A SILICON PHOTOMULTIPLIER BASED DUAL READ-OUT CALORIMETER MODULE

Massimo Caccia, Università dell'Insubria @Como & INFN-Milano
[massimo.caccia@uninsubria.it]

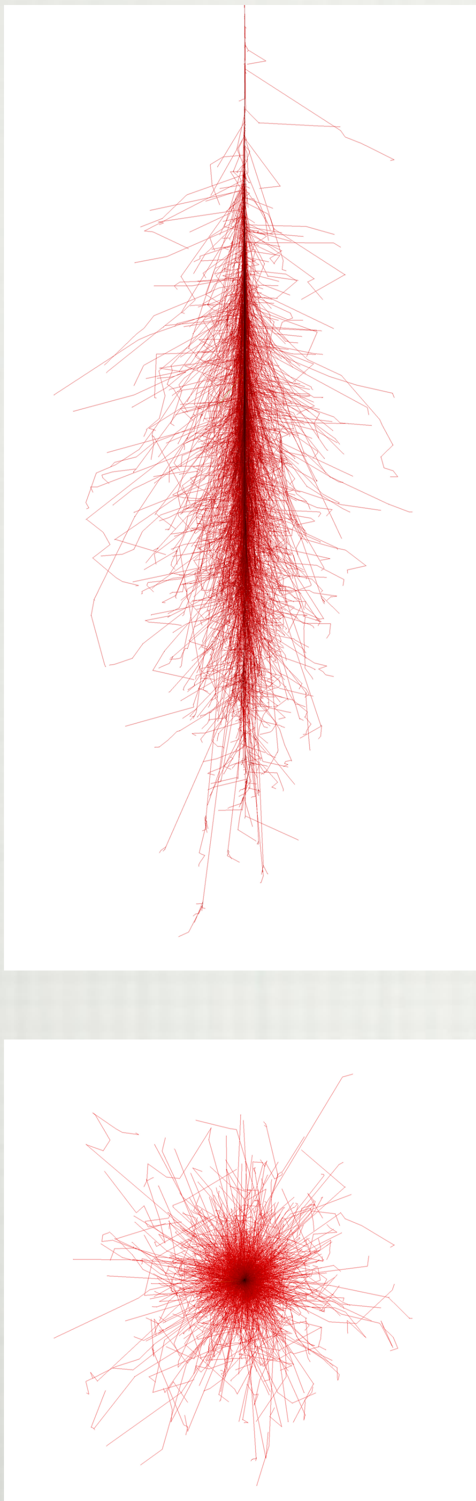
on behalf of the RD52 2016 test beam team:

- **Richard Wigmans** (Texas Tech) & **John Hauptman** (Iowa State Uni.) + students
- **Romualdo Santoro & Massimiliano Antonello** (Uni. Insubria)
- **Andrea Abba & Francesco Caponio** (Nuclear Instruments)
- Seehwook Lee (Kyungpook National University) & his students
- Michele Cascella (UCL)
- Silvia Franchino (CERN)
- Roberto Ferrari (INFN Pavia)
- Fabrizio Scuri (INFN Pisa)
- guest star: Manqi Ruan (IHEP, Chinese Academy of Sciences)

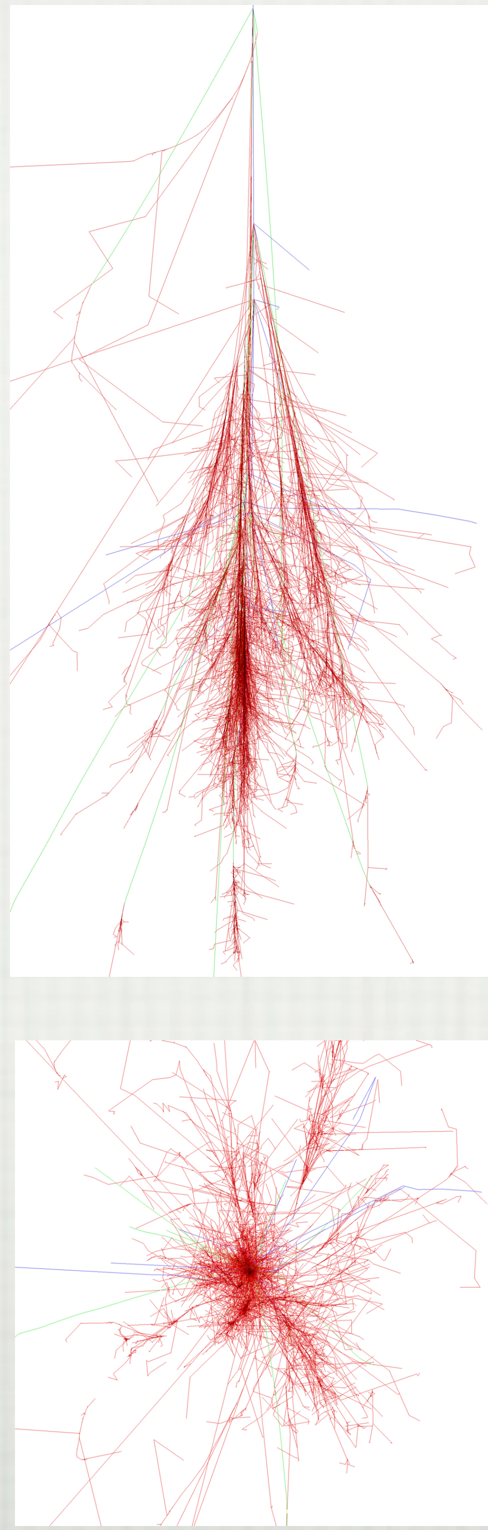
HKUST - CepC workshop, January 25th, 2017

Calorimetry is a "fluctuation game" [leakage, sampling, e.m. fraction, invisible energy, noise]:

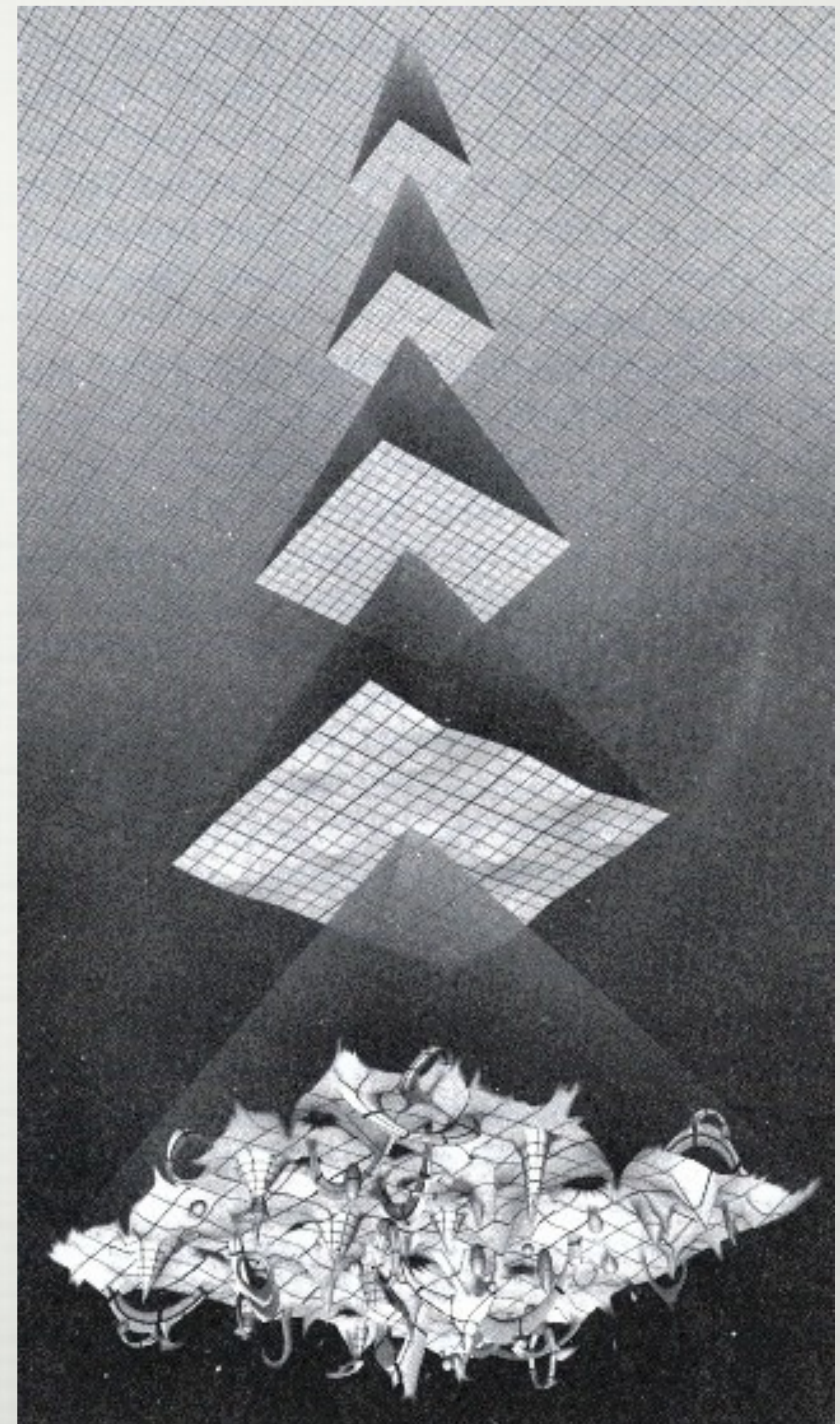
50 GeV photon in air *



100 GeV proton in air *



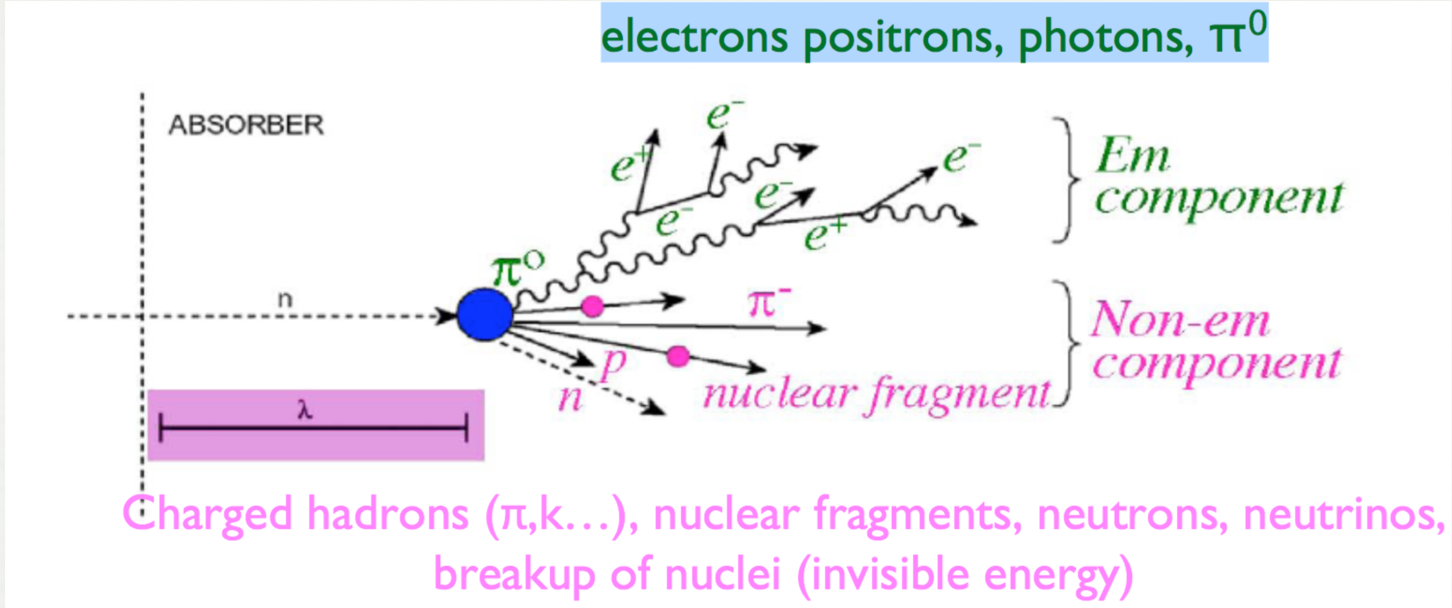
an artist's view (Quantum Spacetime - http://newabstraction.net/2013/07/31/further-inside/)



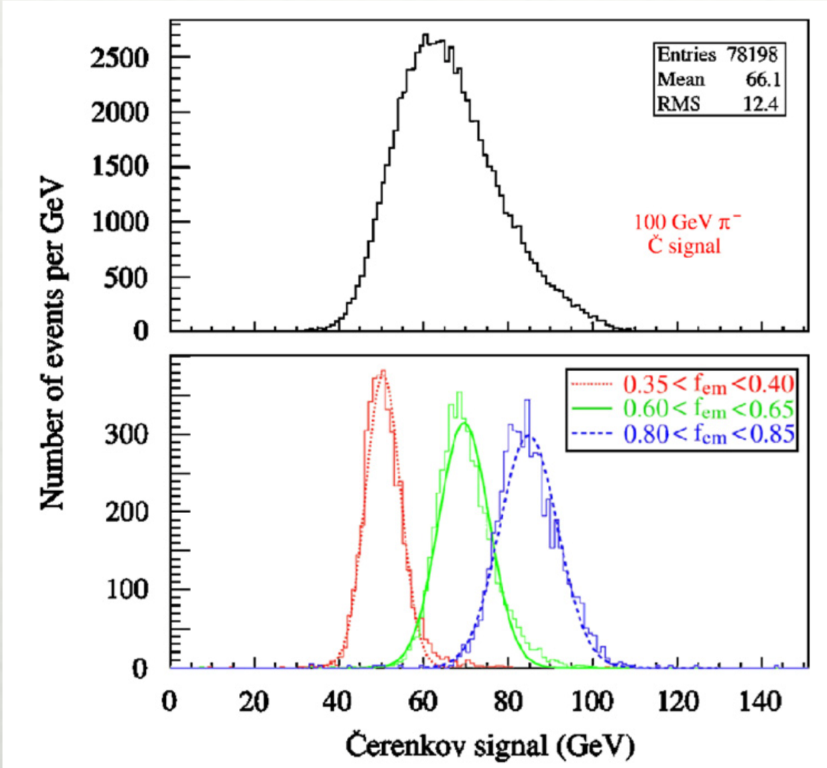
*from the corsika library (https://www.ikp.kit.edu/corsika/)

In hadron initiated showers, the main fluctuations in the event-to-event response are due to:

- the share between the e.m. and and hadronic component
- the fluctuations in the "invisible energy"



and the e.m. component is giving a significant contribution, growing with energy:

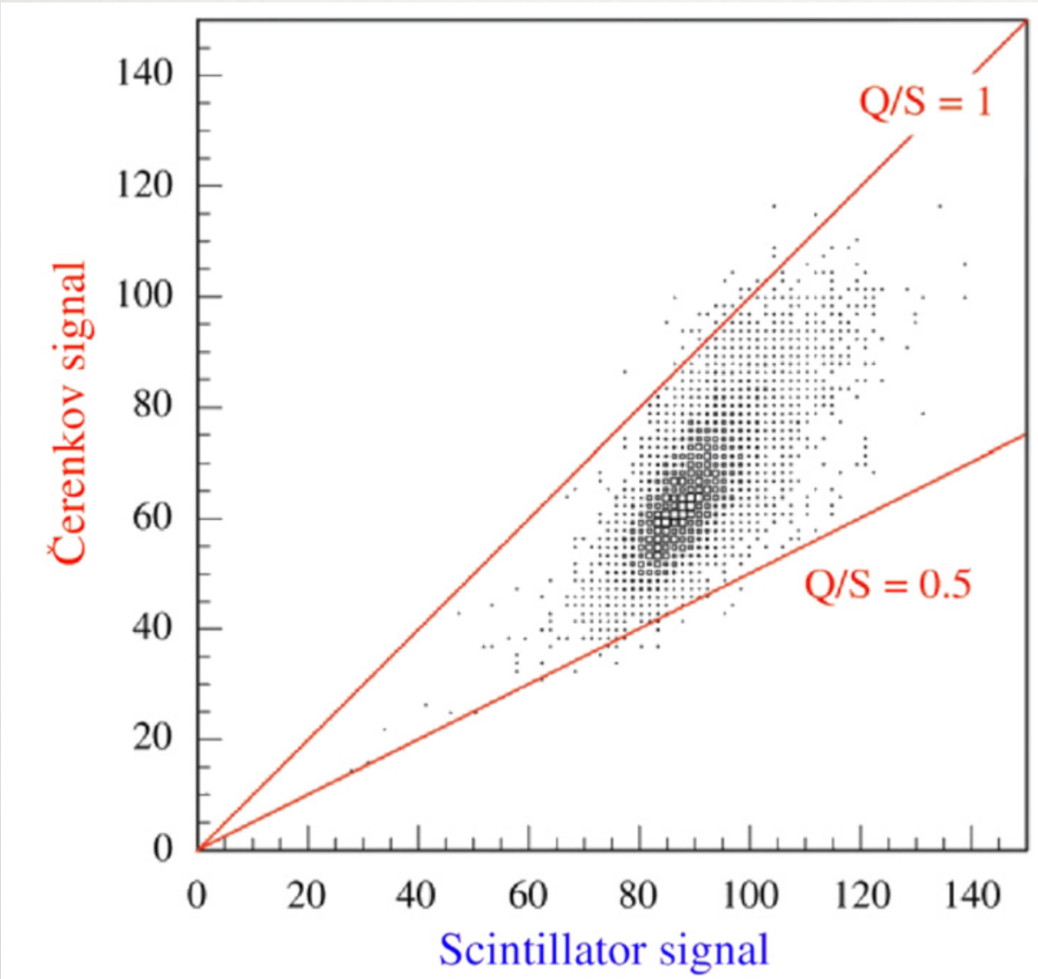


an example of the improvement that can be expected in the measurement of a sample of 100 GeV **π**'s if $f_{e.m.}$ is NOT measured (top plot) or if $f_{e.m.}$ bins are singled out

R. Wigmans, NIM A572 (2007) 215-217

The DUAL READOUT concept is based on the idea that if you embed in the same calorimeter a detector responding primarily to the e.m. fraction and detector responding to the total dE/dX, you can single out $f_{e.m.}$.

This was proposed (and successfully demonstrated in a series of different implementations) using Cherenkov light [produced by relativistic particles and dominated by the e.m. shower component] and scintillation:



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

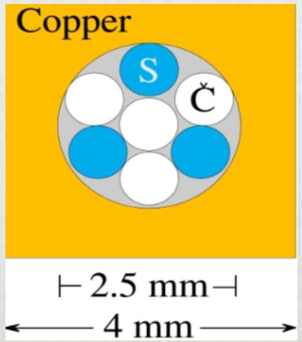
$$S = E\left[f_{em} + \frac{1}{(e/h)_S}(1 - f_{em})\right]$$

e.g. If $e/h = 1.3$ (S), 4.7 (Q)

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

$$E = \frac{S - \chi Q}{1 - \chi}$$

with $\chi = \frac{1 - (h/e)_S}{1 - (h/e)_Q} \sim 0.3$



"Building block" of the DREAM calorimeter

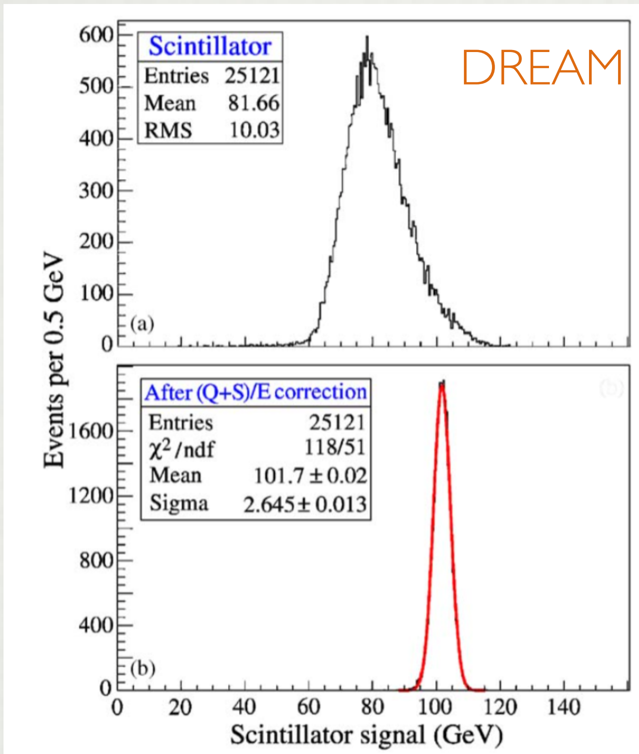
2m long (10 λ_{int}) [5130 blocks, ≈ 16 cm radius]
$R_{Molière}$ = 20.4 mm

R. Wigmans, NIM A617 (2010) 129-133

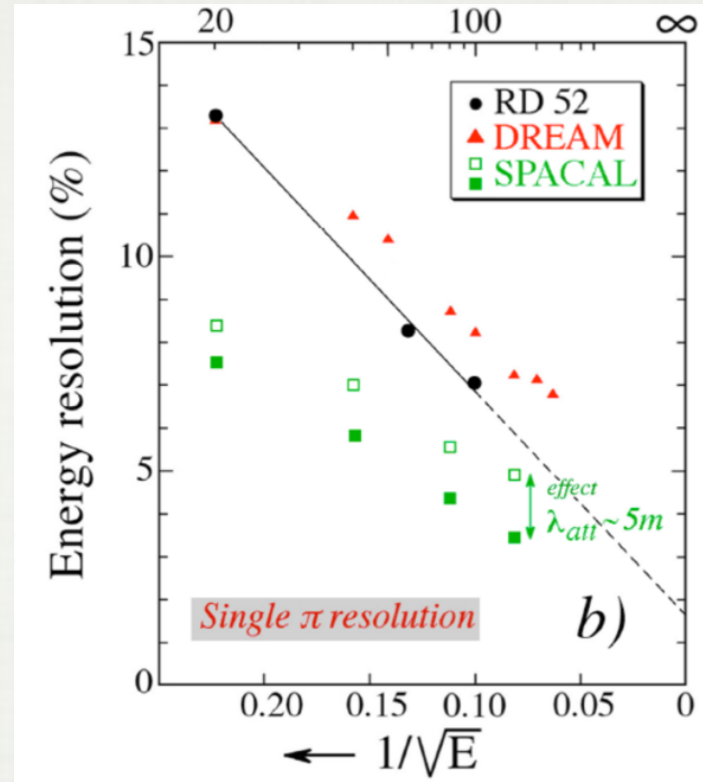
Four exemplary results from the DREAM/RD52 calorimeters:

[NIM A537 (2005) 537-561 - NIM A735 (2014) 130-144 - NIM A732 (2013) 475]

Response to 100 GeV π



Single π resolution vs energy



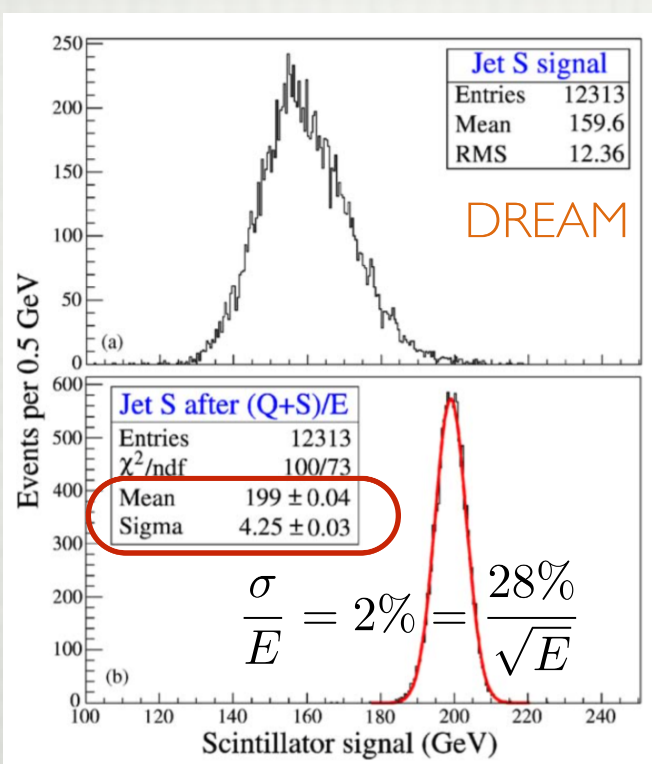
$$\frac{\sigma}{E} = \frac{53\%}{\sqrt{E}} + 1.7\%$$

- referred to the RD52 calo with Pb converter
- affected by lateral leakage and light attenuation

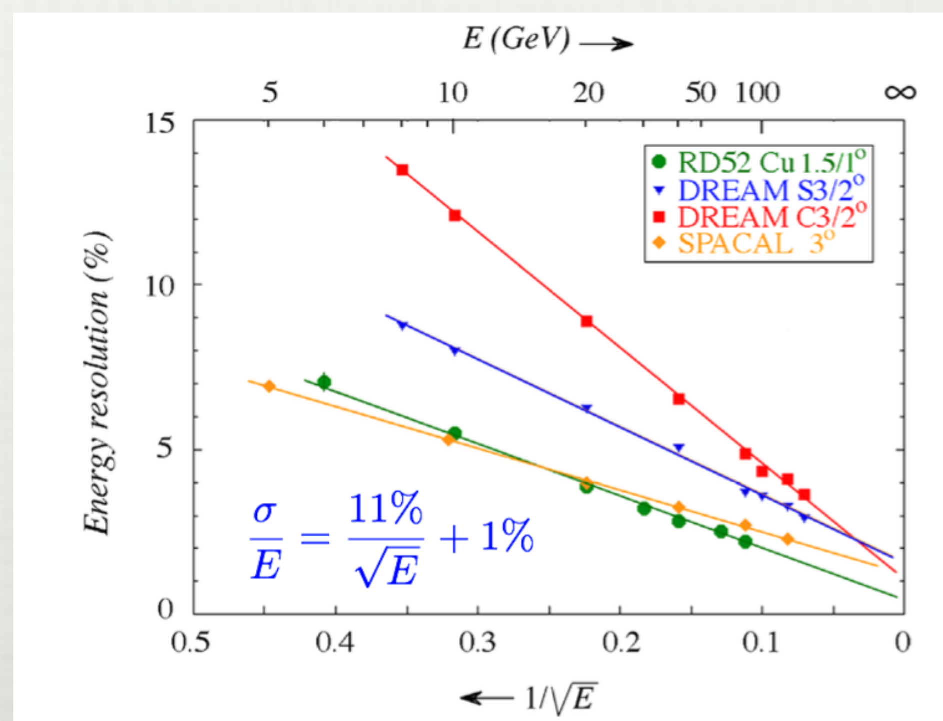
VERY CONSERVATIVE

(the SPACAL values are close to 30%/sqrt(E))

Response to 200 GeV @"jet like"

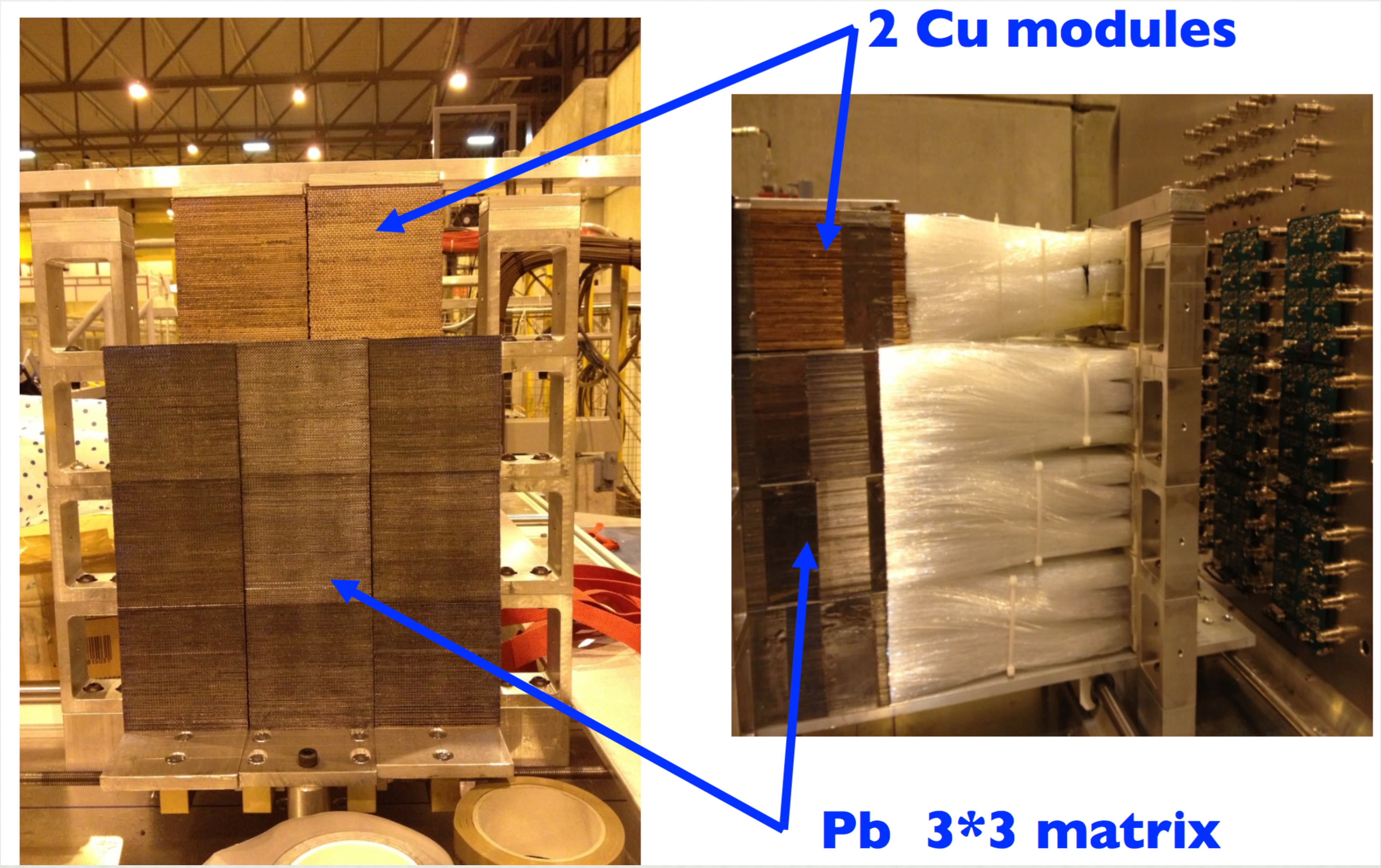


Electromagnetic Resolution



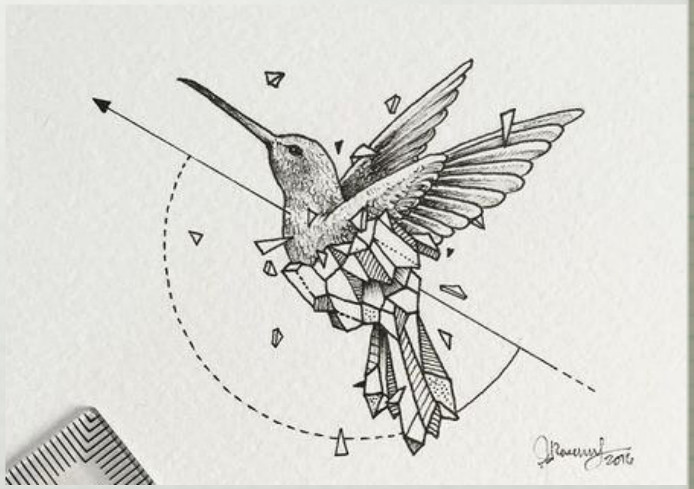
So far, so good.

BUT (there is always a BUT in life)



How to fit such a geometry in a collider experiment?

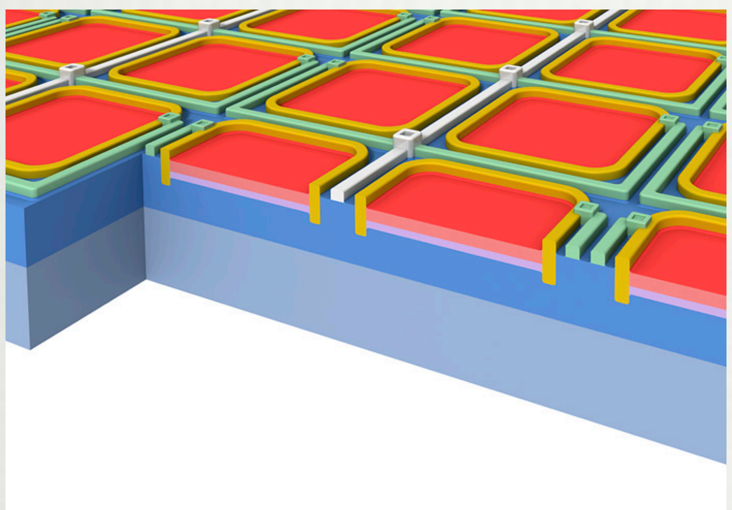
1. Move away from the good old PMT's and step into the digital age

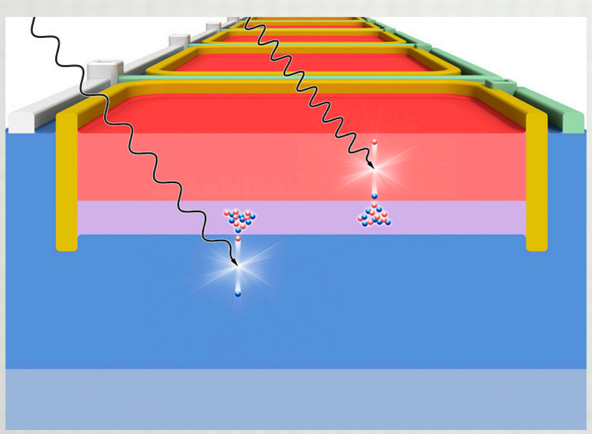


Silicon Photomultipliers: introducing the Silicon Age in Low Light Detection

I Principles

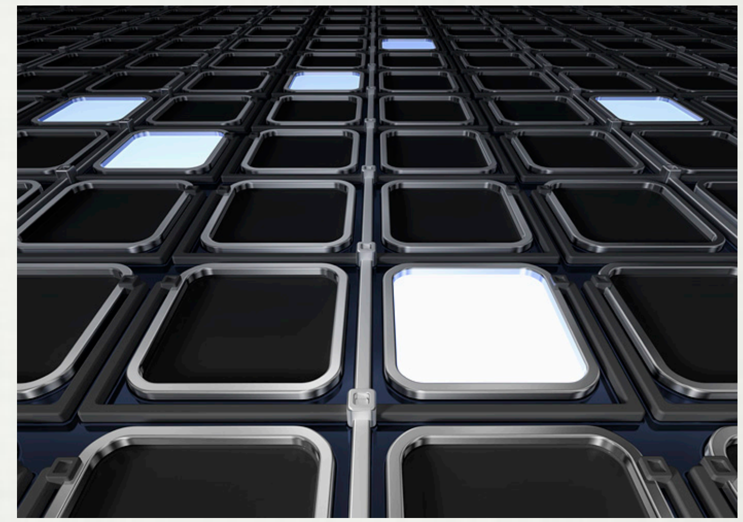
SiPM = High density (~10^4/mm^2) matrix of diodes with a common output, reverse biased, working in Geiger-Müller regime



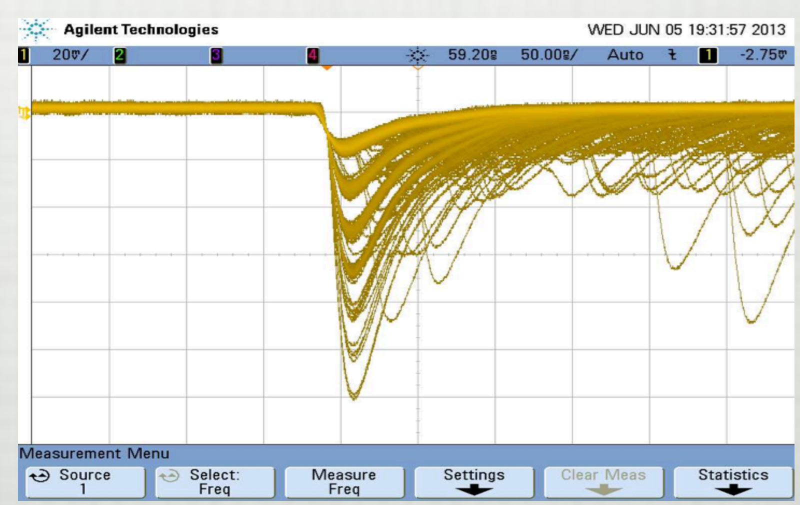


When a photon hits a cell, the generated charge carrier triggers an avalanche multiplication in the junction by impact ionization, with gain at the 10^6 level

II Operation



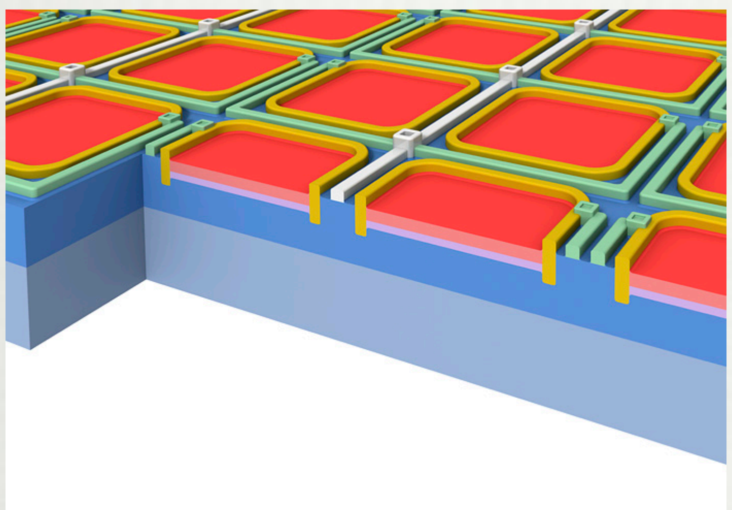
- SiPM may be seen as a collection of binary cells, fired when a photon in absorbed
- "counting" cells provides an information about the intensity of the incoming light:



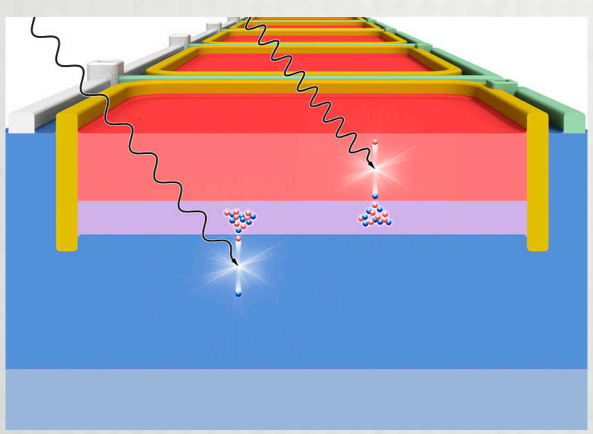
Silicon Photomultipliers: introducing the Silicon Age in Low Light Detection

I Principles

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

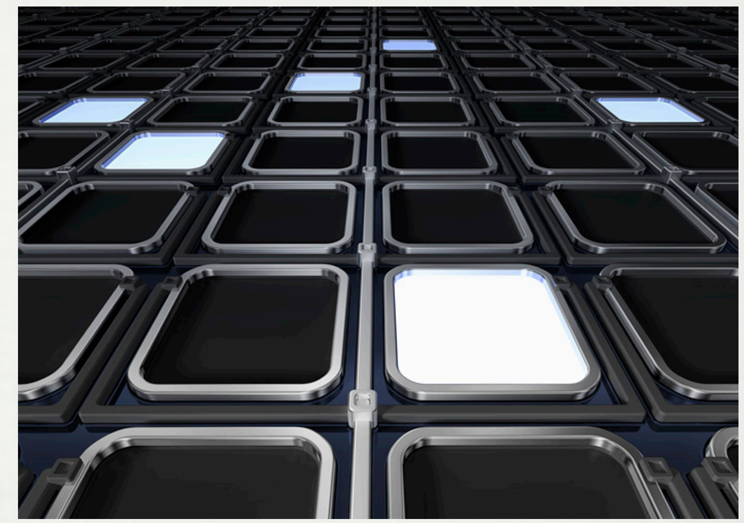


Courtesy http://www.yk.rim.or.jp/~reyhori/pages/galacc2_e.html

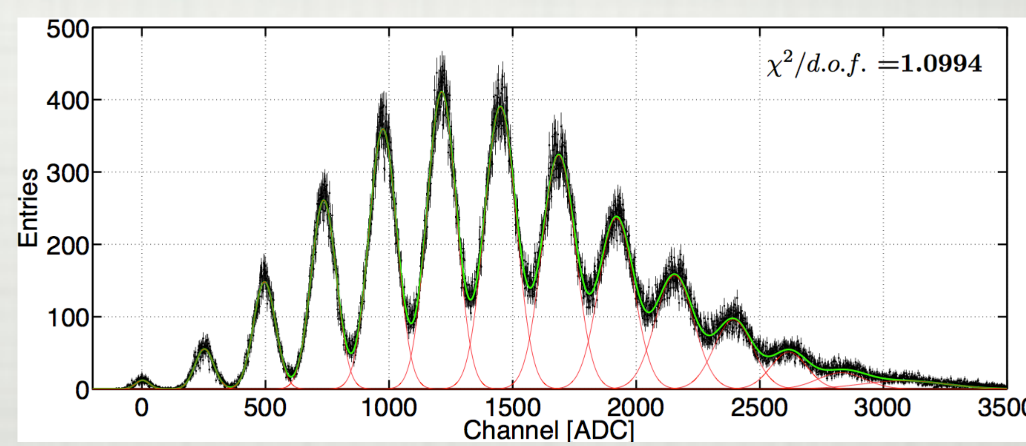


When a photon hits a cell, the generated charge carrier triggers an avalanche multiplication in the junction by impact ionization, with gain at the 10^6 level

II Operation



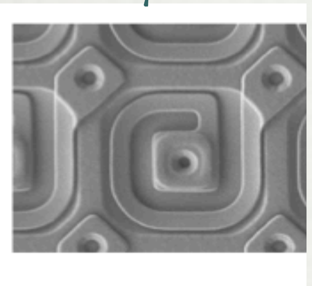
- SiPM may be seen as a collection of binary cells, fired when a photon in absorbed
- "counting" cells provides an information about the intensity of the incoming light:



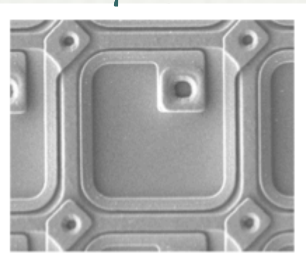
Over 15 years, the SiPM technology achieved its maturity and today different vendors are offering a wide variety of continuously improving sensors, so that users have a real *"Menu à la Carte"* to choose the "*best fit*" device for their application:

in terms of pixel pitch:

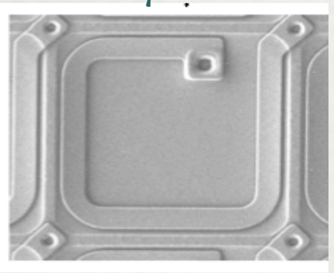
10 μm



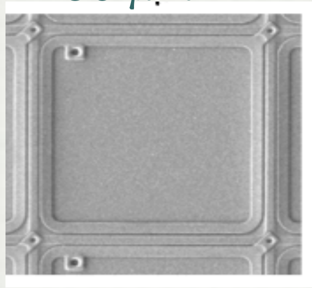
15 μm



25 μm



50 μm



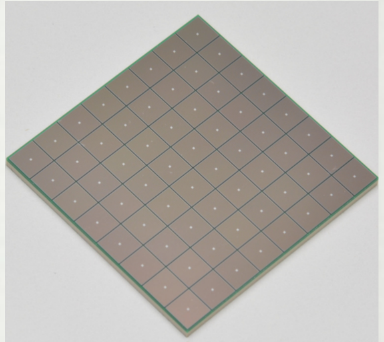
75 & 100 μm *are available as well*

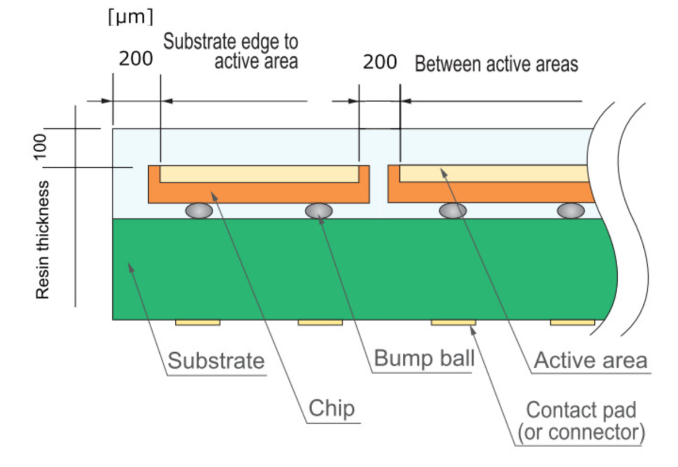
Not to mention the variety of available options for the front-end, the packaging and the near future integration with the read-out electronics

in terms of sensor area:

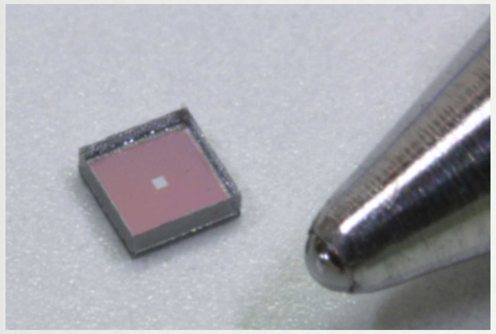
- 1x1 mm^2
- 3x3 mm^2
- 6x6 mm^2

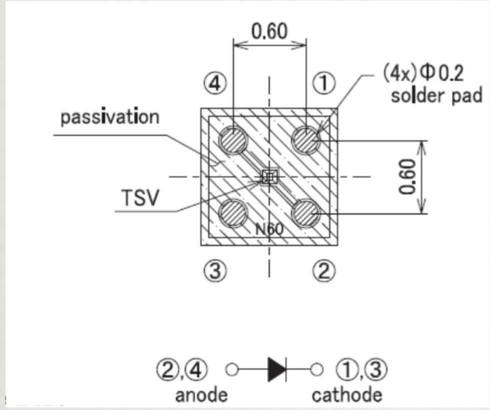
- 1x4 mm^2
- 12x12 mm^2
- 24x24 mm^2

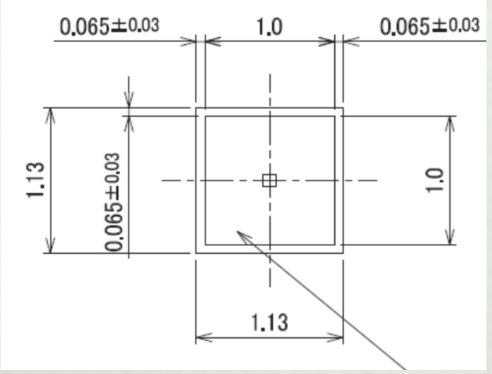




Recently, thanks to the Through Silicon Via (TSV) technology, HAMAMATSU offered arrays built up on a mosaic of 1x1mm² sensors, quite appealing for the envisaged application:





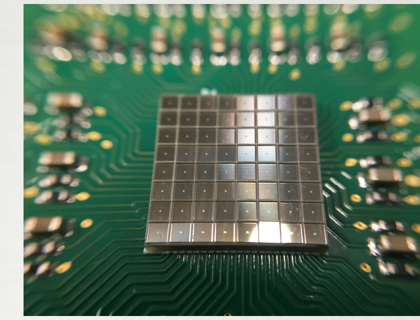


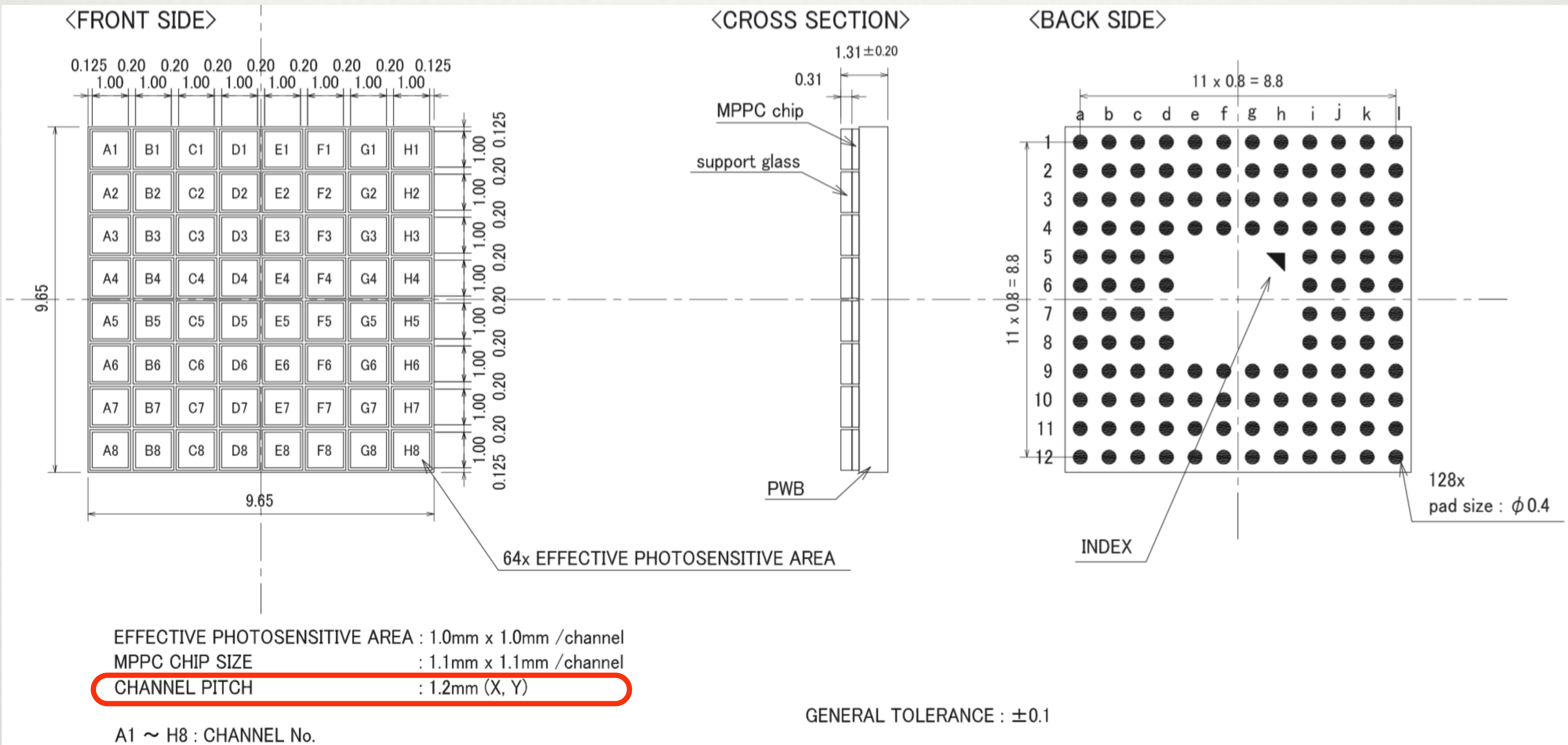
Parameters	S13615 -1025	S13615 -1050	Unit
Effective photosensitive area	1.0x1.0		mm^2
Pixel pitch	25	50	μm
Number of pixels / channel	1584	396	-
Geometrical fill factor	47	74	%

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	7.0×10^5	1.7×10^6	-

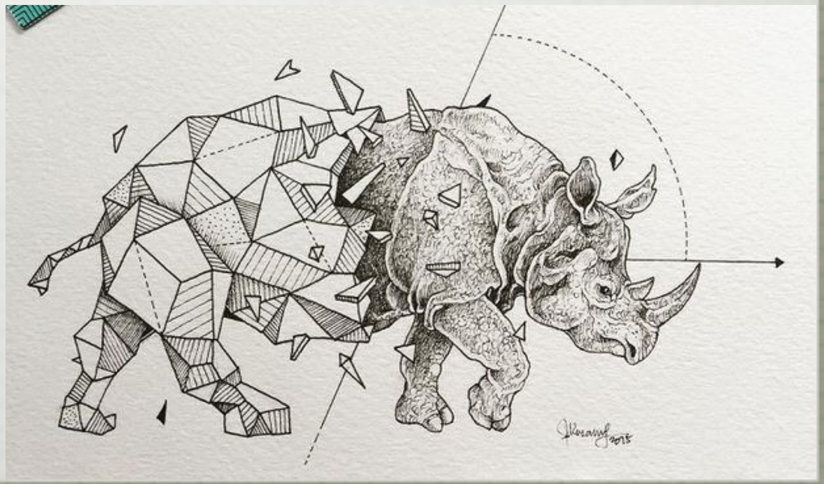
Main characteristics of the "building block"

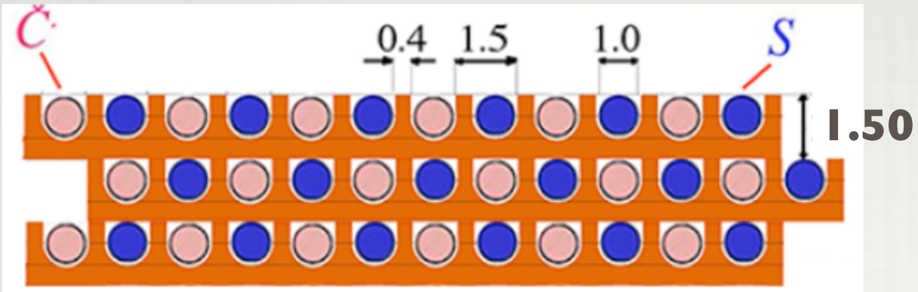
The development was based on 8x8 channel arrays and we have got in September 2016 the first samples ever produced (serial no. 1 & 2) with both 25 µm and 50 µm pitch [the latter only was used in the test beam]





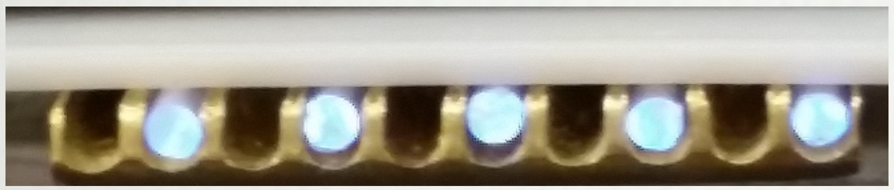
2. Design, machine and produce a module pairing with the sensor array [Iowa state]



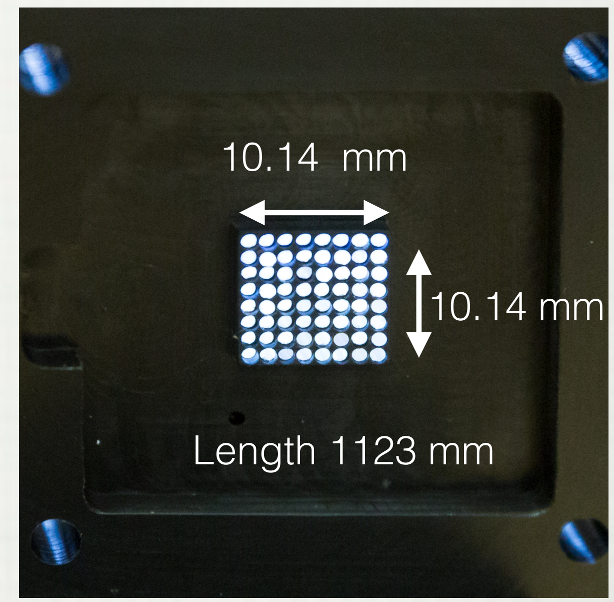


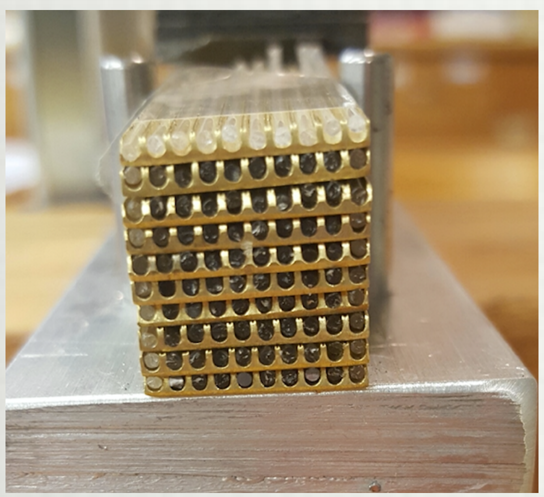
The module(s) are built from stacked copper layers, housing 1mm diameter clear & scintillating fibers* with a pitch of 1.5 mm [sampling fraction 4.5%]

dimensions in mm (spacing in the actual module was 1.65 mm due to imperfections in the skiving procedure)



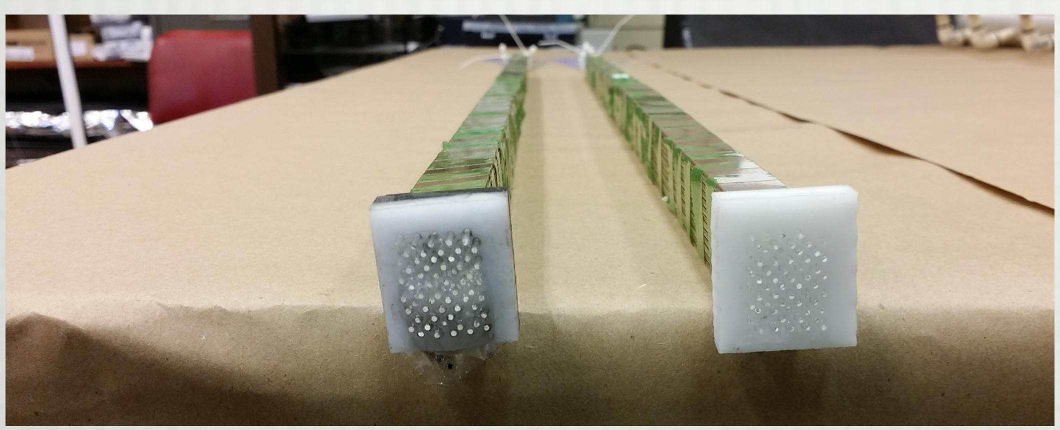
1D



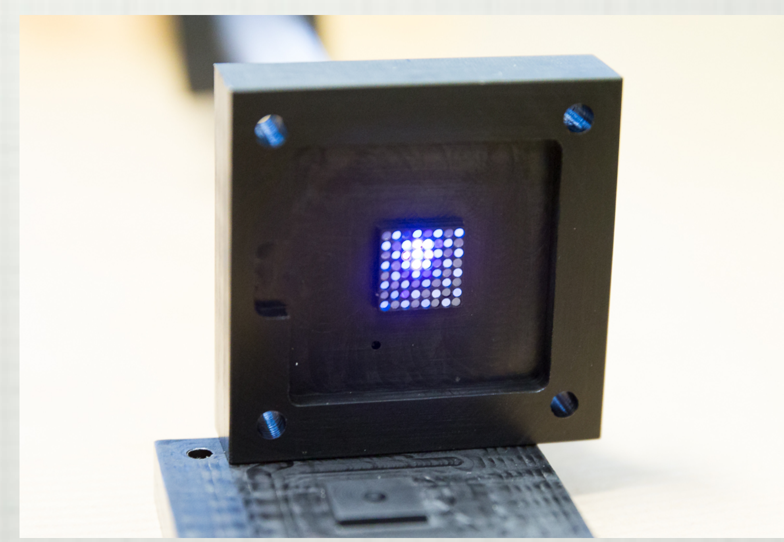


10x10 fibers

2D



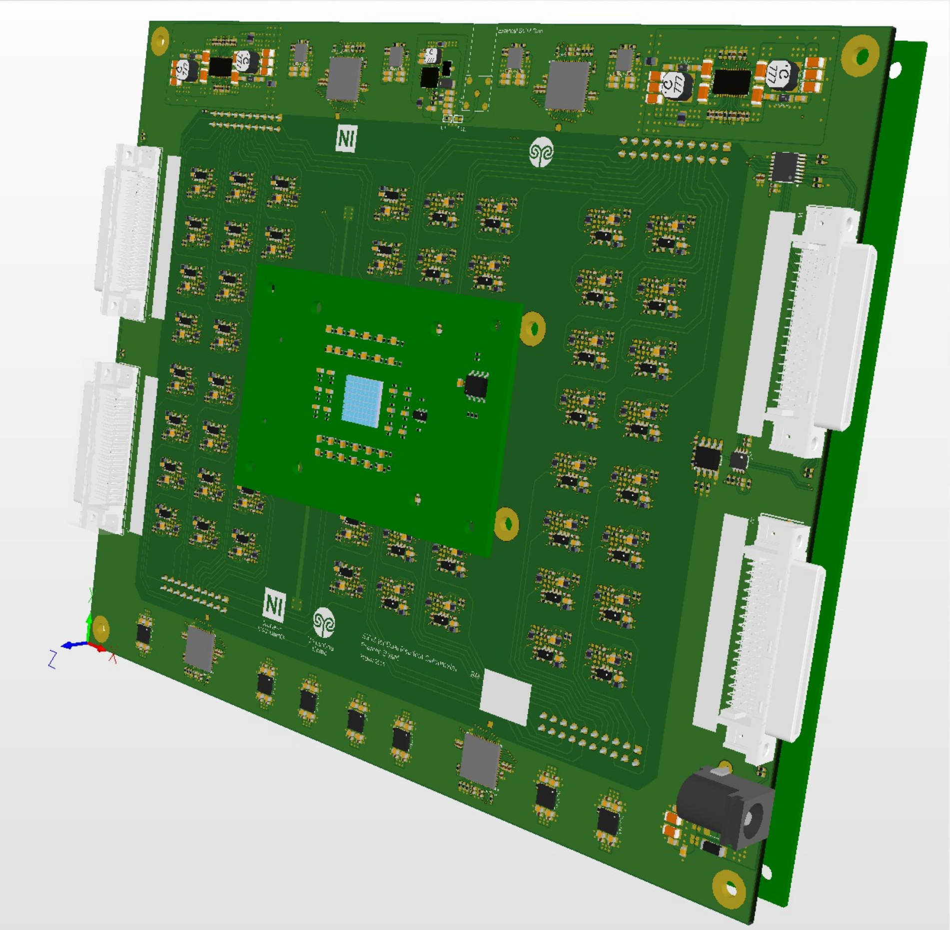
3D

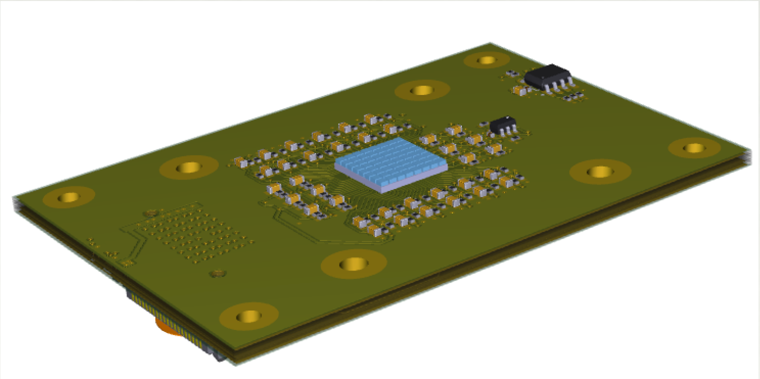


* [KURARAY SCSF-78, with 2.8 ns scintillation light decay time]

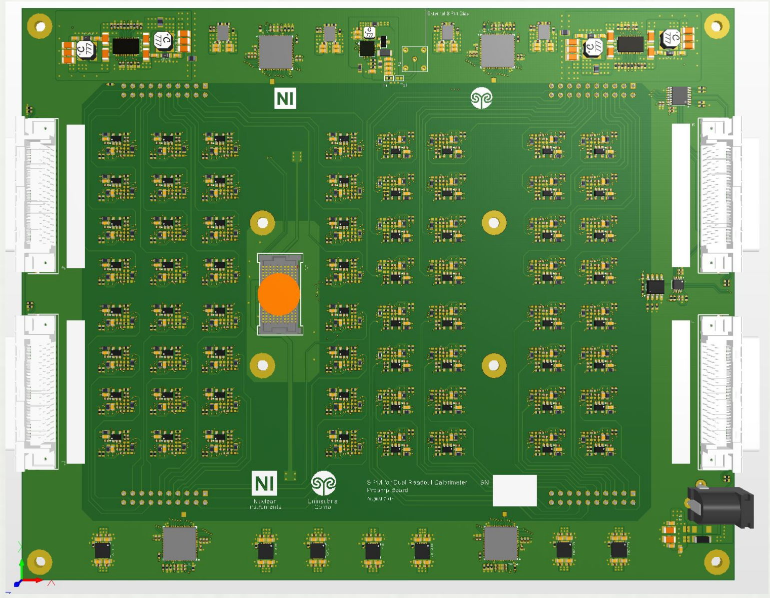
3. Design, produce, commission and qualify the boards hosting the sensor and the DAQ [Nuclear Instruments and Uni. Insubria]

The sensor system

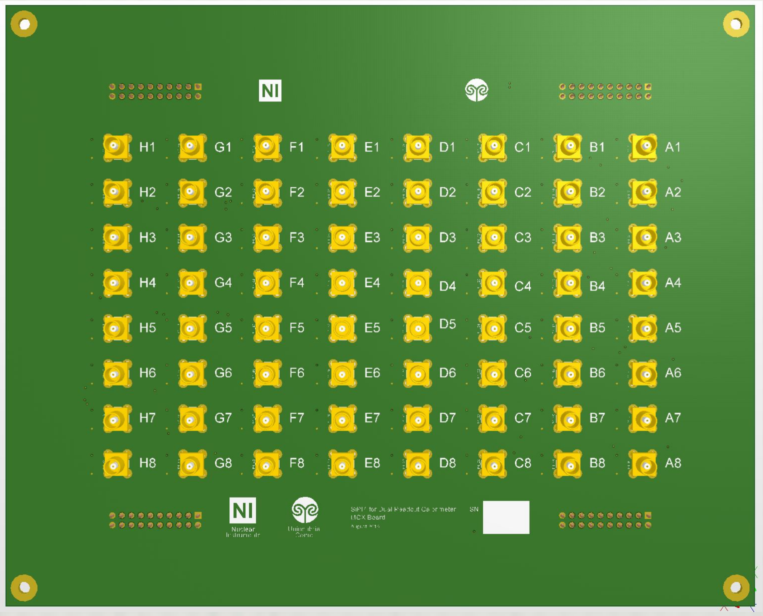




1. the daughter board,
providing an independent bias to the 64 sensors and integrating T measurement for gain compensation



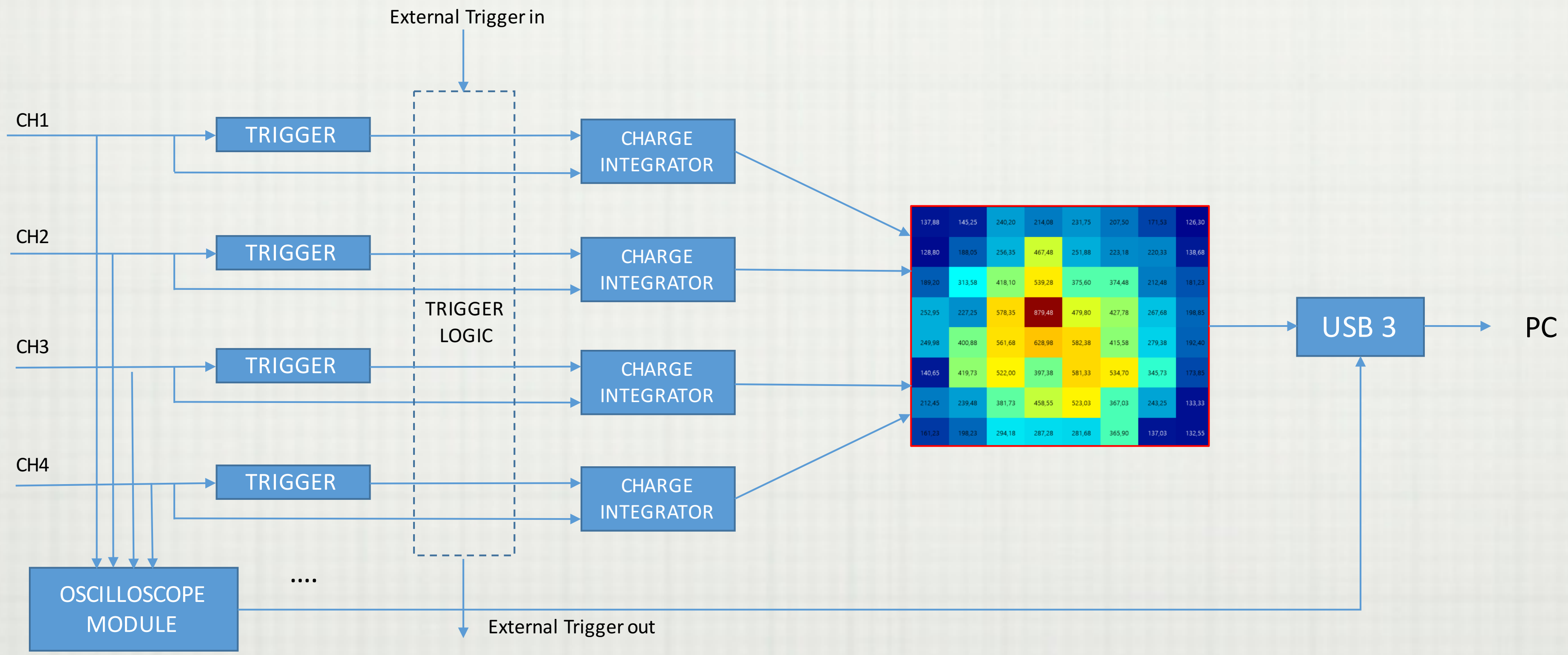
2. the mother board
   - amplifying & shaping the output of each sensor
   - routing the signals to the digitisation system



3. the backplane board
allowing to probe via mcx connectors each channel

The DAQ system

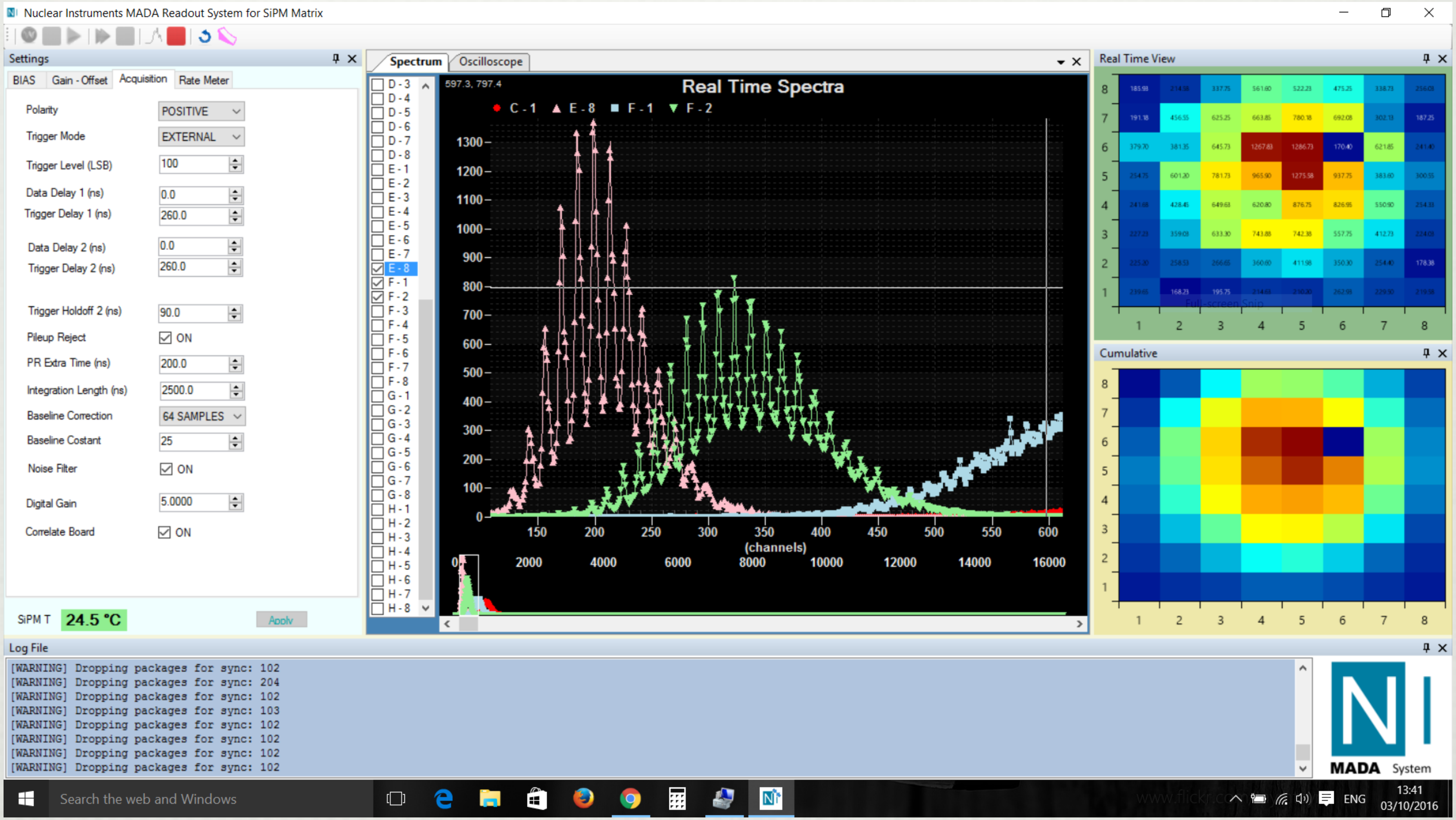
- the MADA is a 32 channel digitiser with on-bord intelligence
- sampling rate 80MSpS/14-bit ADC
- FPGA based charge integration algorithm.
- the output of the board is a list of timecode events providing the integrated signal in every sensor



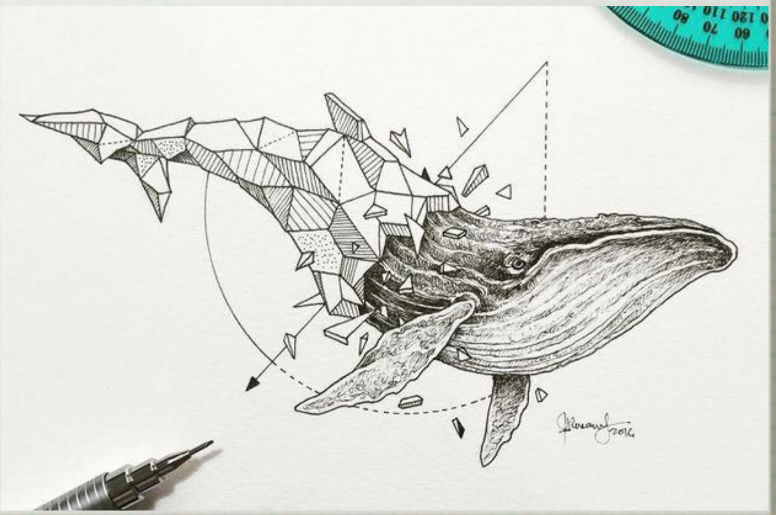
TRIGGER LOGIC:

- Pixel mode: each pixel is indipendet and fire a data transfer on a singe channel
- Frame mode: if a pixel fire a trigger, a charge integration process is performed on all channels and a whole frame is transfered to the PC

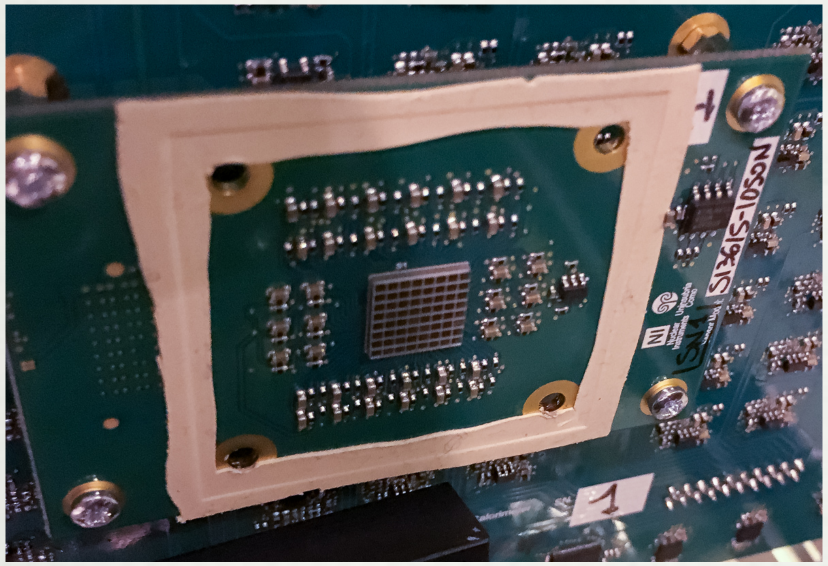
A nice example of the response of the system to a light pulse, during the qualification phase

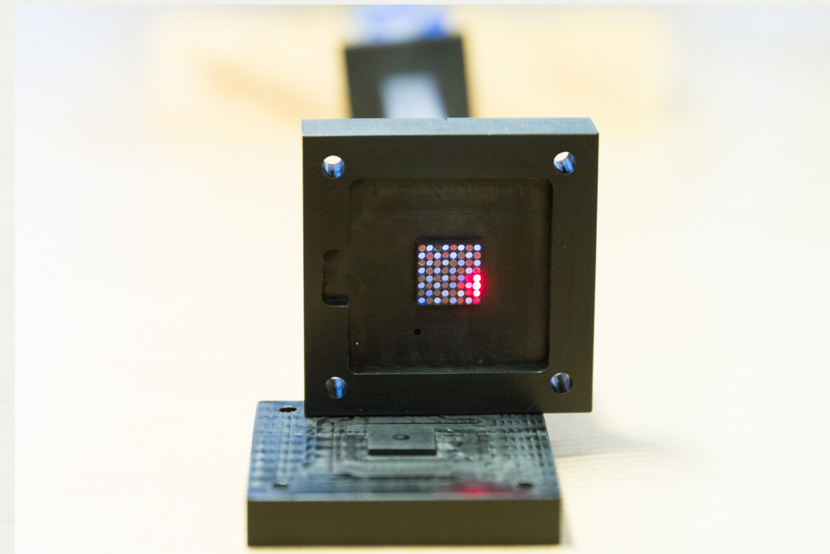


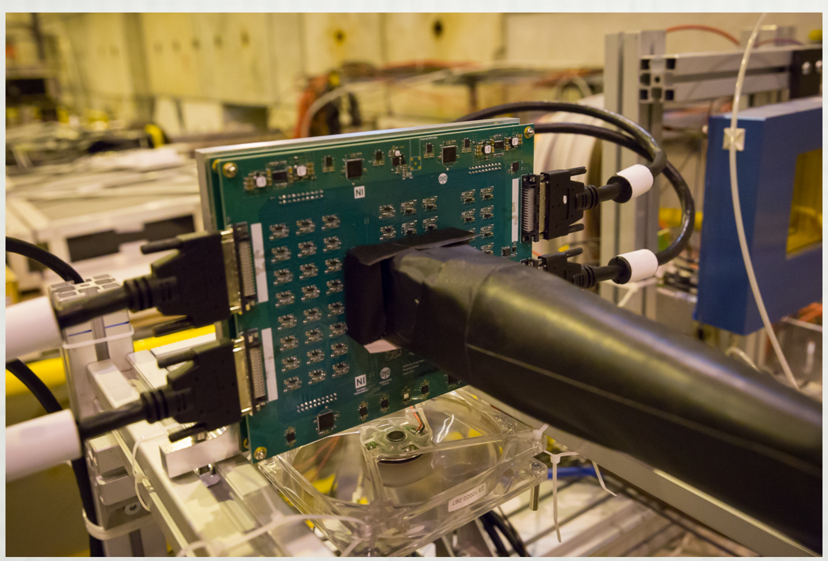
4. Integrate the module to the sensor and qualify it

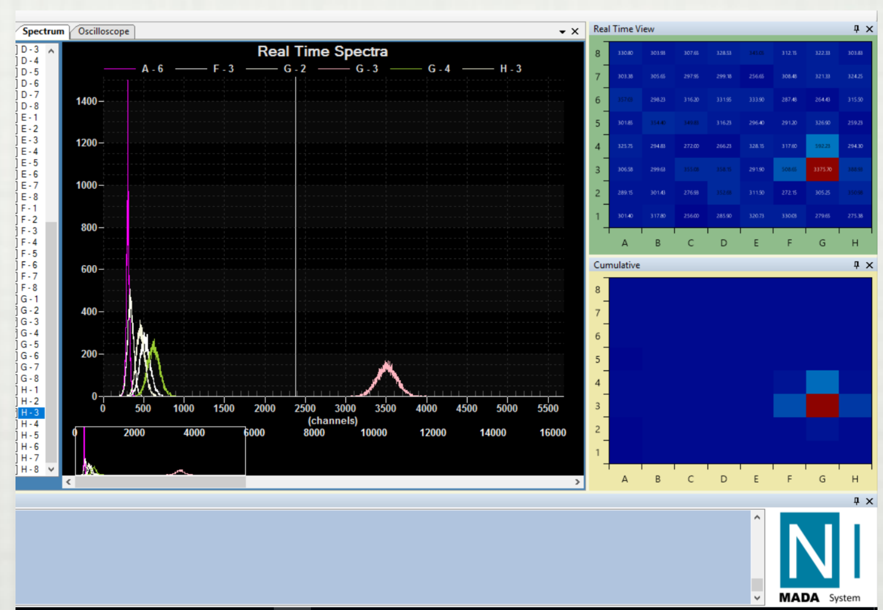


4 pictures to summarise 1 week of work (and stress)





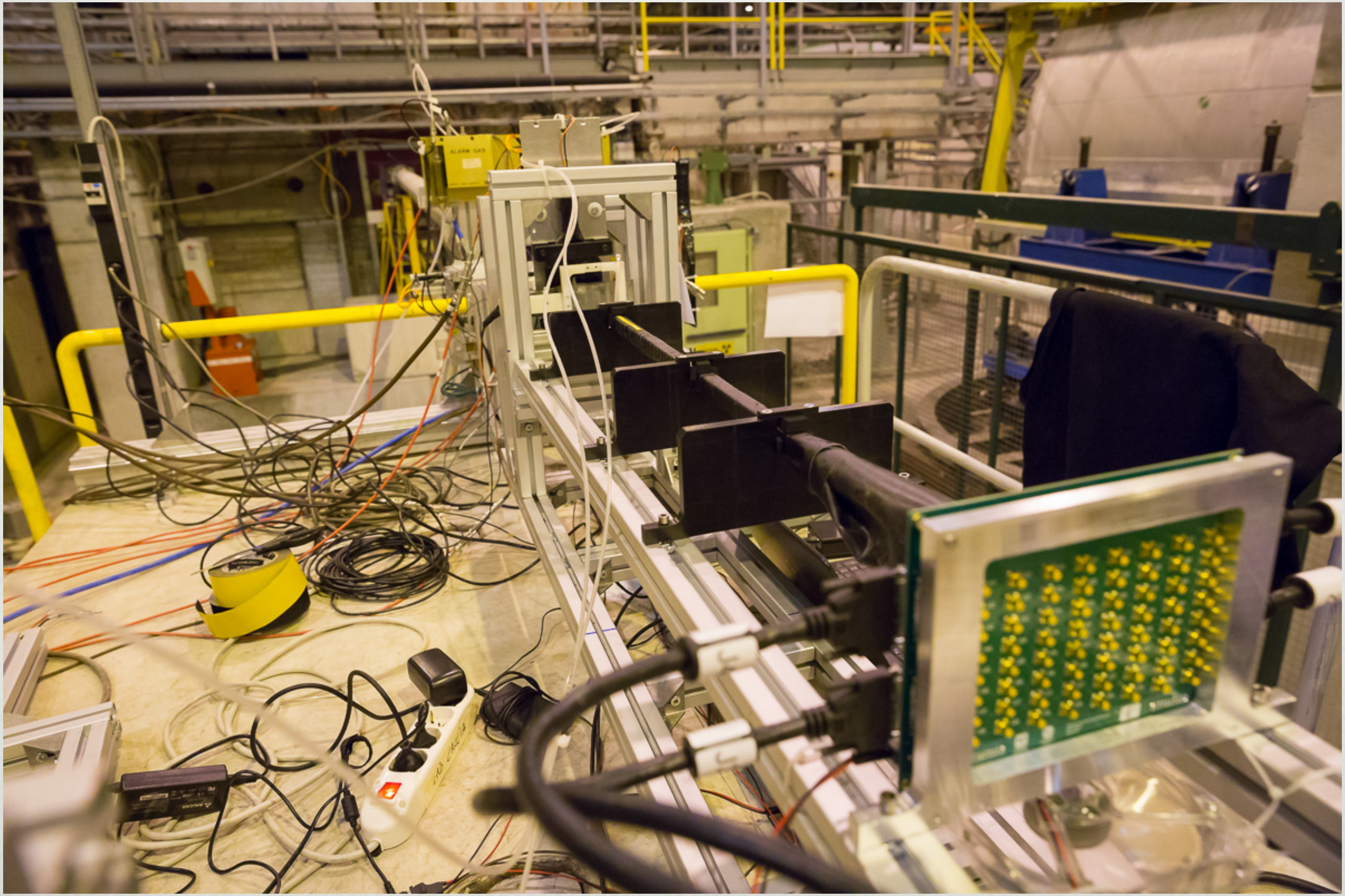




optical cross-talk between the fibers:
possibly the most critical issue

5. ON BEAM, at last [mid October 2016, @CERN]!

The module on the CERN North Area beam line



A short summary of the data taking conditions:

- two modules, both based on the array with 50 μm pitch cells:
  - module 1: both scintillating and Cherenkov fibres connected to the pixels of the array
  - module 2: Cherenkov fibers only were connected

driven by two main reasons:
- the saturation of the sensors connected to the scintillating fibres
- the study of the optical cross talk

- recorded data:

Module 1

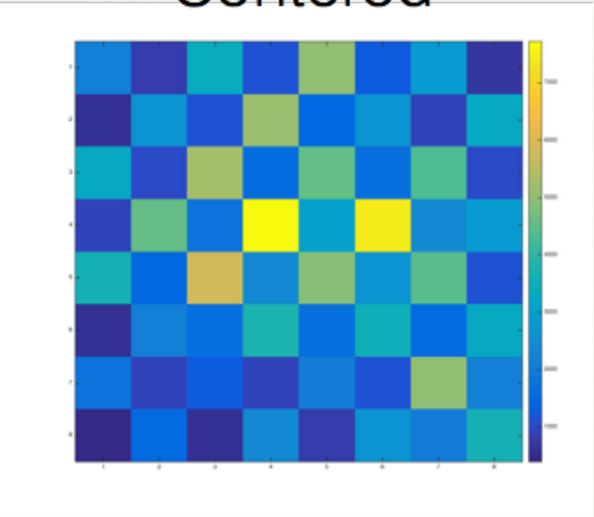
- **e^+:**
  - 20 GeV (> 54.000 events)
  - 40 GeV (> 146.000 events)
  - 60 GeV (> 173.000 events)
- μ^+: 180 GeV (> 100.000 events)

Module 2

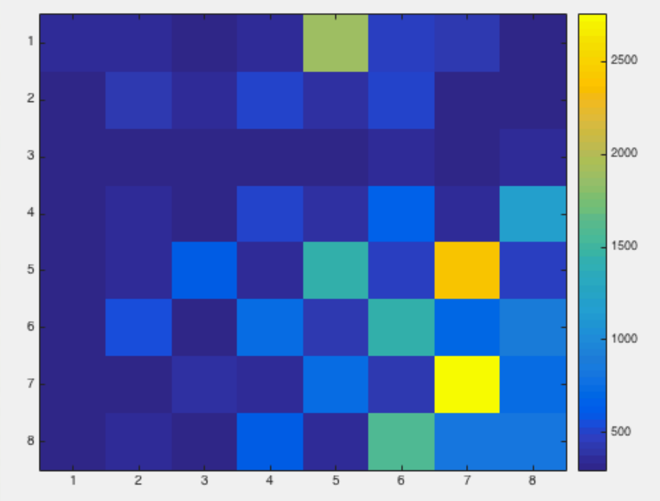
- **e^+**:
  - 20 GeV (> 178.000 events)
  - 40 GeV (> 300.000 events)
  - 60 GeV (420.000 events)
  - 80 GeV (340.000 events)
  - 100 GeV (300.000 events)
- μ^+: 180 GeV (400.000 events)

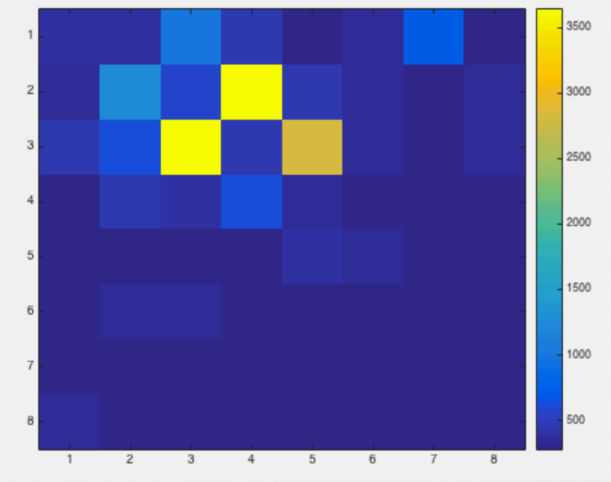
Exemplary event displays:

Centered



Off-centered





40 GeV electrons

A muon

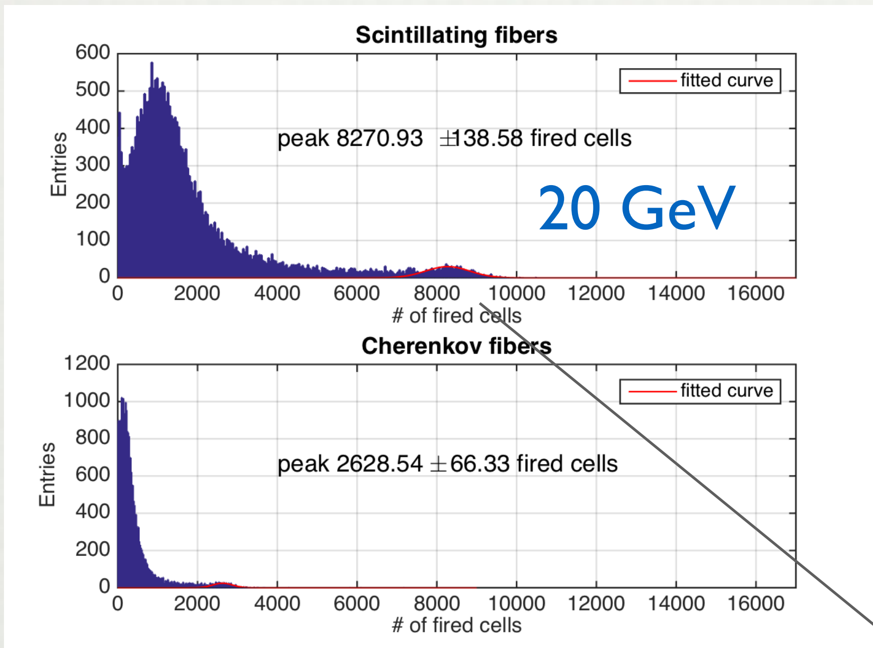
Results from Module I

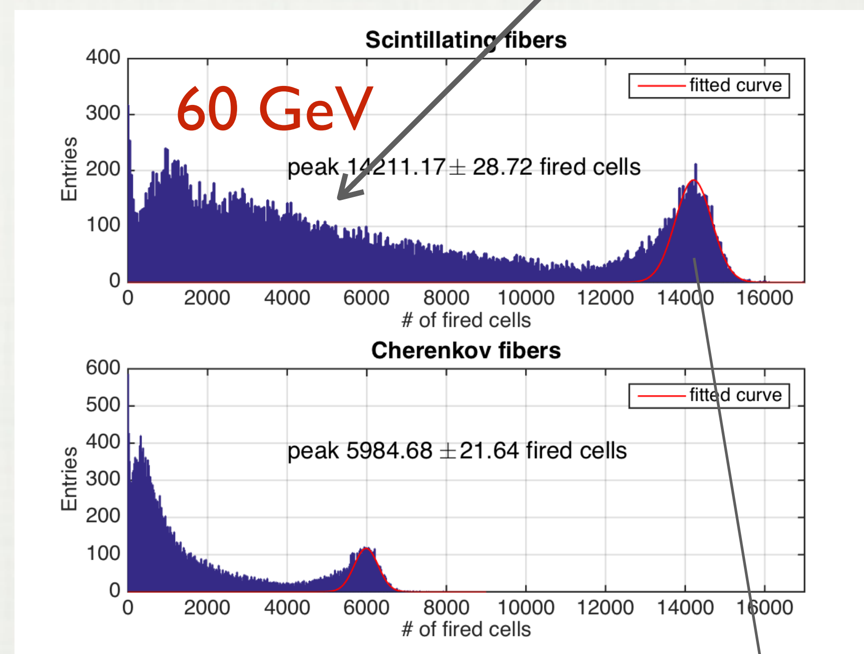
Event selection criteria:

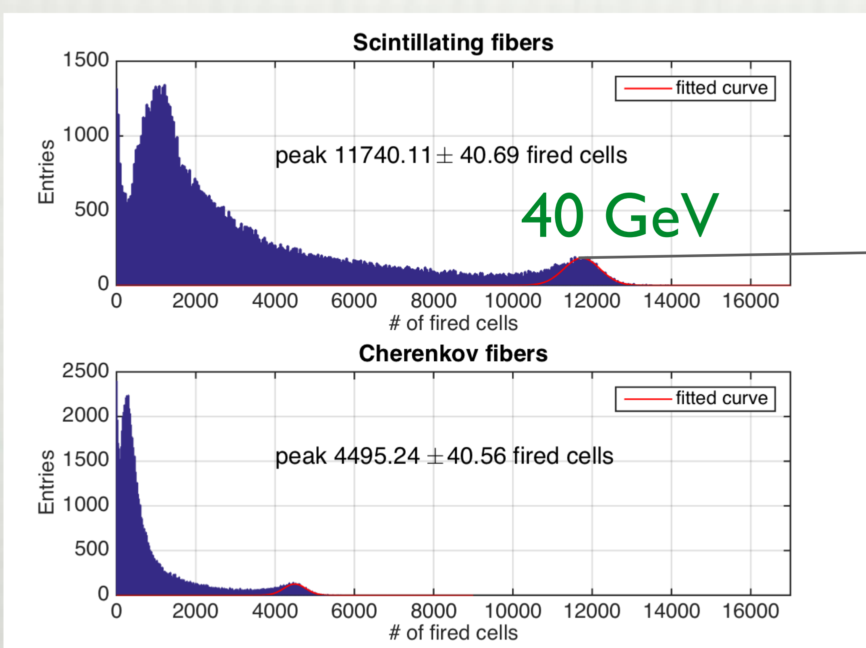
- signal from the array exceeding a 20 cell threshold
- highest signal in the 4x4 core of the array

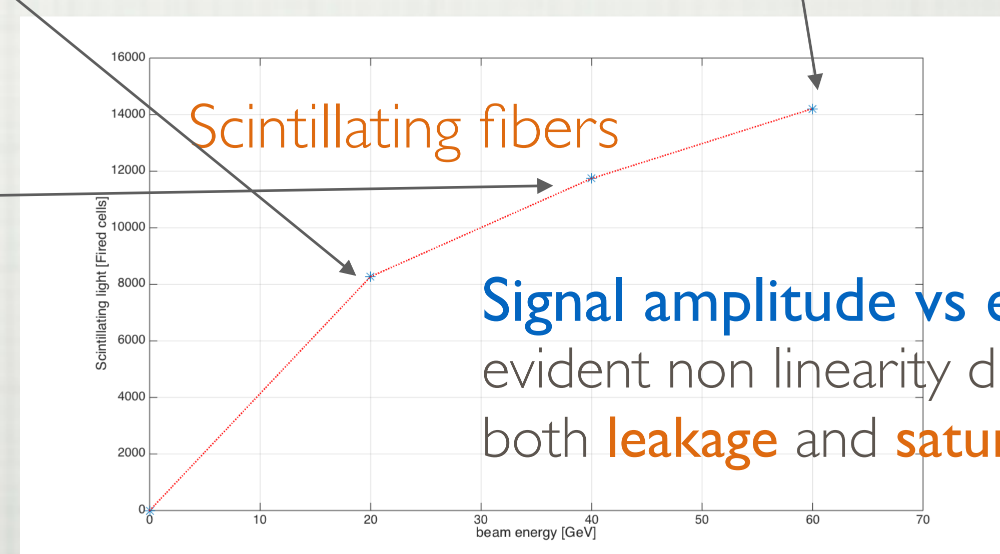
shoulder due to μ's contaminating the beam

Spectra of the Total Signal Amplitude (sum over 32+32 channels)









Signal amplitude vs energy

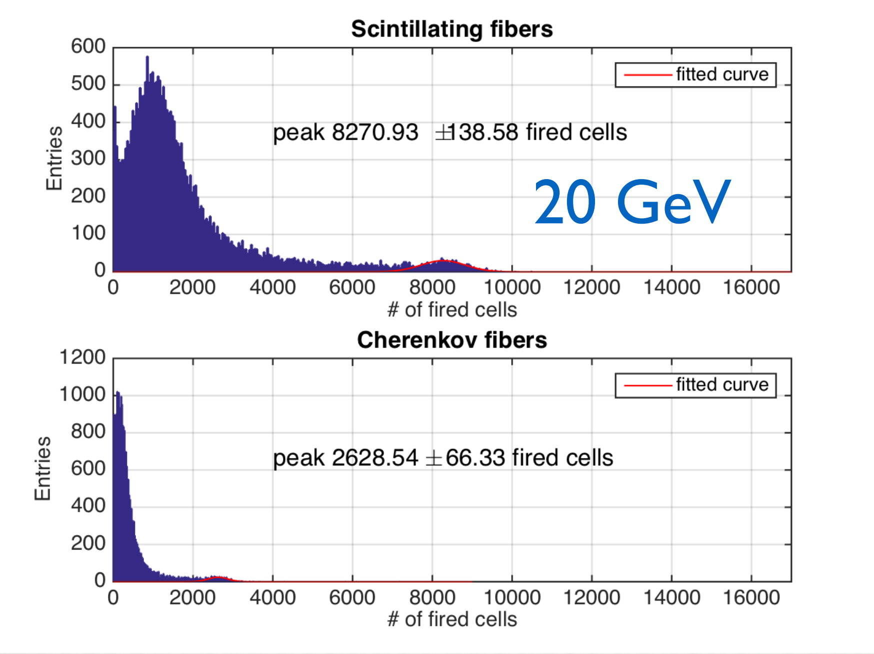
evident non linearity due to both **leakage** and **saturation**

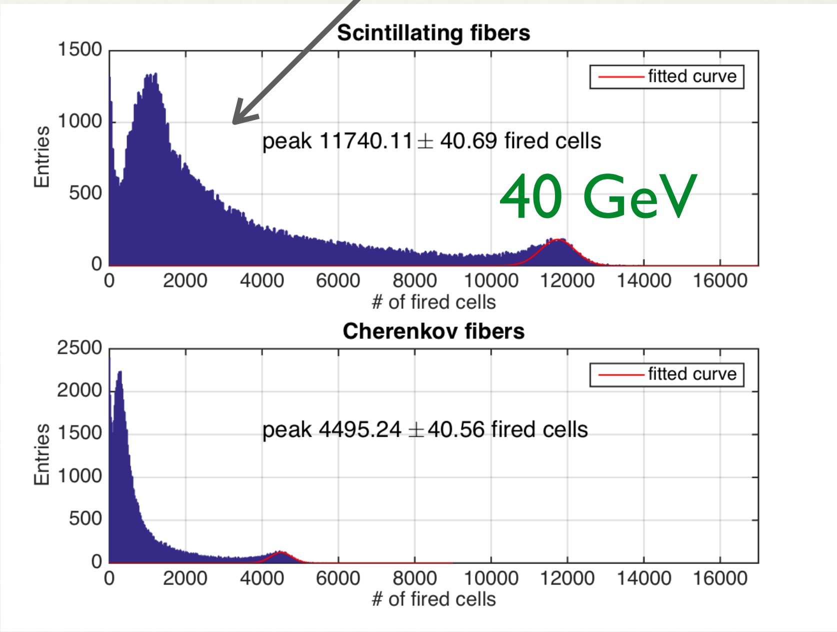
Results from Module I

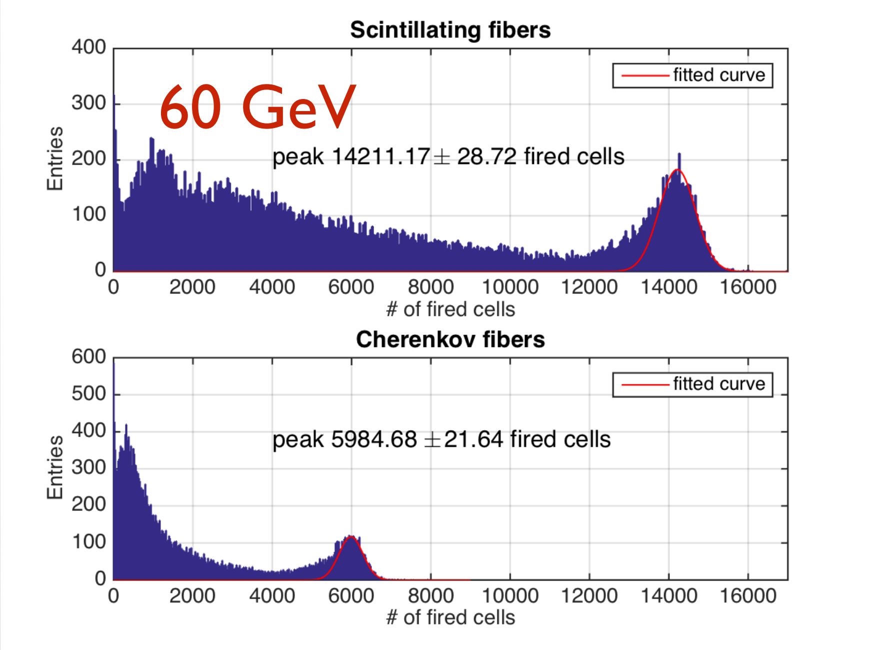
Event selection criteria:

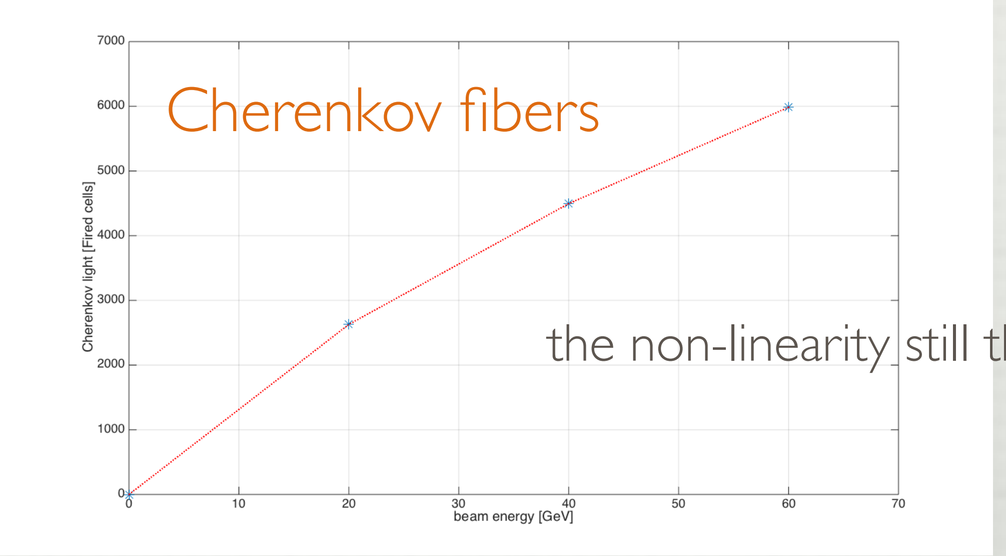
- signal from the array exceeding the 20 cell threshold
- highest signal in the 4x4 core of the array

shoulder due to μ contaminating the beam



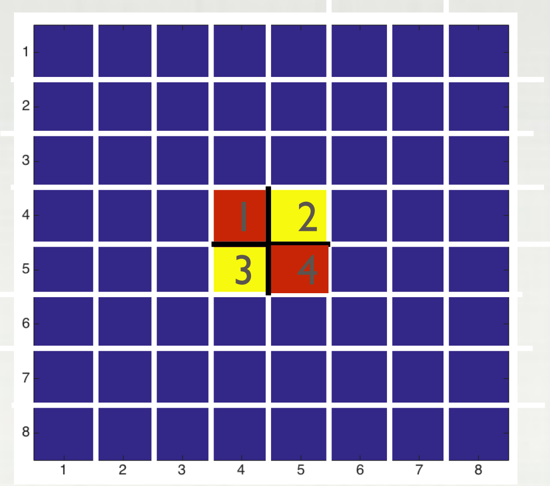




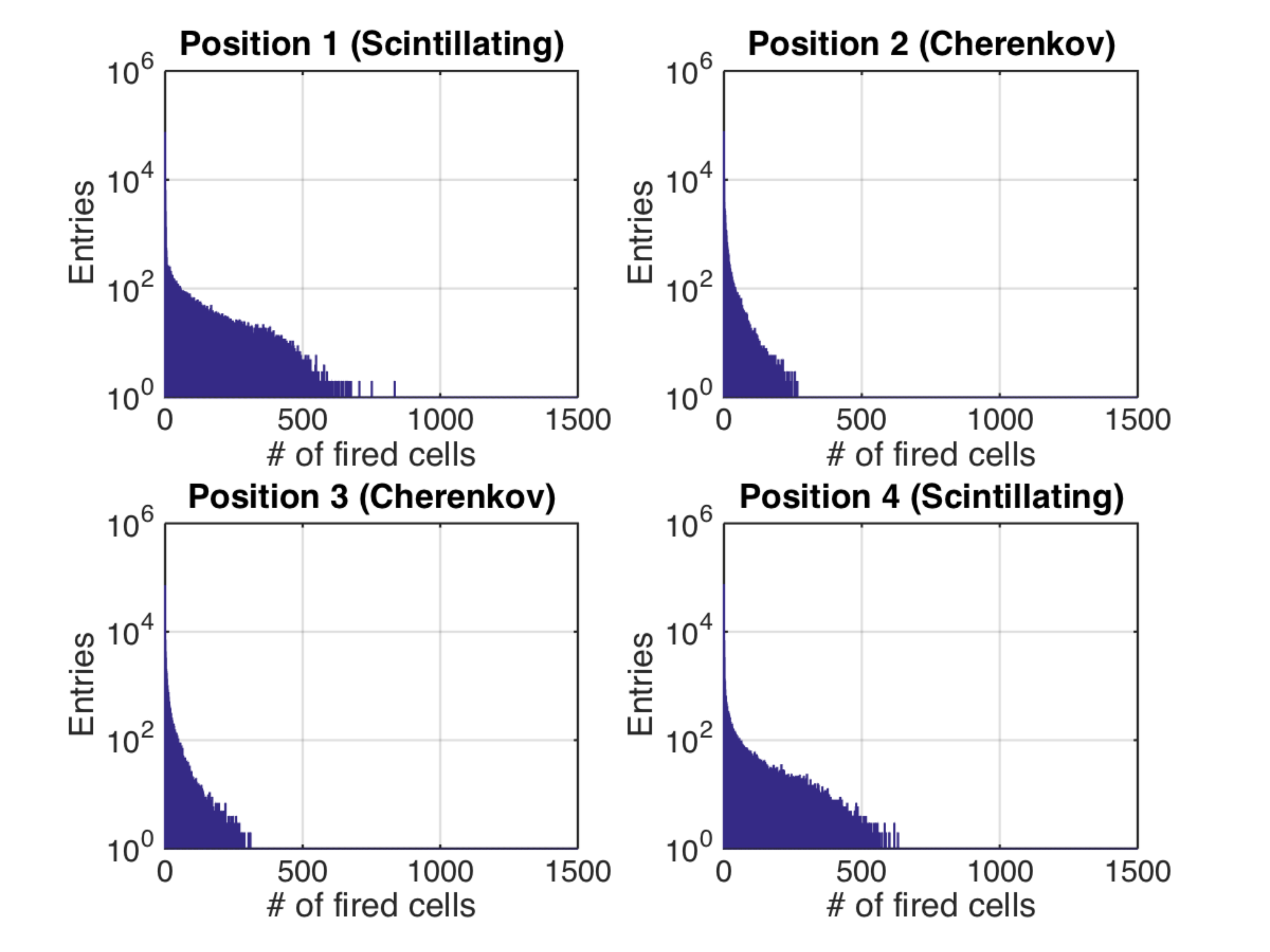


the non-linearity still there

Quantifying the saturation:



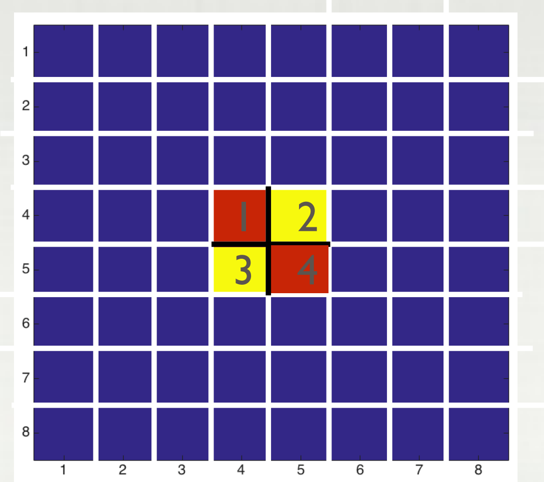
look at spectra of fibres 1-4



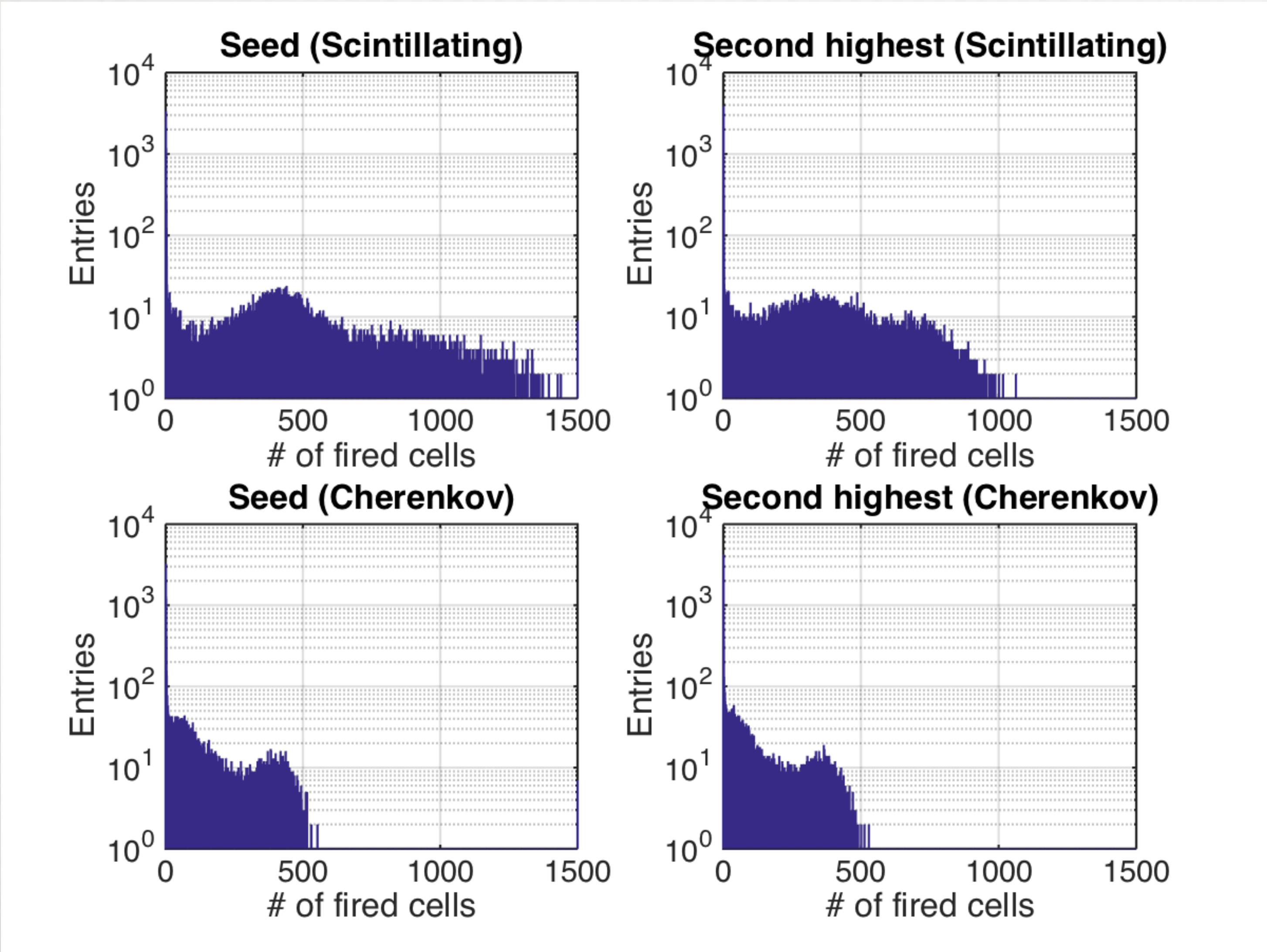
20 GeV

- a sizeable fraction of events shows saturation in the sensors connected to scintillating fibres (well, I see even more cells that I have in the sensor, possibly due to after-pulsing in the 1.8 μs long integration time)
- pixels connected to Cherenkov fibers are "polluted" by the light from the scintillating fibres

Quantifying the saturation:



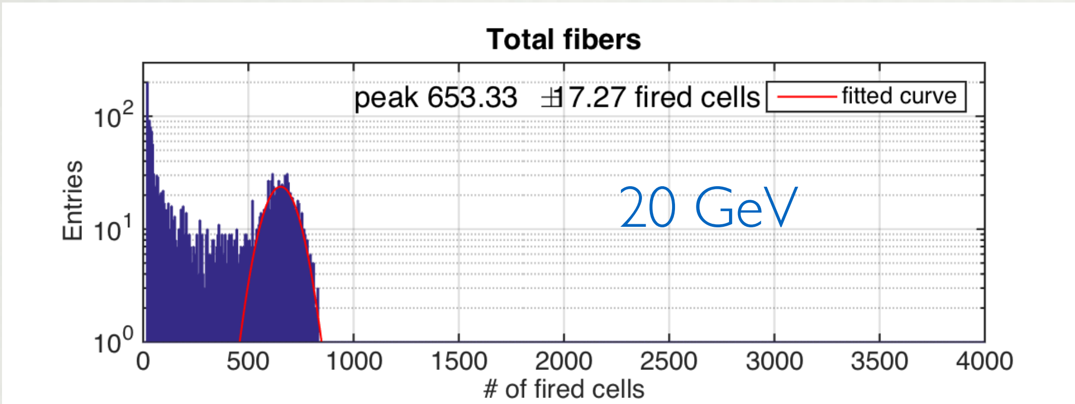
look at spectra of fibres 1-4

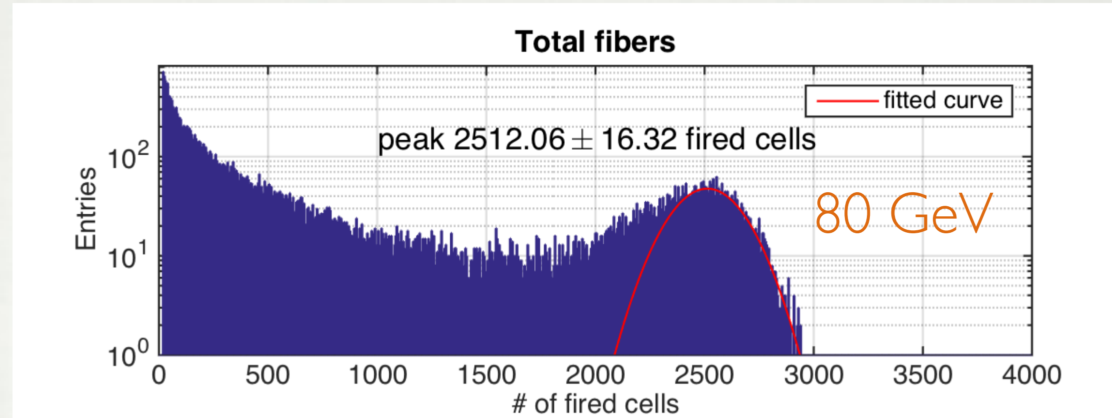


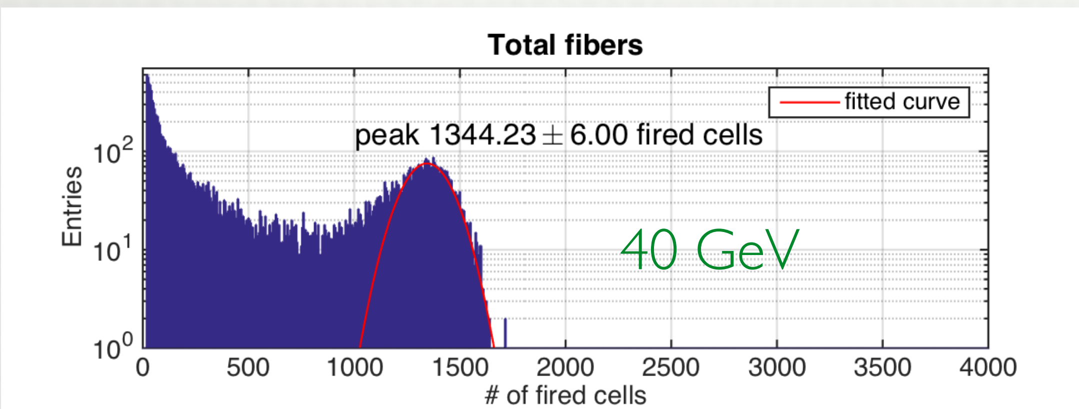
60 GeV

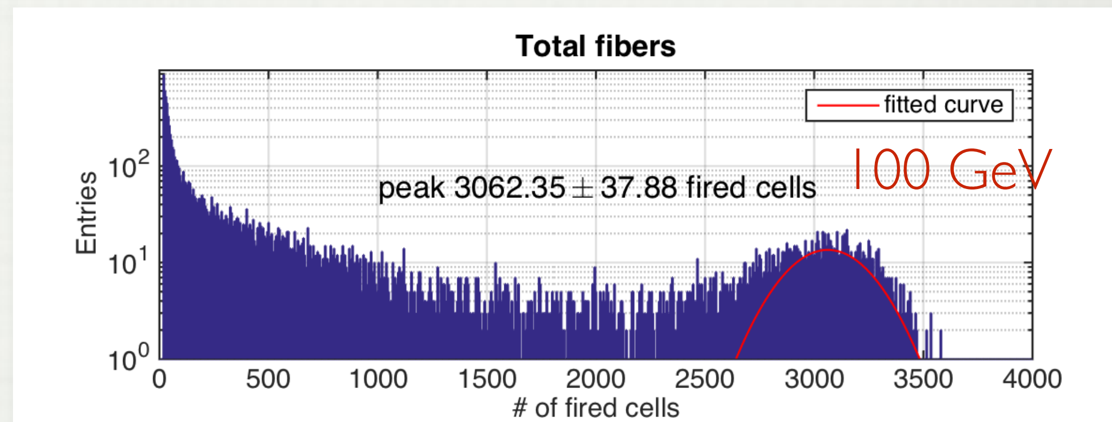
- about 16% events suffers from pile-up
- even pixels connected to Cherenkov fibers are close to saturation

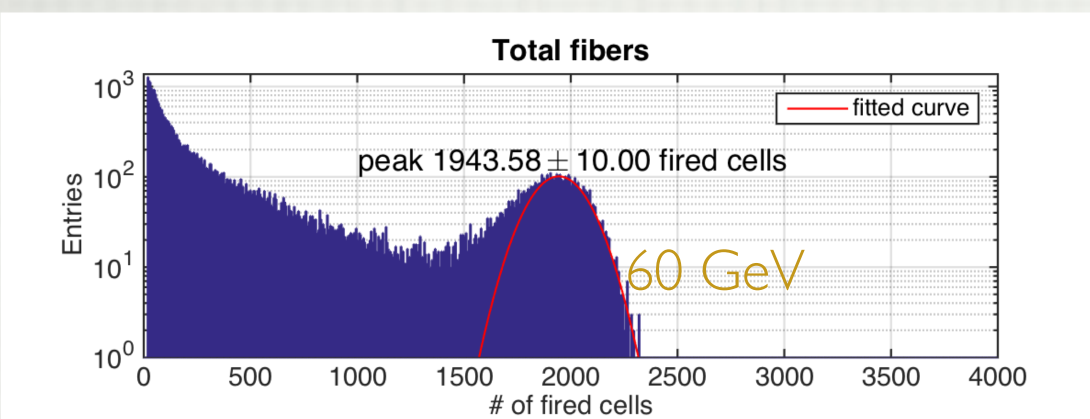
Results from Module 2 [Cherenkov fibres only connected to the SiPM pixels]

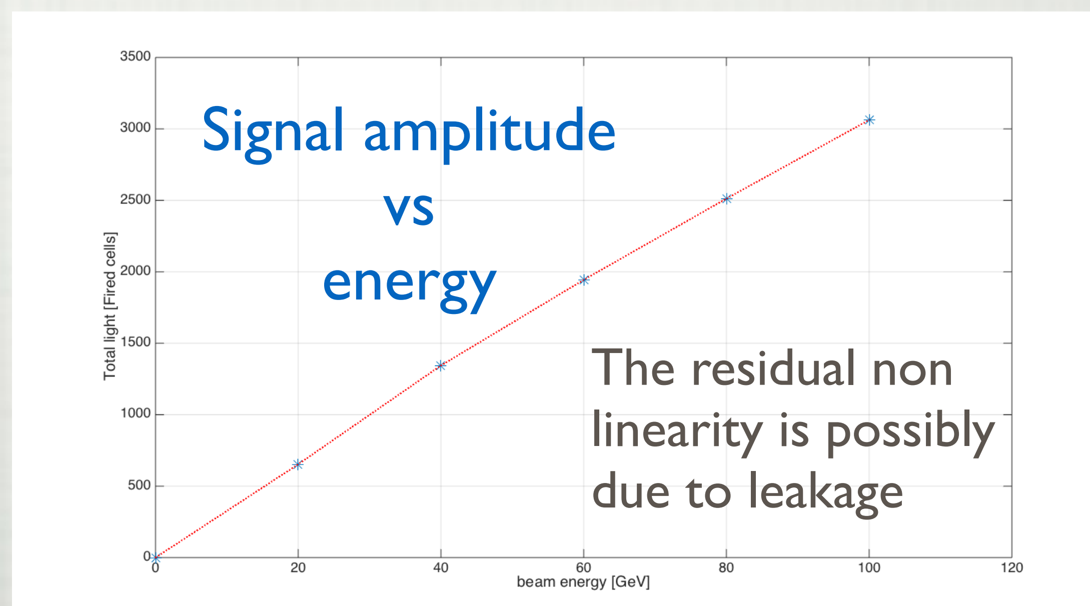




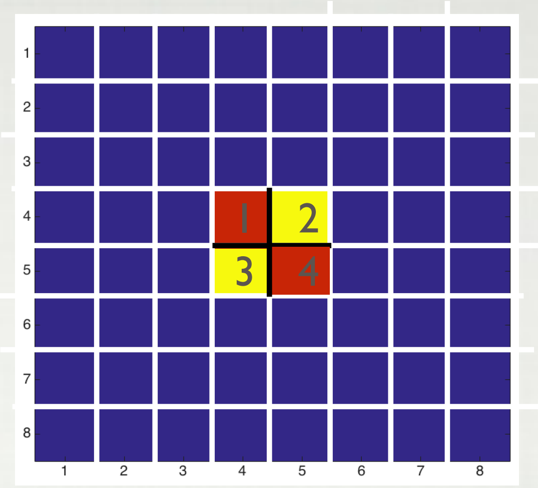


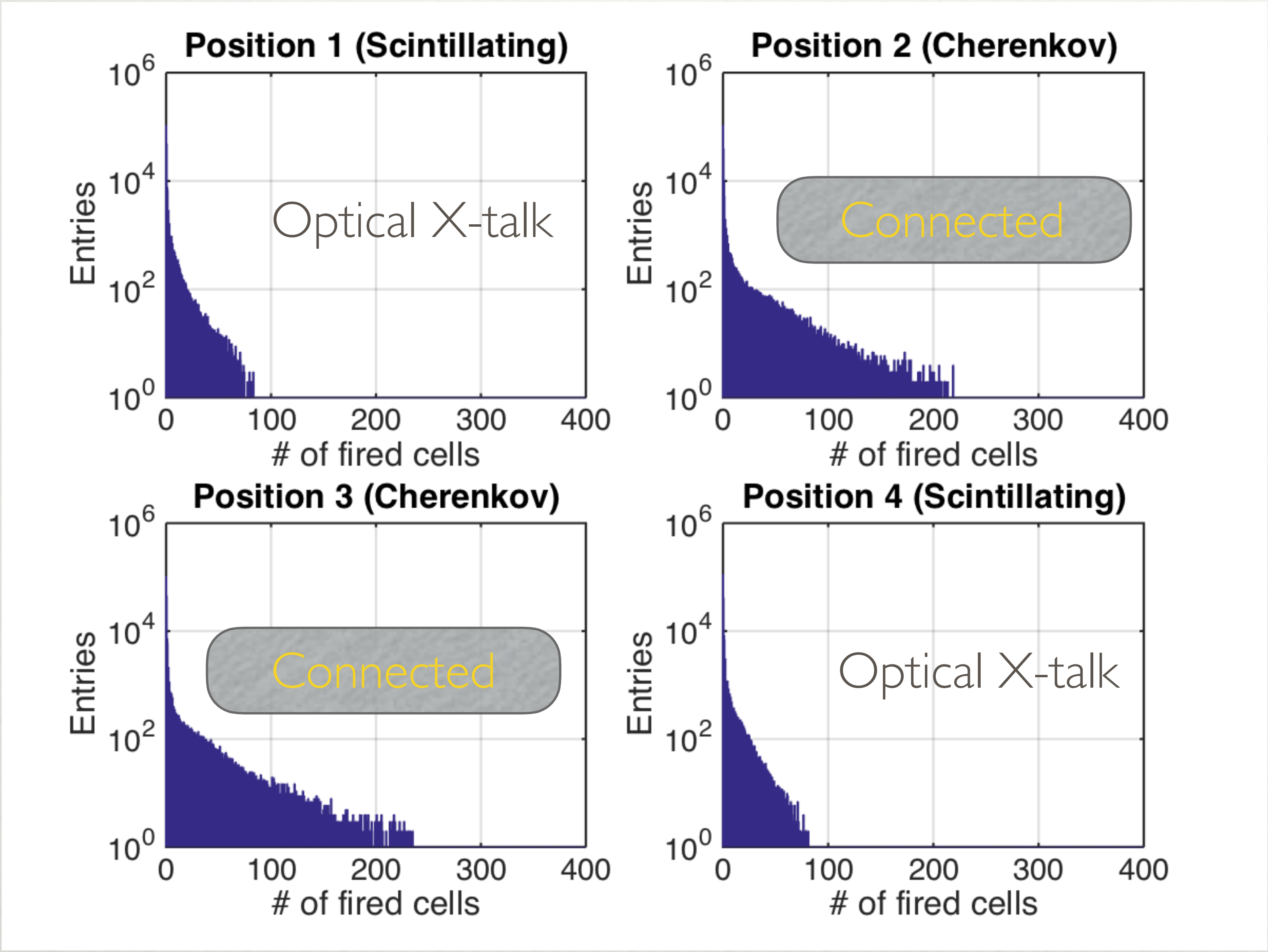






In fact, looking again at single fibre spectra in the core:





- sensors are away from saturation
- however:
  - at 20 GeV the tail of the spectrum ends at ≈ 40 cells, so "single photon sensitivity" and good Photon Detection Efficiency has to be retained
  - SiPM are affected by not linear response well before the saturation*:

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

so the response in this regime shall be handled with care

* [due to their intrinsic and irreducible nature of being granular & operated in Geiger-Mueller regime]

From Module 2, the optical cross talk between neighbouring cells can be measured:

$$X - talk = \frac{\sum_{i=1}^{32} S_i^{scinti}}{\sum_{i=1}^{32} (S_i^{scinti} + S_i^{cherenkov})}$$

leading to these consistent results:

Energy (GeV)	20	40	60	80	100
X-Talk (%)	25.1	25.4	25.9	26.4	26.8

telling us we did well but we have to get better….

Conclusions & outlook

- a dual read-out module was interfaced to a SiPM array, qualified and commissioned on beam

- as a proof-of-concept, it was a success. However:
  - the sensor choice & the operating conditions shall be optimised independently for sensors connected to Cherenkov and Scintillating fibres
  - sensors reading out the two kind of fibres shall be decoupled

- how I see the way forward:
  - in 2017, address the 2 major issues outlined above
  - start in 2018 the design and construction of a "significant volume module", mimicking a wedge of a real calorimeter