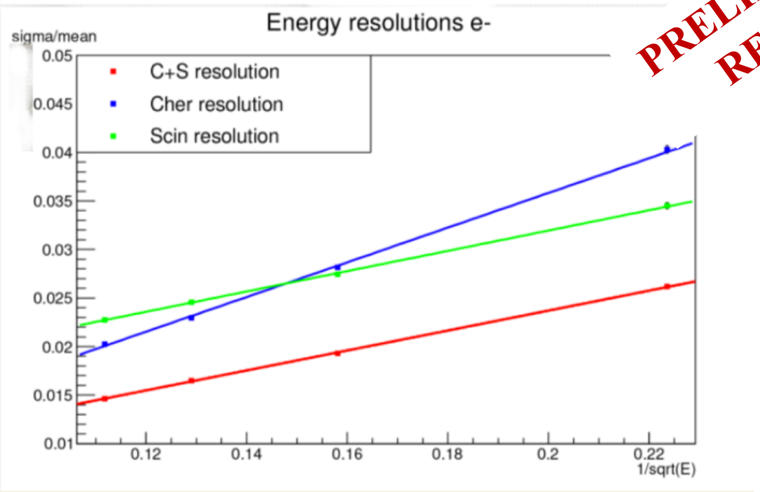
$$r_i = \sqrt{(x_i - \bar{x})^2 + (y_i - \bar{y})^2}$$

Latest GEANT4 simulation results

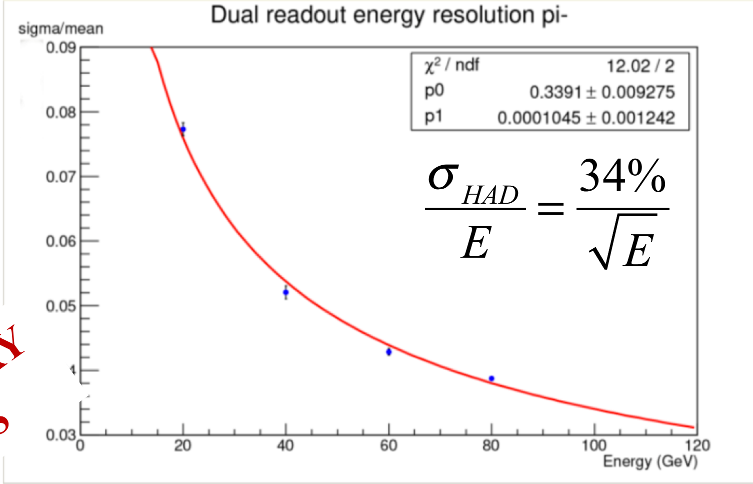
Electromagnetic resolution:



$$\frac{\sigma_{EM}}{E} = \frac{10.3\%}{\sqrt{E}} \oplus 0.3\%$$



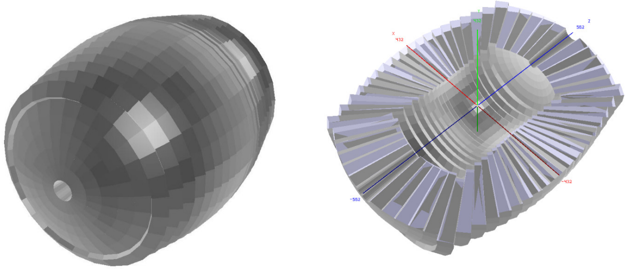
Hadronic resolution:



$$\frac{\sigma_{HAD}}{E} = \frac{34\%}{\sqrt{E}}$$

PRELIMINARY RESULTS

4π simulation with the latest results
to be implemented:



Outline

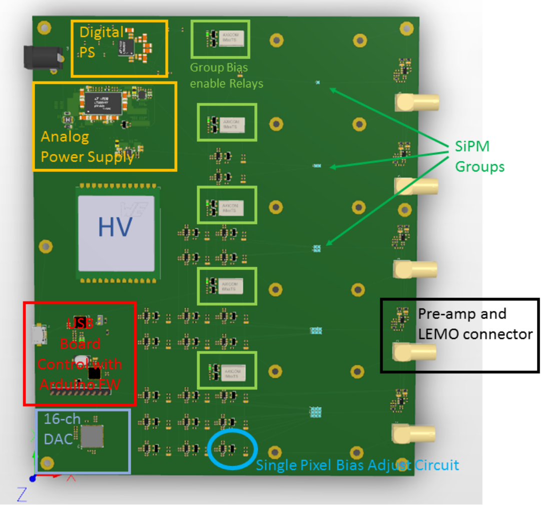
- Dual Readout Calorimetry
- Summary of the test beam results
- What next?
    - Try do contain the number of channel to be readout
    - Try to avoid the non-linearity and cross-talk
    - Start testing the ASICs to readout the SiPMs

Too many channels to be readout?

- If we think that the number of SiPMs are too much, we could still consider to group the analogue signals
- In this case, the main questions to be addressed are:
  - **Signal Goruping:** How many SiPMs can be grouped guarantying the Multi-Photon spectrum?
  - Is the space granularity something that we are ready to reduce?
  - **SiPM dynamic range:** How many cells would allow us to operate the sensor in a linear regime?

Signal Grouping

- This board allows to investigate the SiPM performances when the signals are grouped analogically (from 1 to 9 SiPMs)
- Each SiPM is individually biased
- Same FEE used in the test beam



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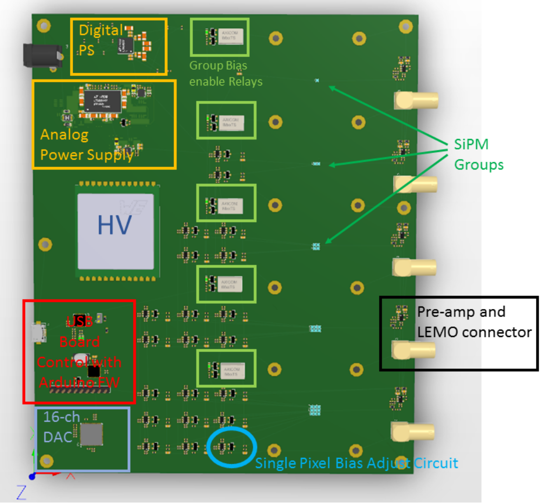
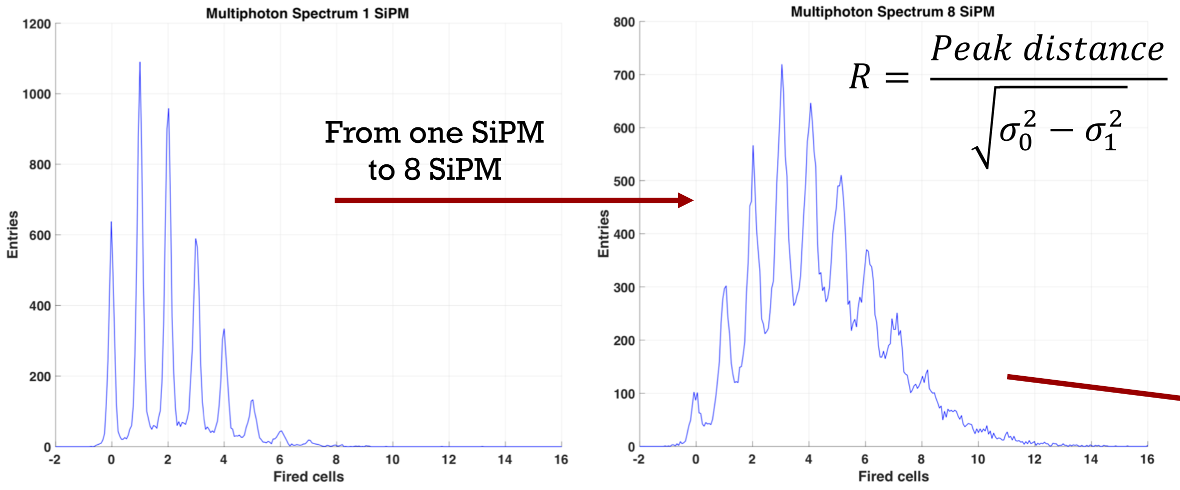
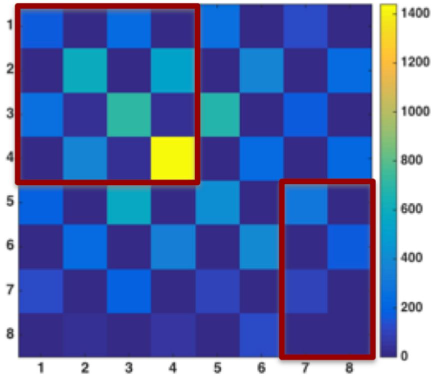




From one SiPM to 8 SiPM

$$R = \frac{Peak\ distance}{\sqrt{\sigma_0^2 - \sigma_1^2}}$$



	1 SiPM	4 SiPM	8 SiPM
R = resolving power (ph-e)	24.5	16.6	10.0
Space granularity (mm²)	≈4.5	≈18	≈36

SiPM dynamic range

A strong push for larger number of cells is not an easy game.

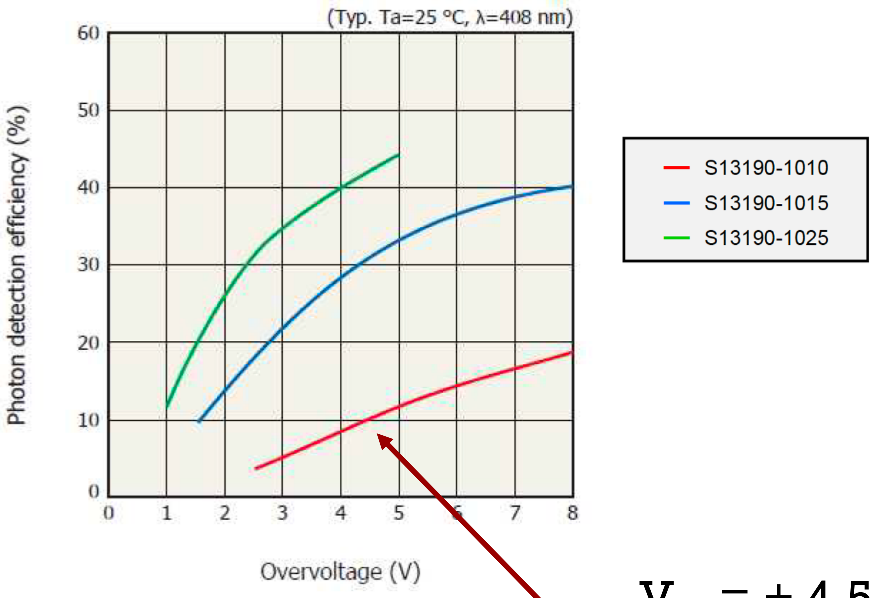
This approach, in a first approximation, would show:

- Reduced fill factor (lower PDE)
- Higher spurious effect (higher Dark counts)
- Lower capacitance ≈ lower gain and reduced possibility to see the multi-photon spectrum

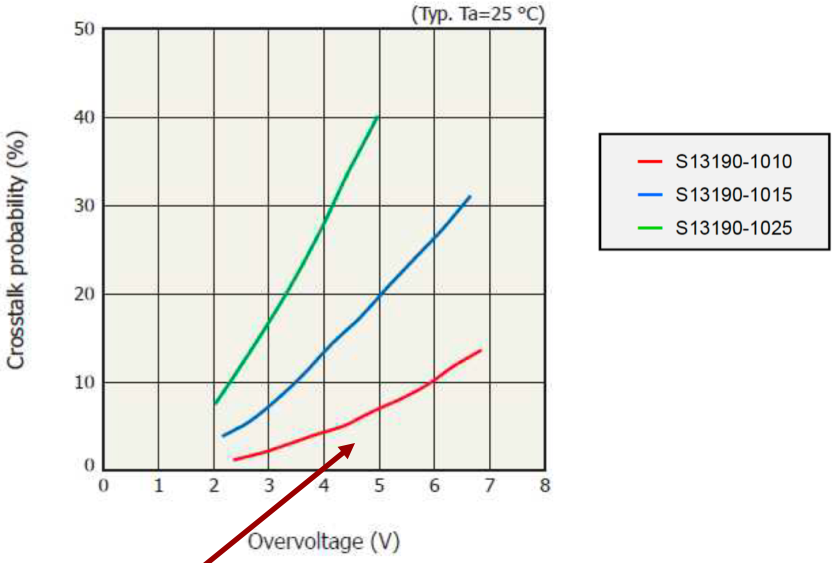
Nevertheless the companies are working hard in this direction …

SiPM dynamic range

- Hamamatsu has the S13190-1010
  - 10 x 10 μm^2, ≈ 10^4 cells, PDE 10%, Typical DCR = 100 kcp, Xtalk 5%, Expected Gain ad Vop = $1.3*10^5$



■ Crosstalkprobabilityvs. overvoltage



V_{op} = + 4.5V over breakdown

SiPM dynamic range

- FBK has Ultra High Density (UHD) SiPM: sensor with 5 μm pitch and $4.6 * 10^4$ cells (IEEE-explore, 24, No. 2, 2018)

Special care has to be used to reduce border region effects at the edge of the high-field region modifying the doping profile (NGR)

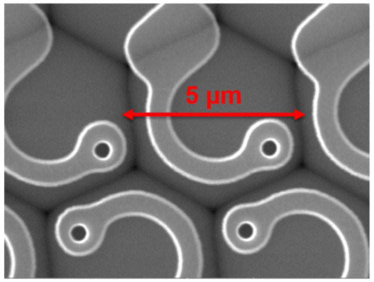


Fig. 4. SEM image of UHD SiPM, with 5 μm cell pitch. The honeycomb configuration of the cells and the top polysilicon resistor are visible.

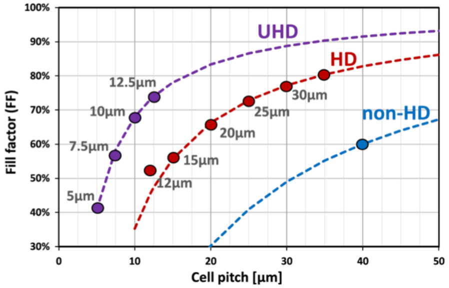
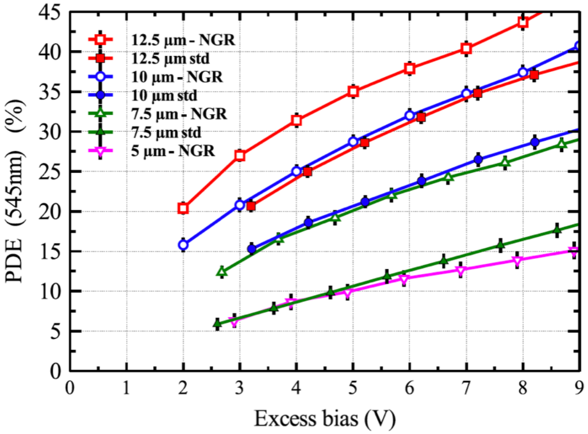
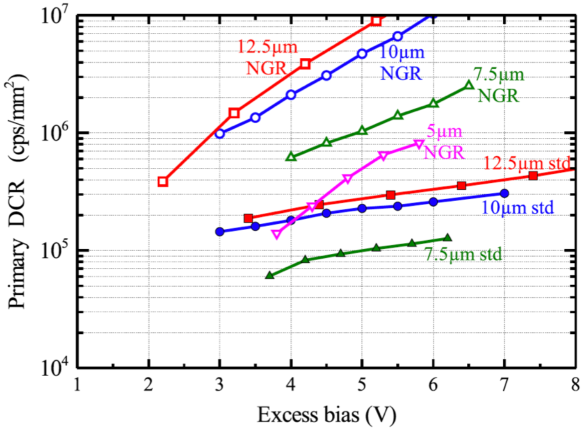
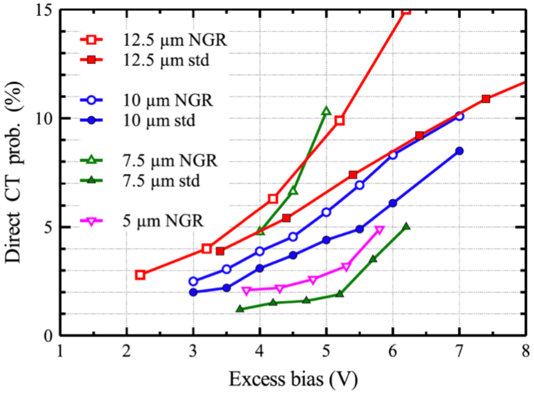


Fig. 5. Nominal fill factor comparison between different FBK SiPM technologies: non-HD, high-density, and ultra-high-density. Thanks to the technology improvements, the fill-factor is generally high, despite the smaller cell pitch. Dots represent the produced and tested variants.



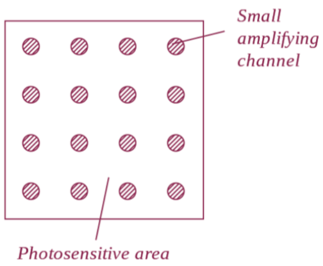




SiPM dynamic range

- A new design where the cells are integrated into a continuous photosensitive area (DEPHAN Solid-State Photomultipliers - SSPM). This concept has been recently proposed by S.V. Bogdanova et al.

Schematic DEPHAN image, top view



https://dephandetectors.com

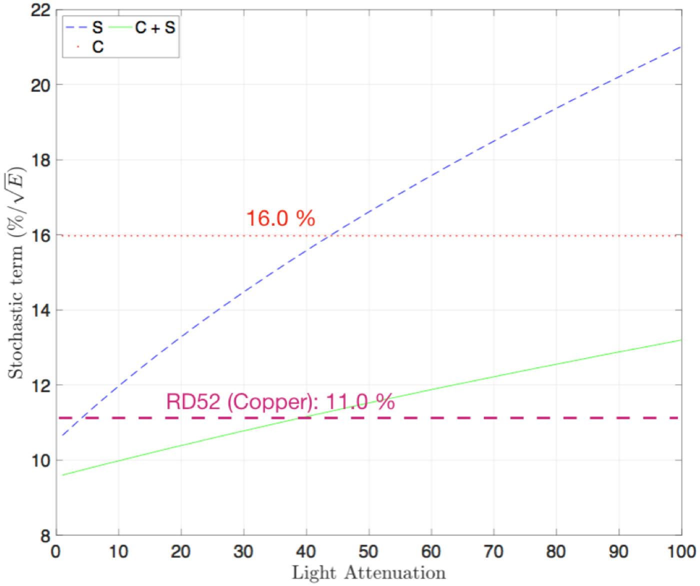
Pilot prototypes of the solid-state photomultipliers DEPHAN with 1×1 mm^2 surface area have amplification channels (cells) density 4.4×10^4 mm^{-2} with light-sensitive area (fill-factor) ***0.83.***

It was compared to the DEPHAN detector, an experimental SSPM of a new type, in which the amplifying channels (cells) are integrated into a continuous photosensitive area. Due to the new design, it became possible to increase its dynamic range by several times (cell density $4.5 \cdot 10^4$ per mm^2), significantly improving the other key characteristics: fill factor > 80%, ***PDE***$_0$~25%, and crosstalk probability < 2%.

(https://doi. /10.1117/12.2290956)

Is the dynamic range not enough?

The stochastic term contribution to the EM resolution considering the latest test beam results

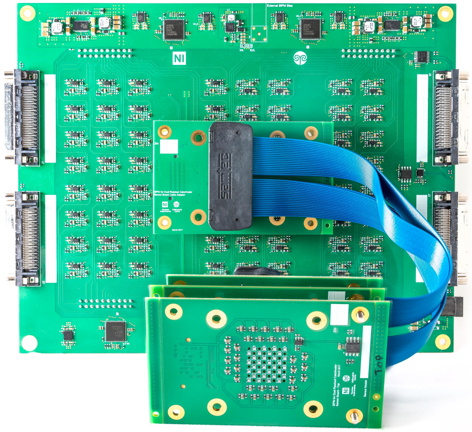


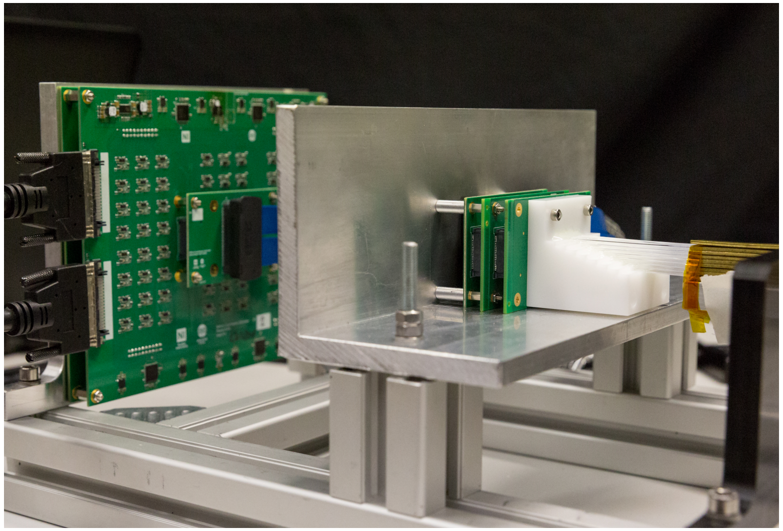
Too much light can always be filtered!

- The error from sampling fluctuations for both S and C channels is: $\varepsilon_{Sampling} \sim 10.5\%$
- The relative error of the number of fired cells/GeV is: $\varepsilon_{N_{FC/GeV}} = \dfrac{1}{\sqrt{N_{FC/GeV}}}$
- The combined error for each channel is: $\varepsilon_{Combined} = \sqrt{\varepsilon^2_{Sampling} + \varepsilon^2_{N_{FC/GeV}}}$
- The stochastic term in the EM resolution is: $\varepsilon_{C+S} = \dfrac{\sqrt{\varepsilon^2_{Combined}(S) + \varepsilon^2_{Combined}(C)}}{2}$

New Readout:

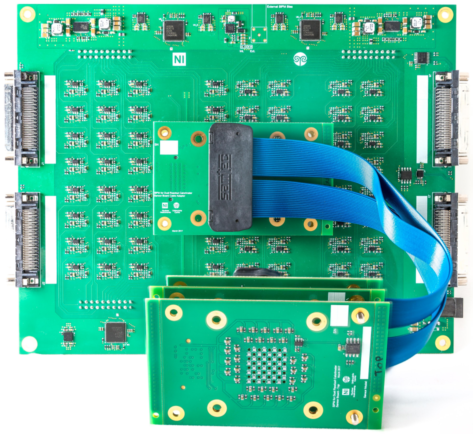
This is what do we have today

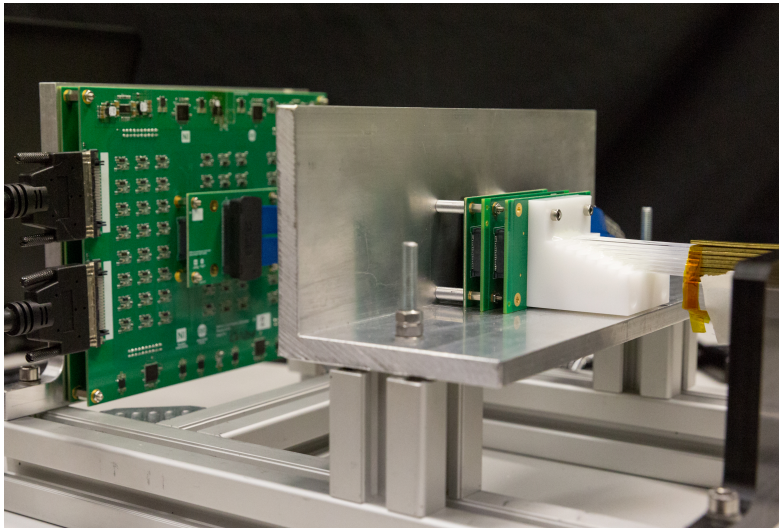




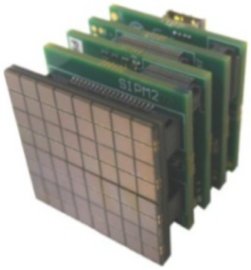
New Readout: We need an ASIC!

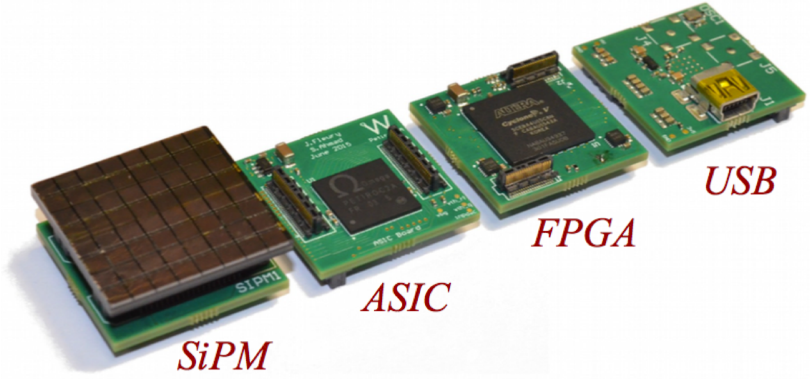
This is what do we have today





This is what do we need:



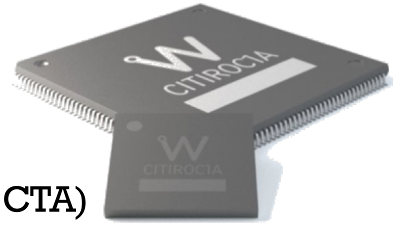


New Readout: it's worth a try!

Qualification of an ASIC read-out

Baseline ASIC:

CITIROC 1A (designed for CTA)



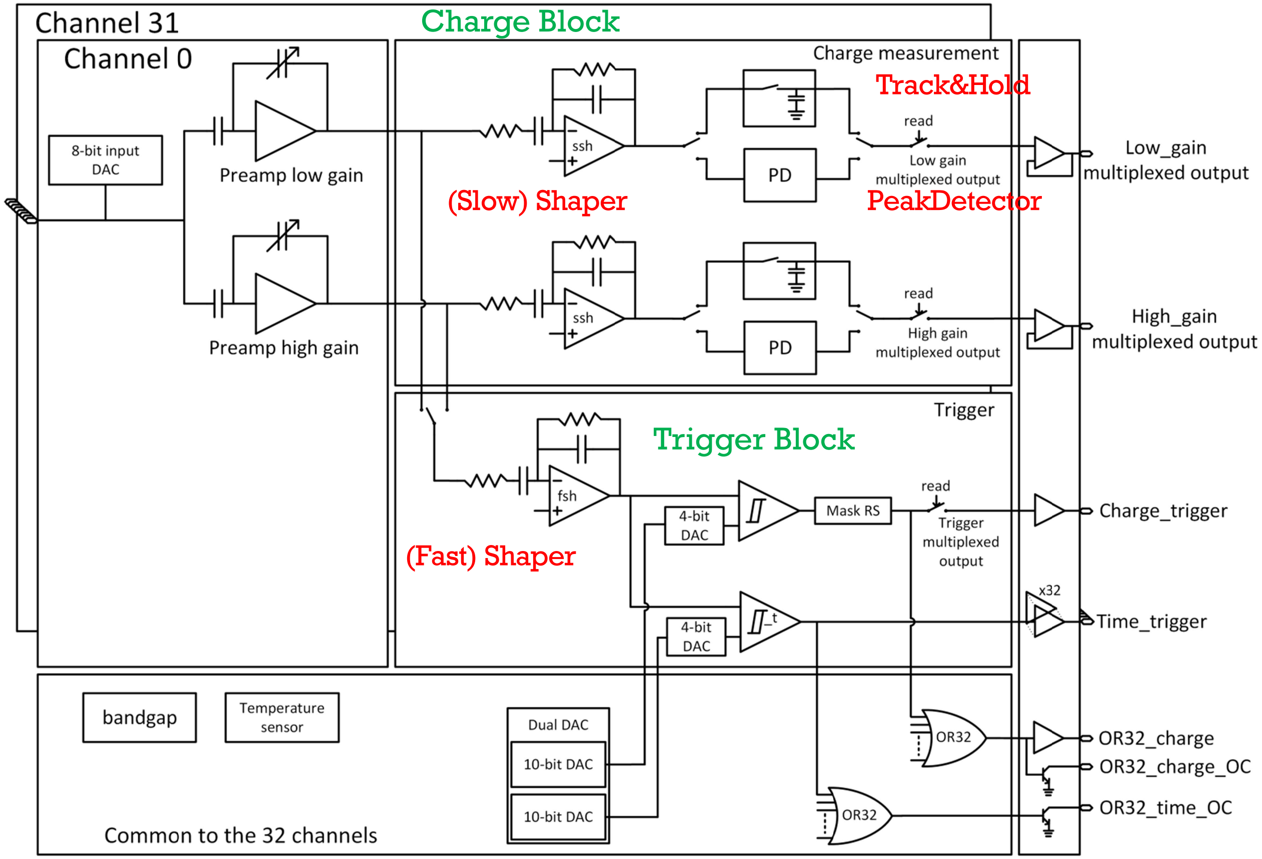
by

weeroc

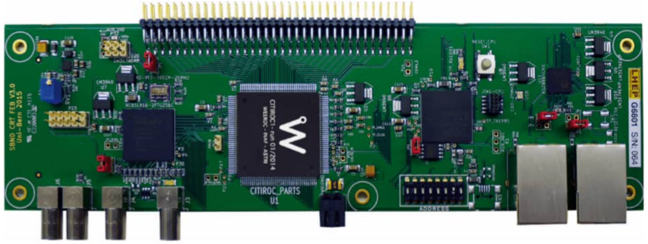
Detector Read-Out	SiPM, SiPM array	
Number of Channels	32	⟸
Signal Polarity	Positive	
Sensitivity	Trigger on 1/3 of photo-electron	
Timing Resolution	Better than 100 ps RMS on single photo-electron	
Dynamic Range	0-400 pC i.e. 2500 photo-electrons @ 10^6 SIPM gain	⟸
Packaging & Dimension	TQFP 160 – TFBGA353	
Power Consumption	225mW – Supply voltage : 3.3V	
Inputs	32 voltage inputs with independent SiPM HV adjustments	⟸
Outputs	32 trigger outputs 2 multiplexed charge output, 1 multiplexed hit register 2 ASIC trigger output (Trigger OR)	⟸
Internal Programmable Features	32 HV adjustment for SiPM (32x8bits), Trigger Threshold Adjustment (10bits), channel by channel gain tuning, 32 Trigger Masks, Trigger Latch, internal temperature sensor	

New Readout: it’s worth a try!

CITIROC 1A schematics

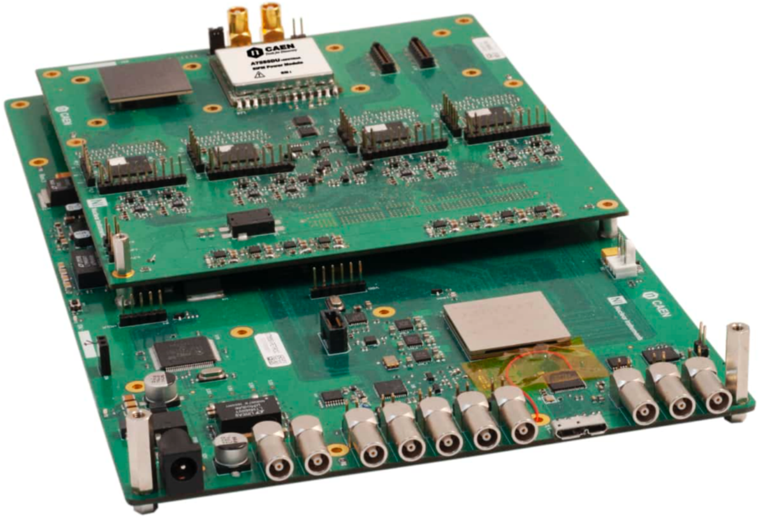


Commercially available



DT5702 Front-end Board for the CITIROC

- Bias voltage in the range of 20-90 V, individually adjustable for each channel
- Amplification and shaping of the SiPM output pulse
- 12 bit ADC for Energy and time measurements
- Trigger source: internal + validation signal
- Daisy chain of up to 256 boards into one network interface



DT5550W: Weeroc ASIC Development System

- Another evaluation board, with larger flexibility.
- At the moment compliant with PETIROC, but the version compliant with the CITIROC will be soon deploy

In short

- The SiPM seems to be a good candidate for dual-readout calorimetry
  - Allows for the 4-π geometry integration
  - Demonstrated a good linearity for Cherenkov light in the 6 – 125 GeV range
  - Showed twice more light yield than PMTs, reducing the stochastic terms contribution to the energy resolution
  - Allowed unprecedented spatial segmentation
  - ASICS have to be considered for the readout
- … but
  - The linearity response for the scintillating fibers has to be handle with care (filters or SiPMs with larger dyn-range)
  - The light contamination between scintillating and Cerenkov light has to be further reduced
  - Signal grouping can be considered to reduce the number of channels (i.e. lower power consumption)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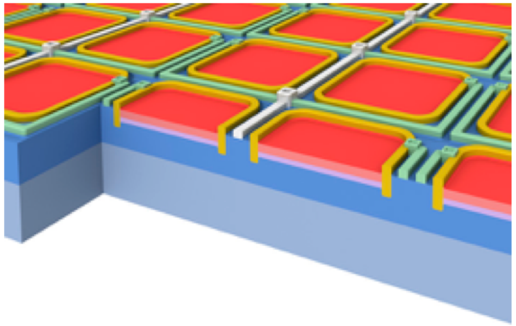
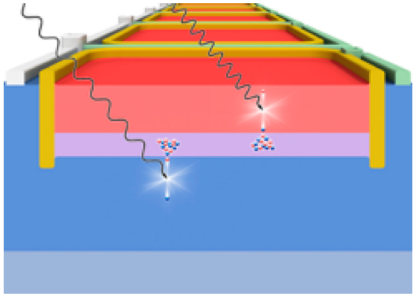
SiPM: short introduction

I Principles

SiPM = High density (~10^4/mm^2) matrix of diodes with a common output, reverse biased, working in Geiger-Müller regime

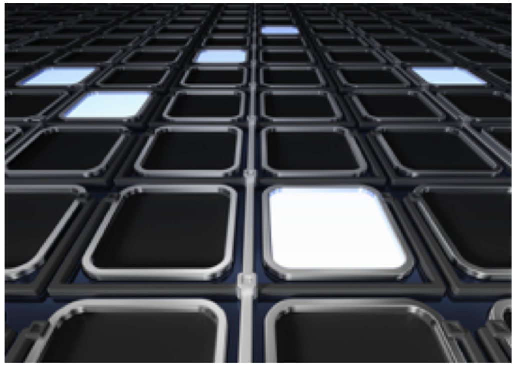
Courtesy http://www.yk.rim.or.jp/~reyhori/pages/galacc2_e.html



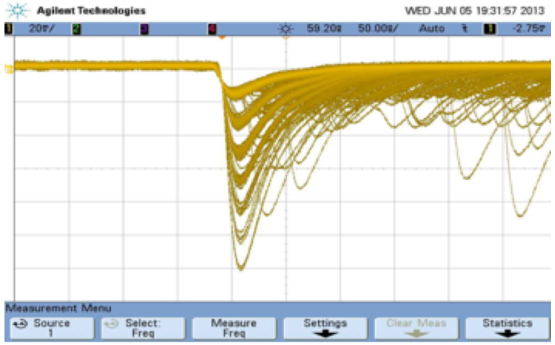


When a photon hits a cell, the generated charge carrier triggers an avalanche multiplication in the junction by impact ionization, with gain at the 10^6 level

II Operation



SiPM may be seen as a collection of binary cells, fired when a photon is absorbed



Bu the output signal is proportional to the number of fired cells providing an information about the intensity of the incoming light

SiPM: short introduction

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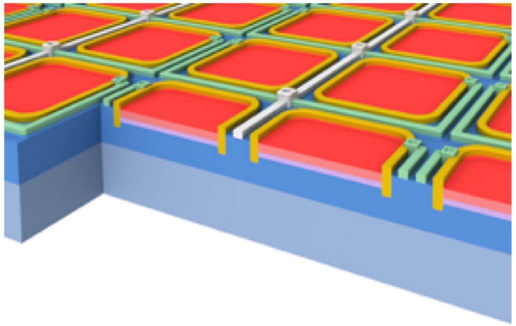

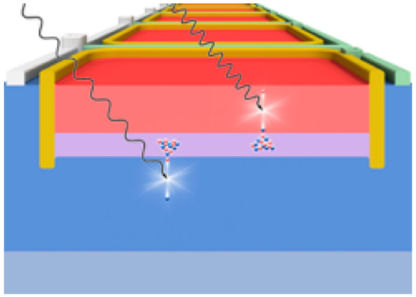

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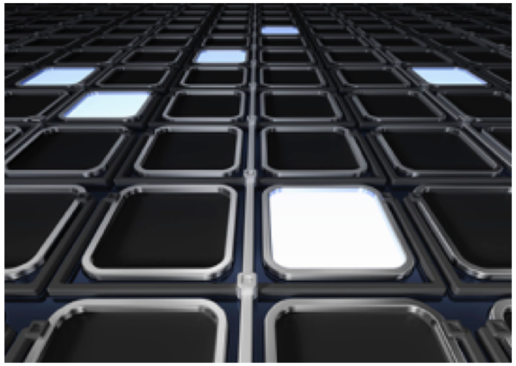

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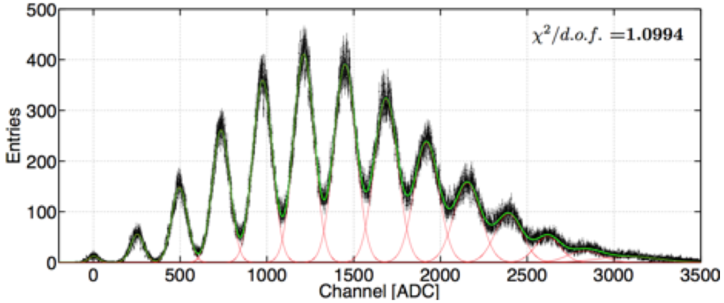

This is what you get integrating the SiPM output signal. Each peak correspond to a specific number of cells fired.