Development of a GEM-based image intensifier for the MONDO project

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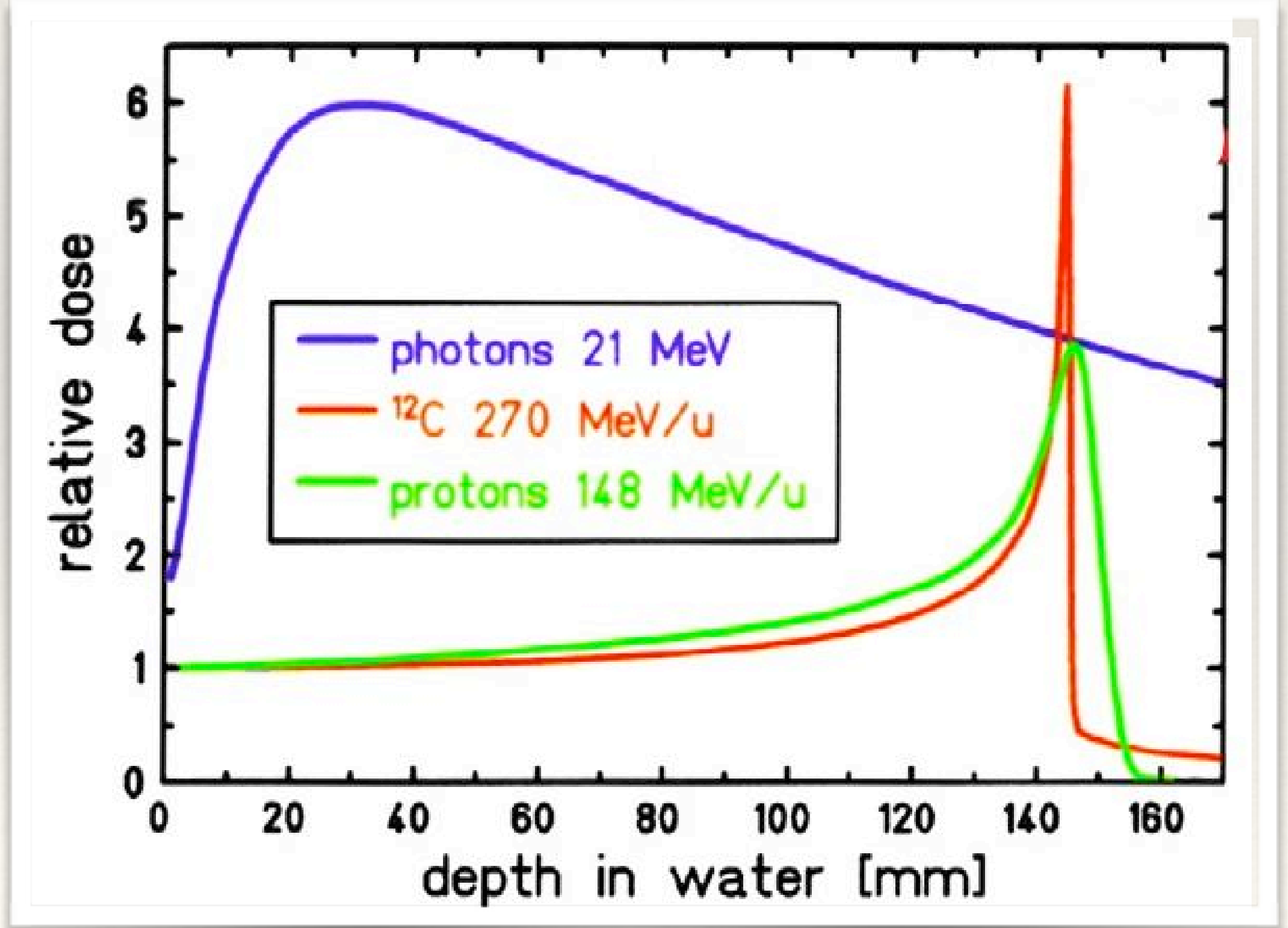
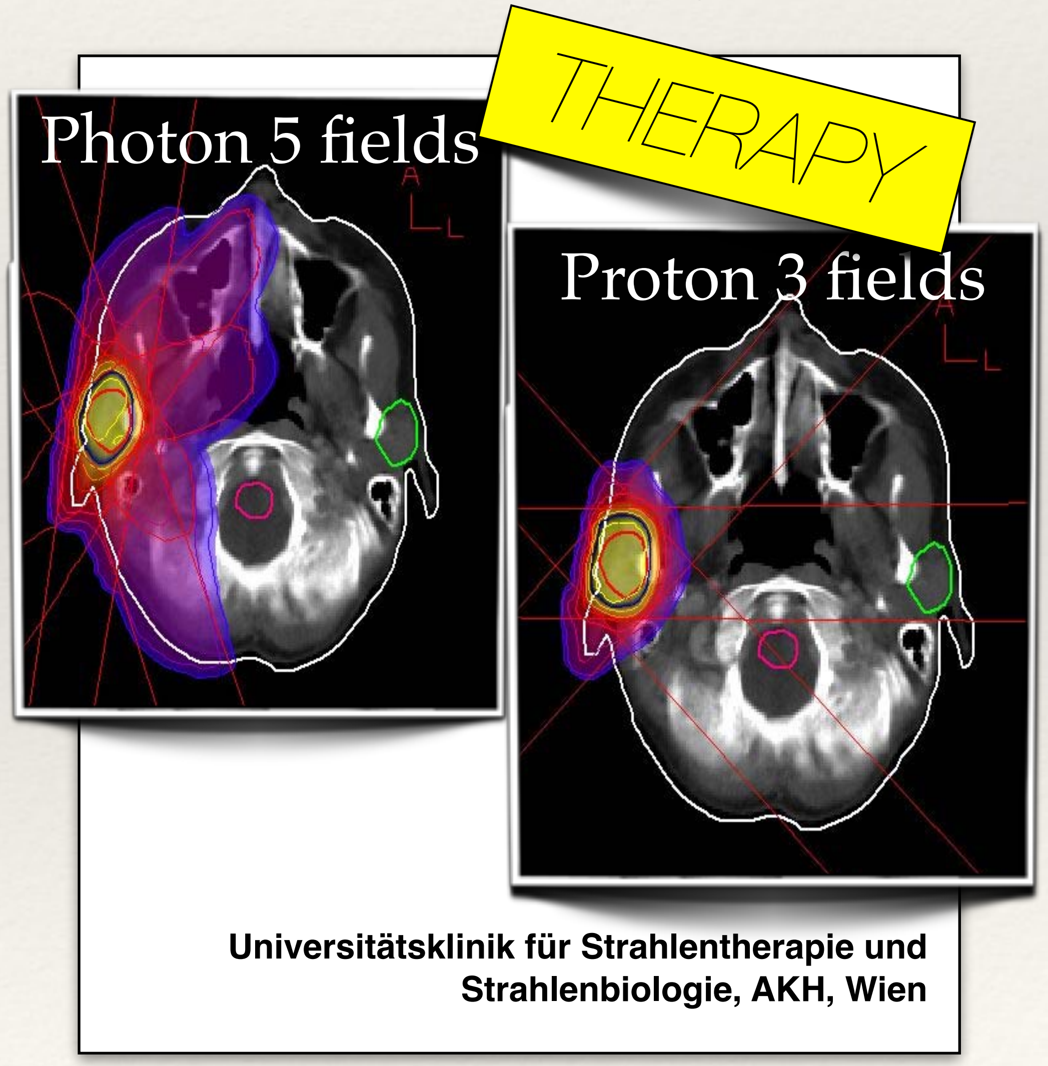
On behalf of MONDO collaboration

MOnitor for Neutron Dose for hadrOnterapy

- Charged particles release energy at the end of their path: Bragg Peak;
- The Radio Biological Effect of ion beam is higher than in X-Ray (Radiotherapy);
- Particle Therapy (PT) exploits this characteristics: it possible to destroy the tumor cells preserving the healthy tissues;





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MOnitor for Neutron Dose for hadrOnterapy

Many secondary particles are produced during PT treatments and we can exploit them to monitor the beam. Secondary addition dose due to charged particles and photons is negligible comparing to the primary one, but for secondary neutrons the scenario is more complicated.

- Biological effects
  - Secondary complication risks (SMN)
- Radio-Protection
  - Shielding, staff safety, … *MC extrapolation from low energy data*
- Induced radioactivity evaluation

Life expectancy

The neutron induced complications are the main concerns in PT administration and planning, in particular in **pediatric treatments**

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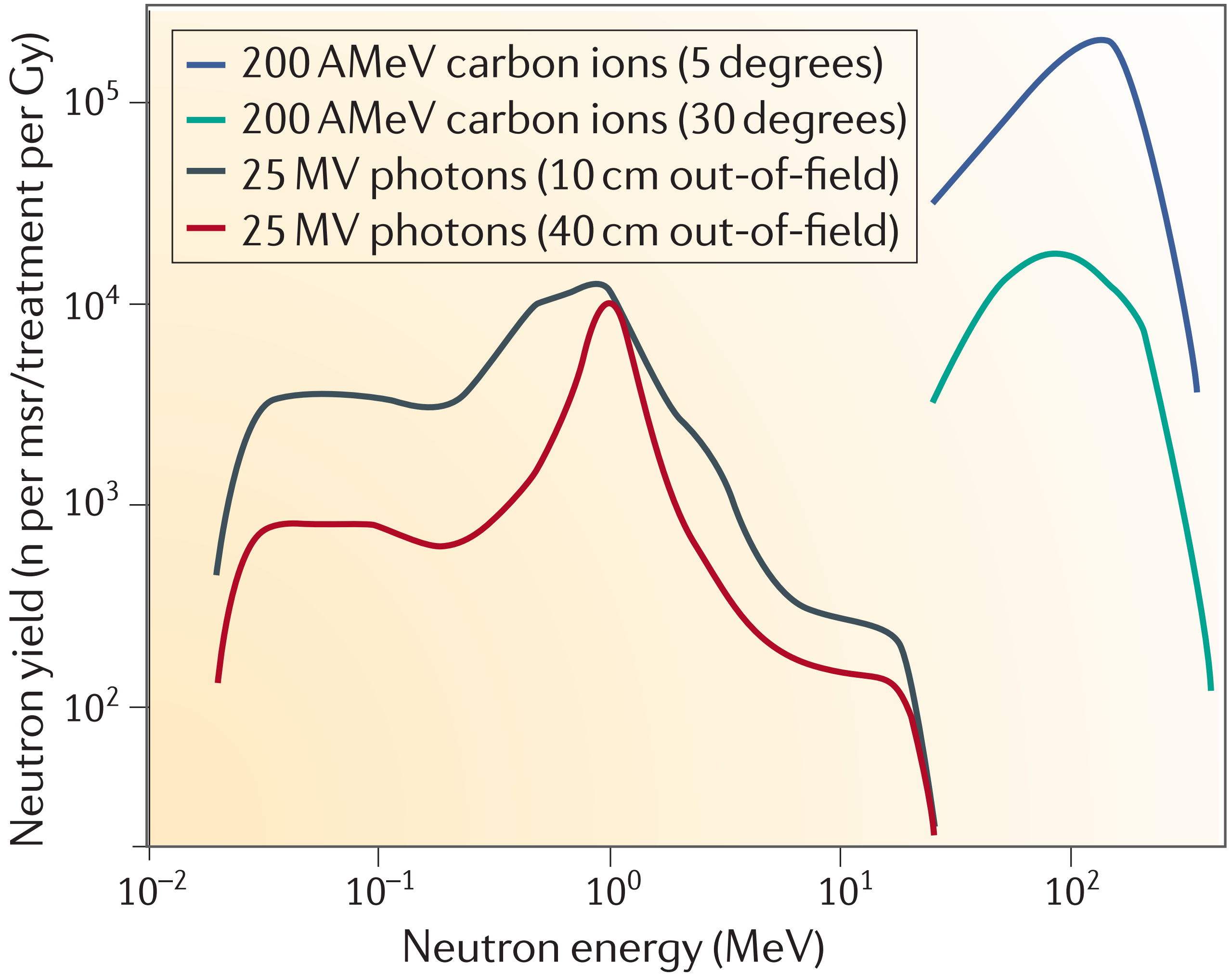
In a carbon ion beam treatment neutrons are produced mainly at energies: 20 - 600 MeV.



Neutrons produced during PT treatments by the beam interactions with the patient are mainly ultra-fast neutrons. Their energy is degraded after several scattering interactions with the target nuclei so that a large flux of slow neutrons is expected.

Is it crucial to measure this produced neutrons

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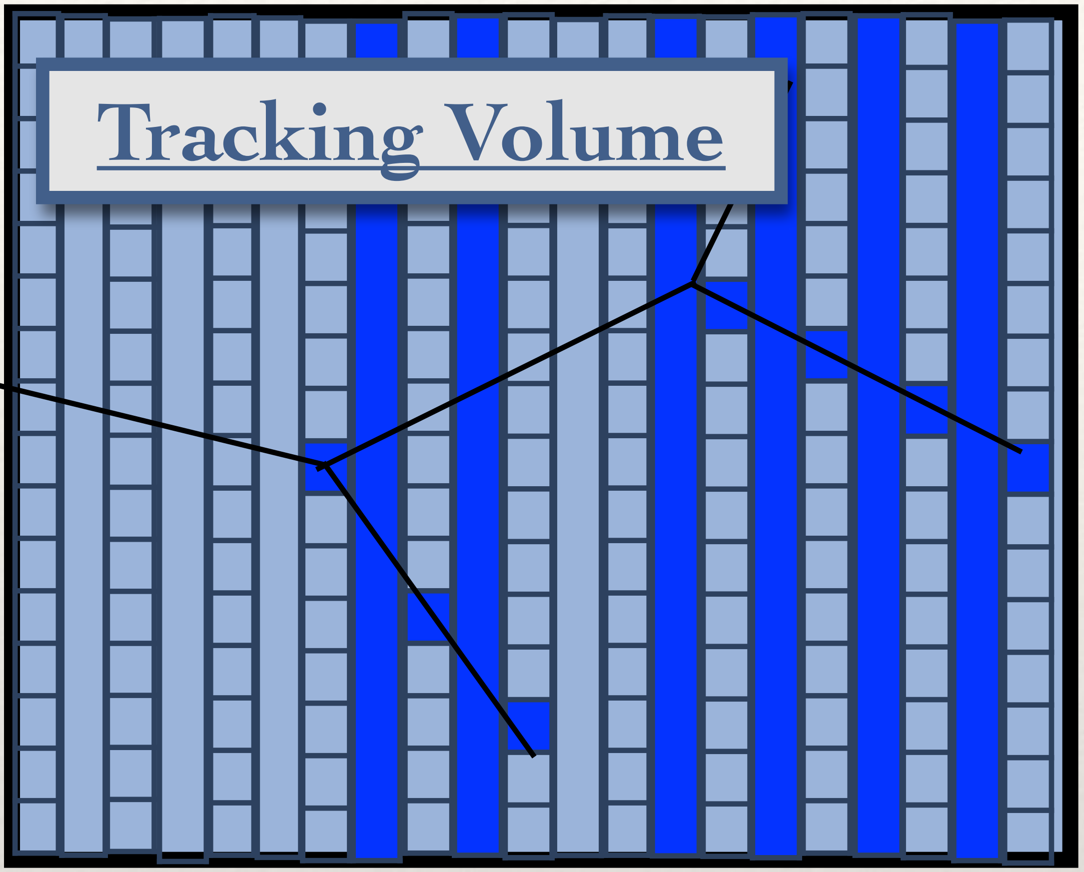
Tracking Detector



Plastic Scintillator

- 20 x 20 x 20 cm^3;
- scintillating fibres 250 μm;
- 800 squared fibres per layer;
- x-y layer orientation;

Neutron

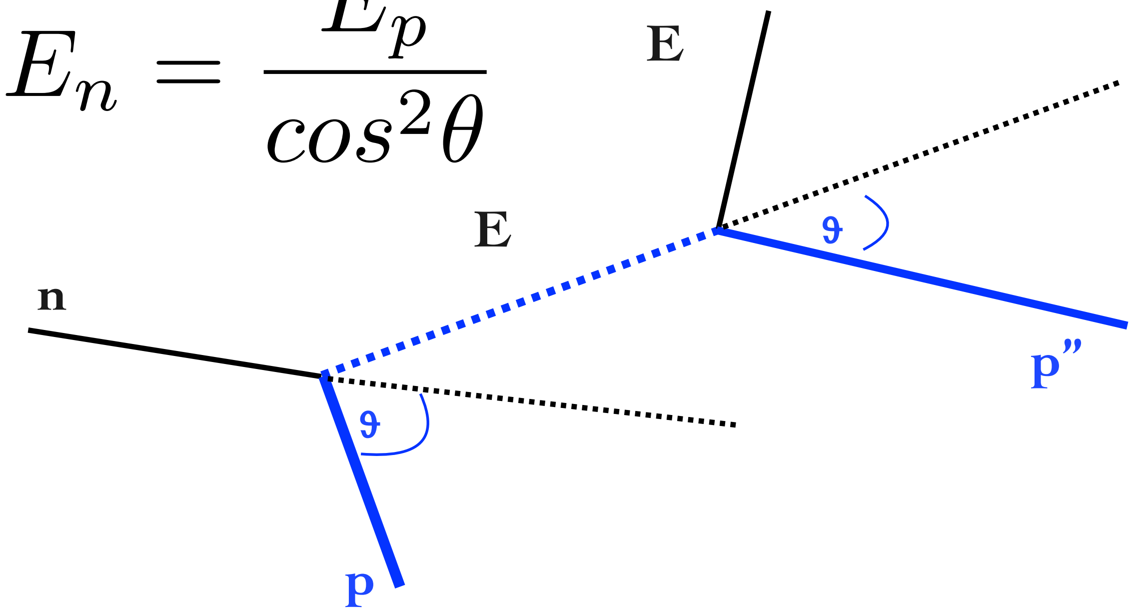
- E_{kin}=[20-200] MeV
- Inter. length. ~ 1m

Proton mean path

- E_{kin} = 100 MeV=> 8 cm
- E_{kin} = 10 MeV=> 0.1 cm

Double elastic scattering interaction

$$E_n = \frac{E_p}{cos^2\theta}$$



The image intensifier

Since the amount of produced light can be too low an image intensifier is needed to increase the number of photons reaching the light sensor;

We are investigating the possibility of developing a triple-GEM based intensifier;

Two main issues:

1) Photo-cathode for visible light. Technolgy exists and some prototypes of MPGD based PMT for visibile light already produced. But it has several serious caveat to be taken into account;

2) Light readout. Commercial CMOS based sensors give possibility of having high granularity along with very high sensitivity. We started a detailed study on this point;

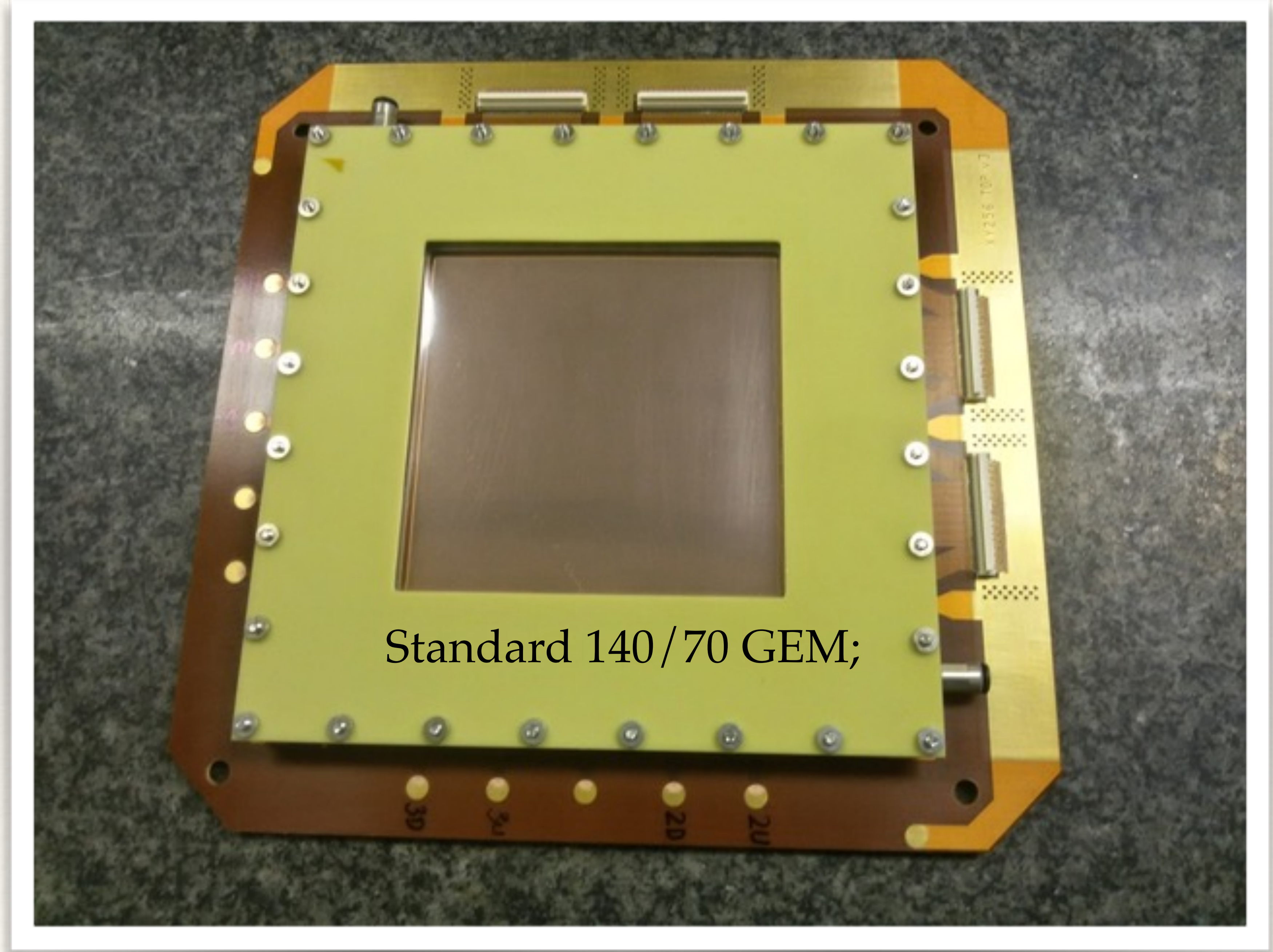
Study and develop 1) and 2) are of general interest not only for the MONDO project.

The Triple-GEM detector

3 mm wide drift gap and two 2 mm wide transfer gaps;

Electrons are collected on the bottom of the third GEM and only photons are read out;

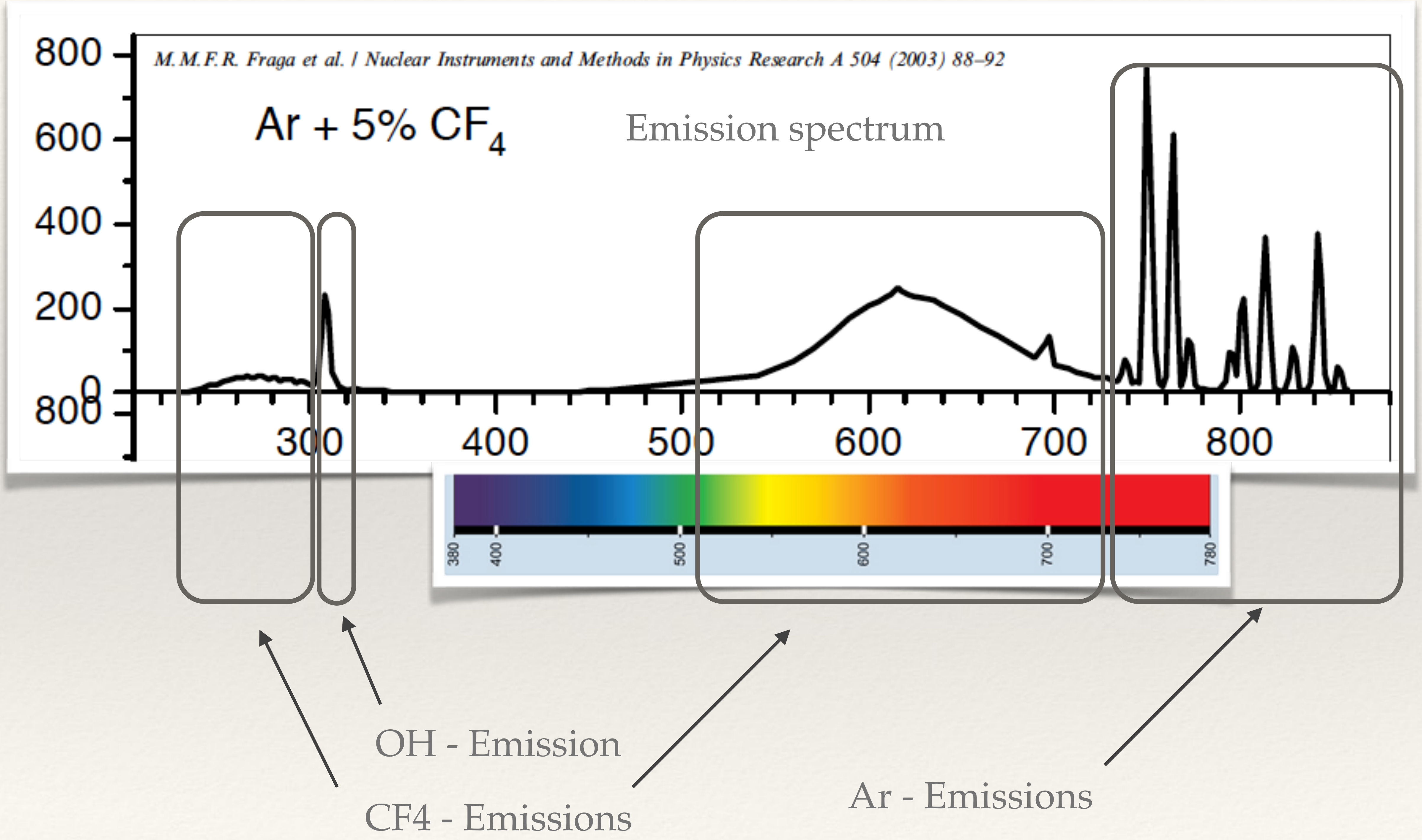
The readout plane was replaced by a transparent plastic foil window.



Standard 140/70 GEM;

The gas mixture

First tests were made by using an Ar/CF4 (95/5) gas mixture (1 bar);



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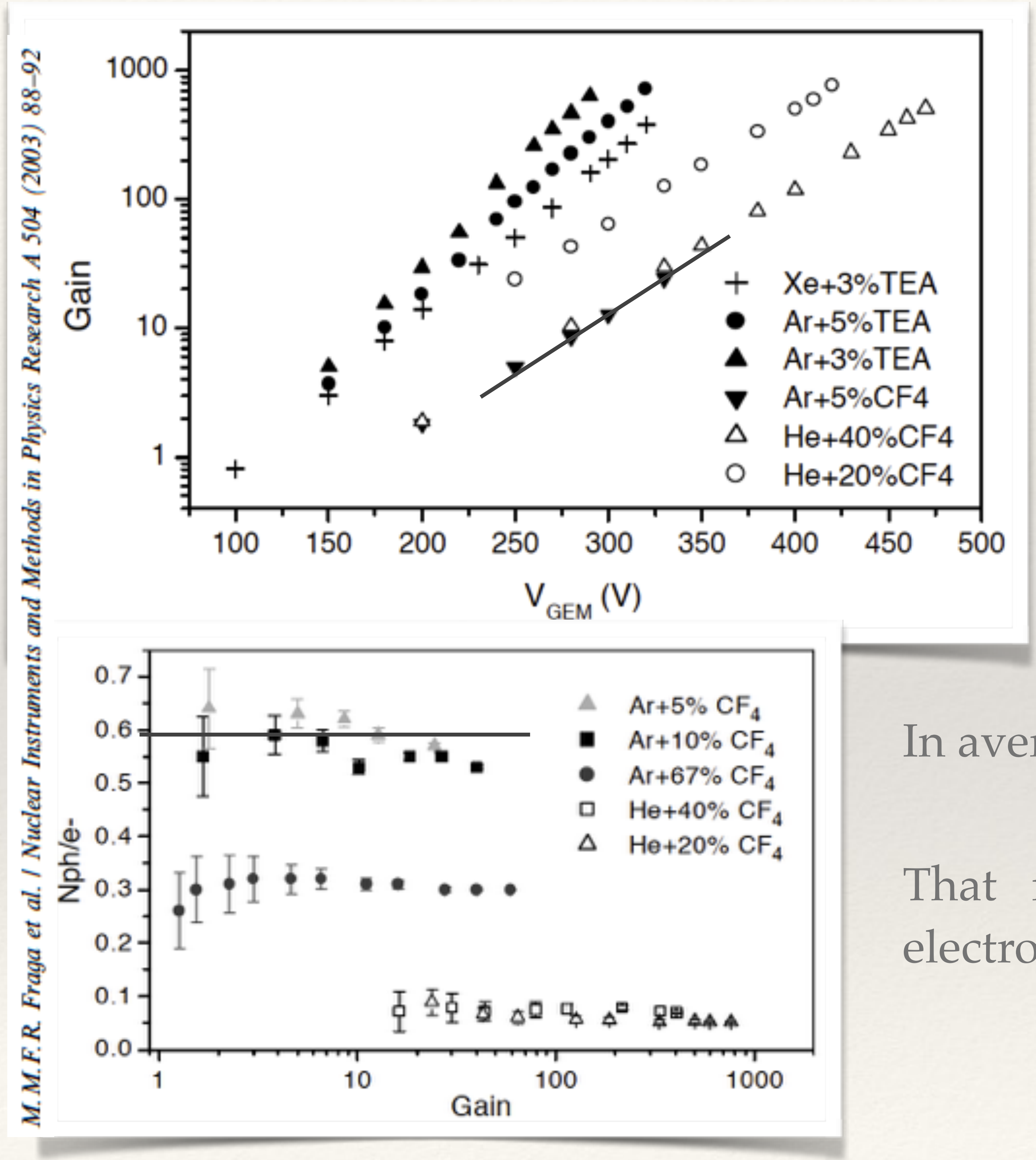
OH - Emission

CF4 - Emissions

Ar - Emissions

The gas mixture



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Data acquired for a V_{GEM} = 360 V.

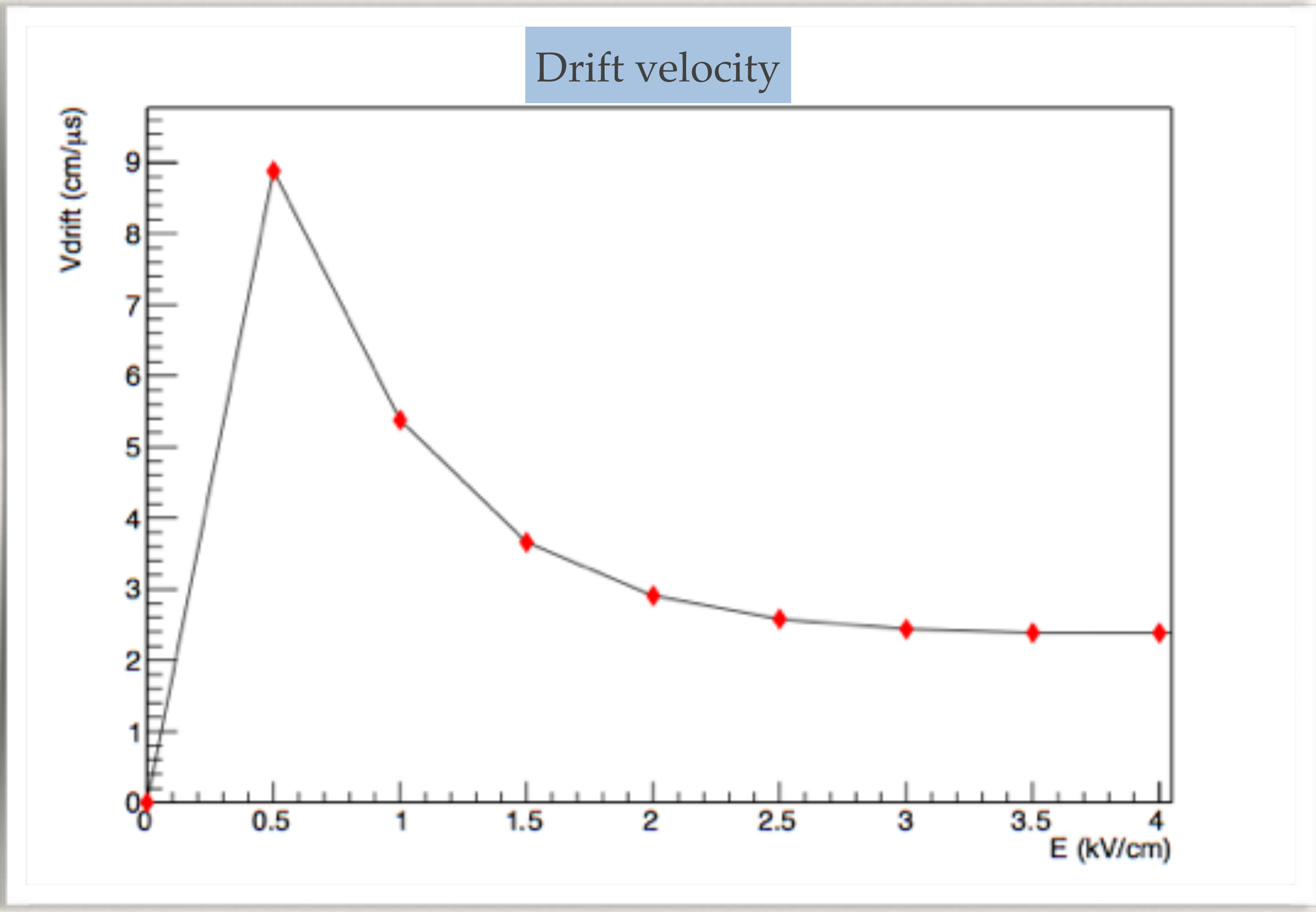
A gain value of about few tens is expected for each GEM. In total a gain as high as few 10^4 can be achieved;

In average we expect 0.6 photons per electron;

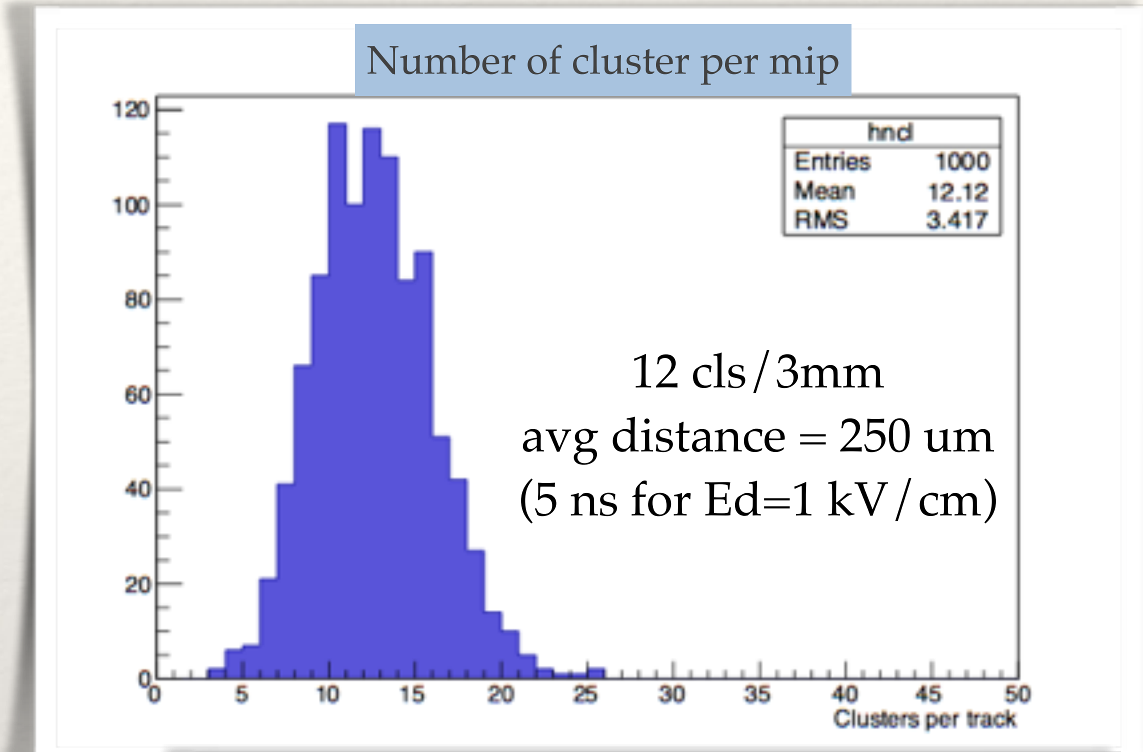
That means up to 10^4 photons per primary electron can be produced;

The gas mixture

We evaluted other properties of the gas mixture by means of Garfield

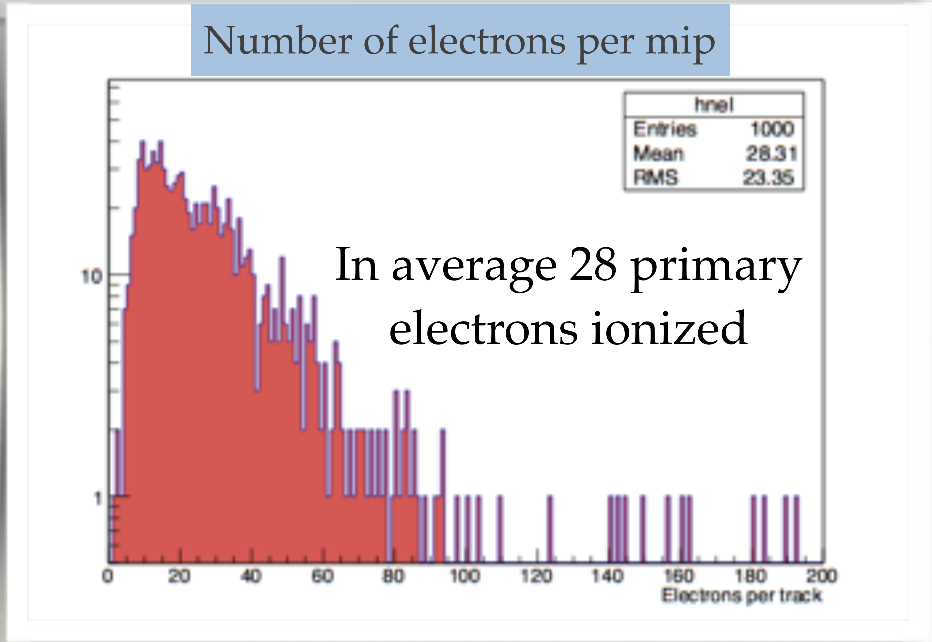


Drift velocity



Number of cluster per mip

12 cls/3mm
avg distance = 250 um
(5 ns for Ed=1 kV/cm)



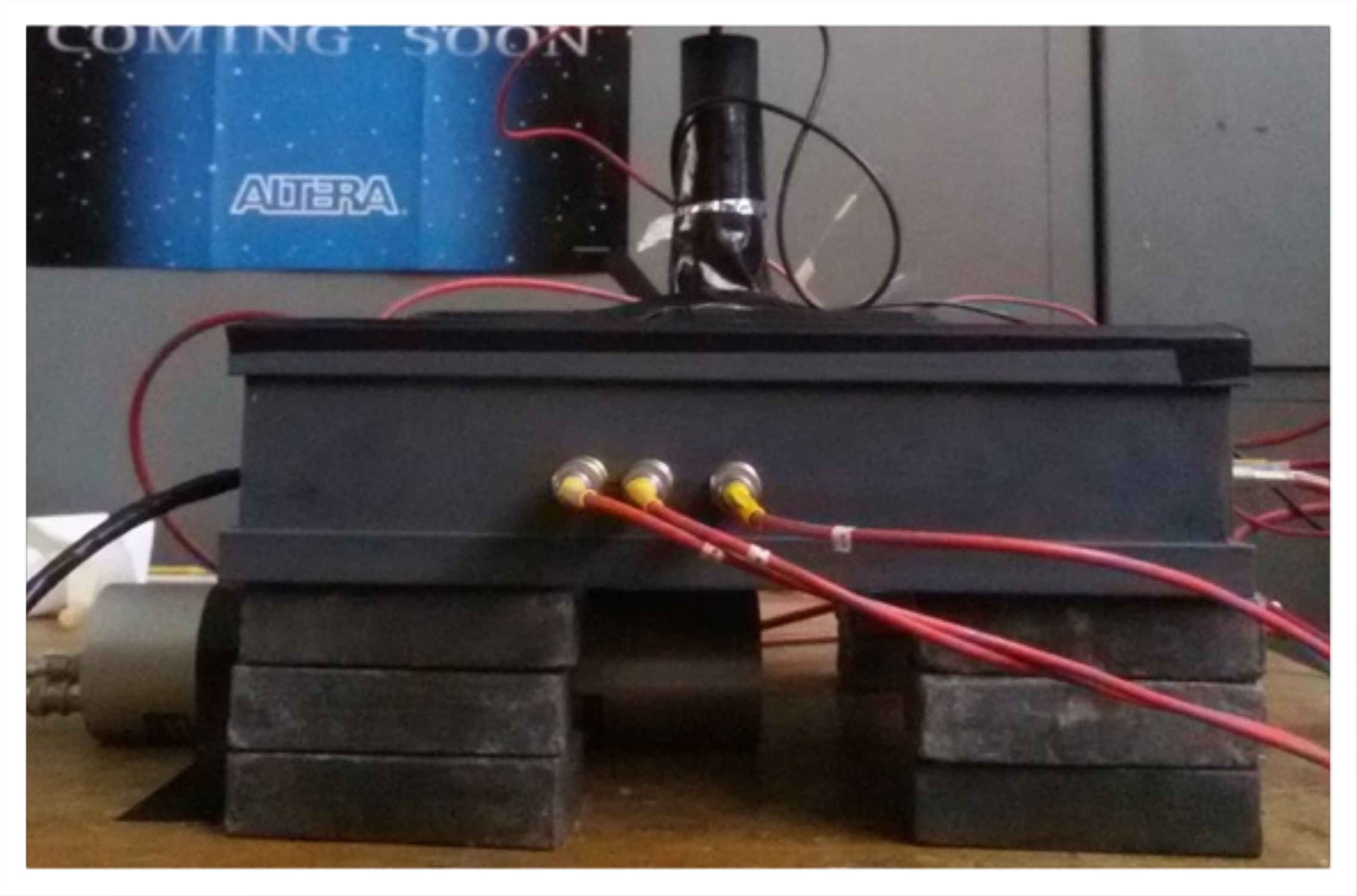
Number of electrons per mip

In average 28 primary electrons ionized

A mip is expected to produce up to 10^5 photons

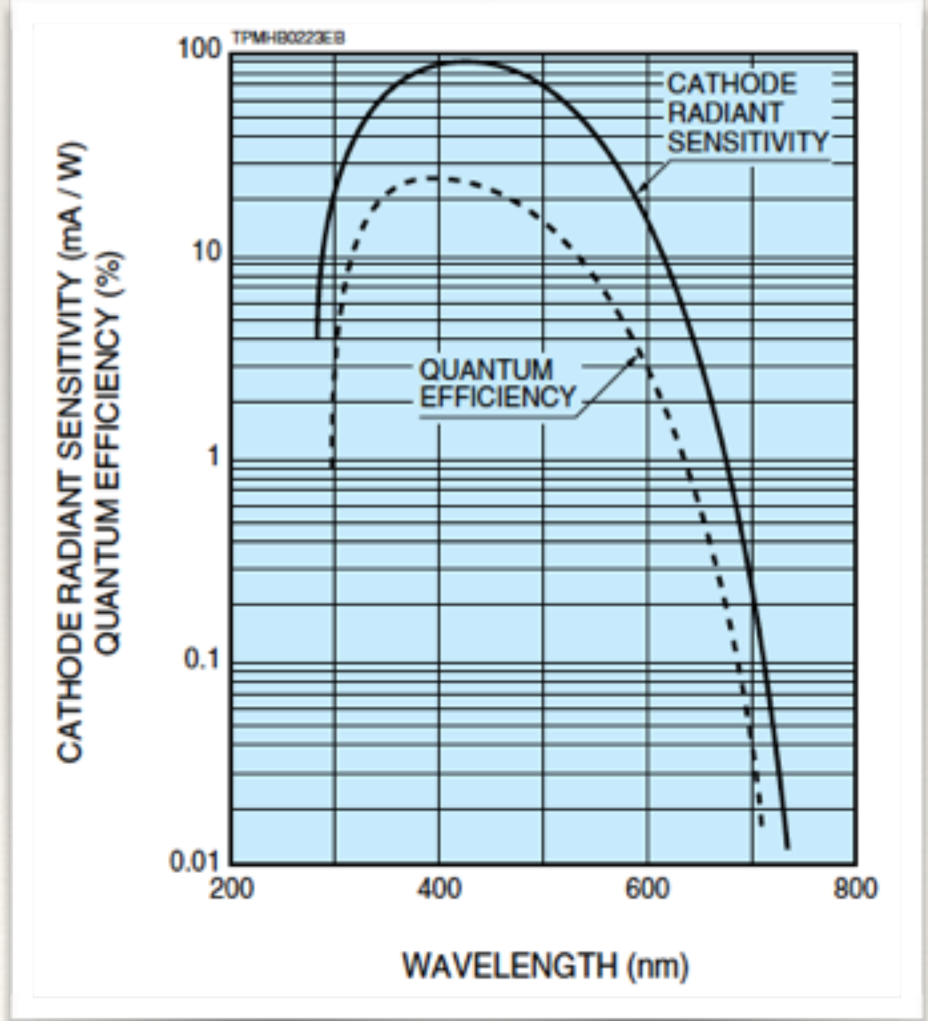
Experimental set-up: PMT

The light yield of the triple-GEM detector was measured by means of cosmic rays;



Two NaI scintillators used to trigger penetrating muon tracks;

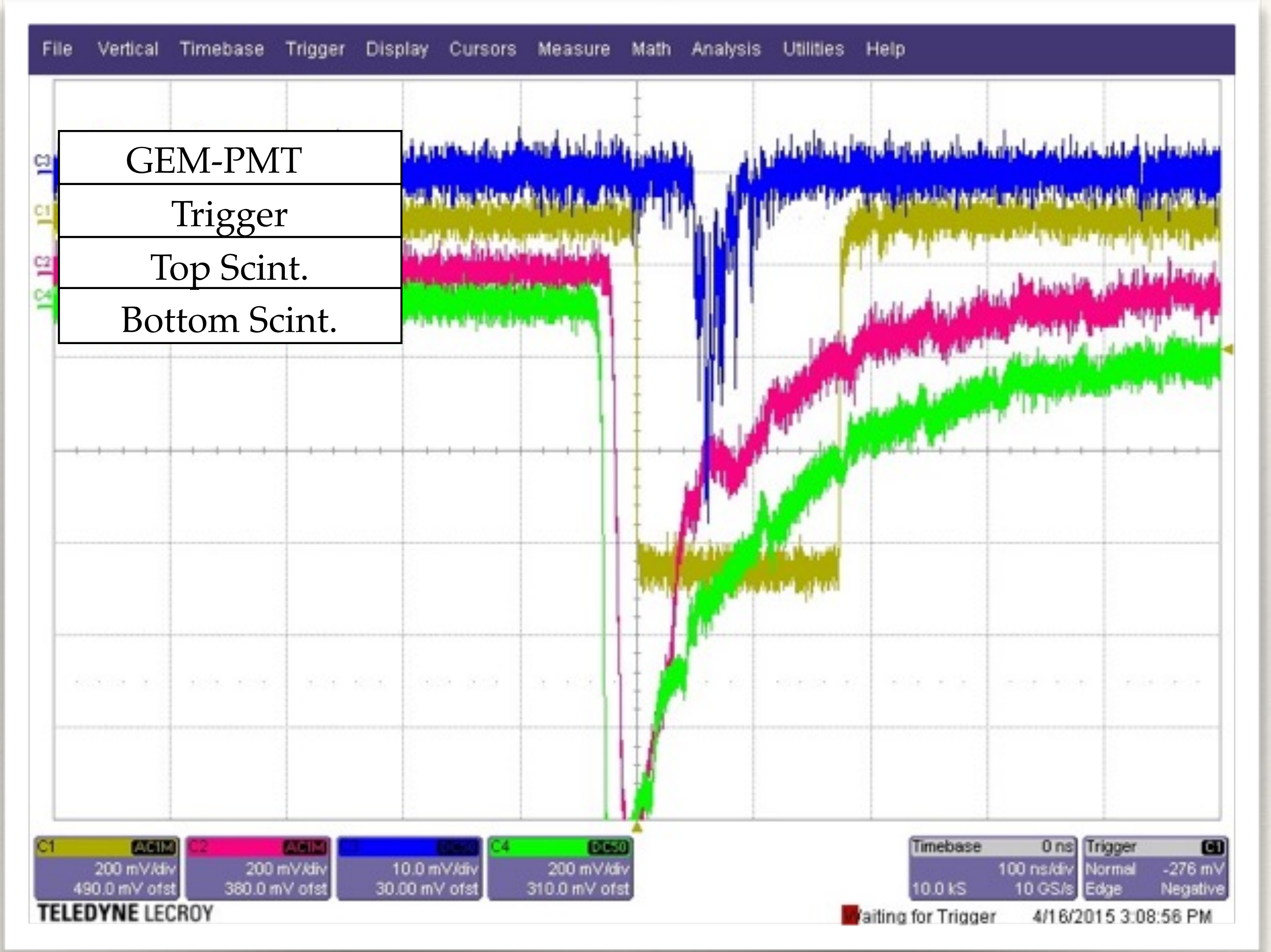
Light produced by the triple-GEM collected by a R9800 PMT;



A quantum efficiency below 5% is expected on the orange-red part;

Experimental set-up: DAQ

All waveforms acquired by means a 10 GS/s oscilloscope;



C1 ACIM 200 mV/div 490.0 mV ofst

C2 ACIM 200 mV/div 380.0 mV ofst

C3 DC50 10.0 mV/div 30.00 mV ofst

C4 DC50 200 mV/div 310.0 mV ofst

Timebase 0 ns 100 ns/div 10.0 kS 10 GS/s

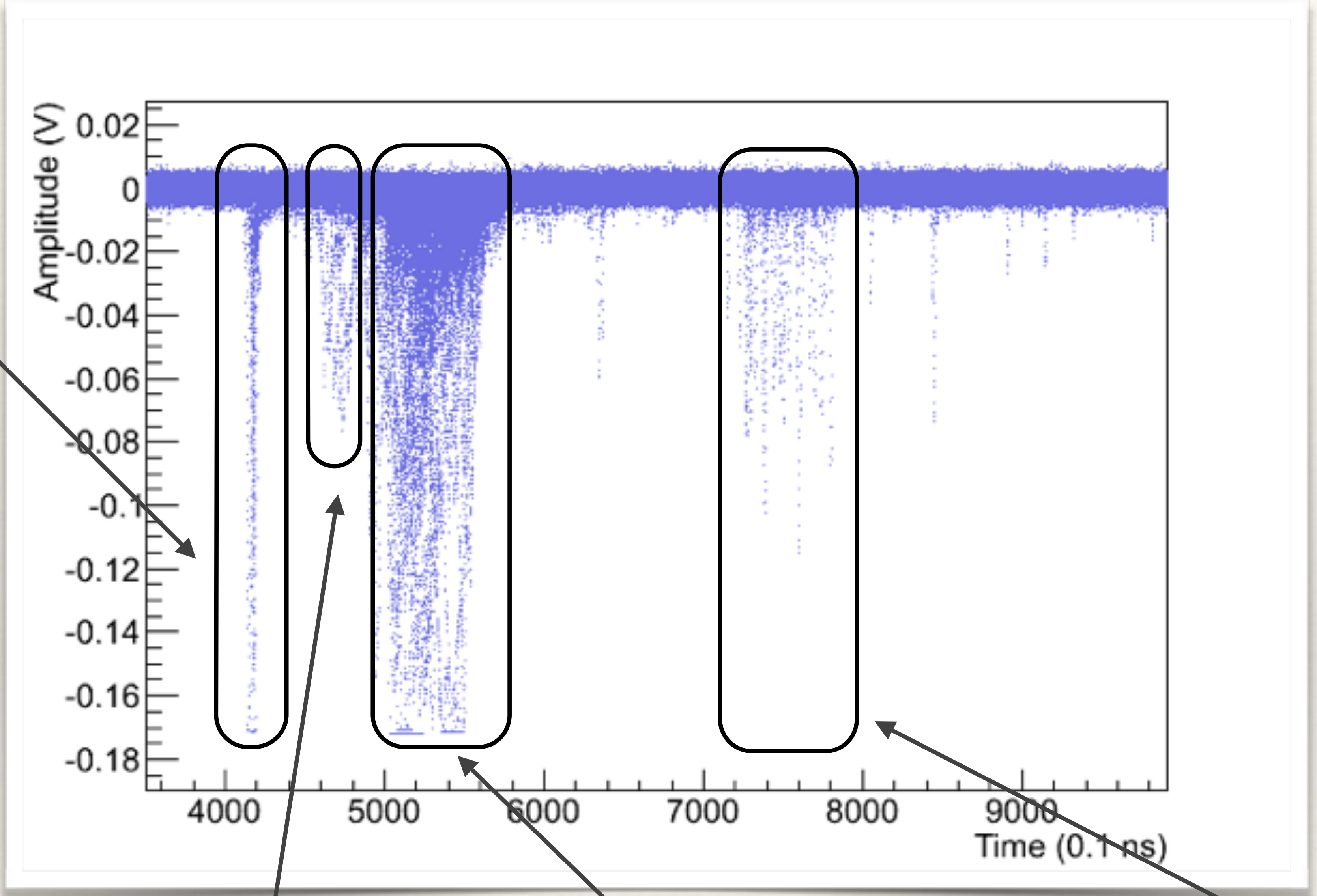
Trigger C1 Normal -276 mV Edge Negative

Waiting for Trigger 4/16/2015 3:08:56 PM

The waveforms were than analyzed to get the charge and the arrival time of the signals;

A complete dataset

Several structures were visible in a complete data taking



These spikes are there also with PMT blinded by black tape. Something within the PMT itself.

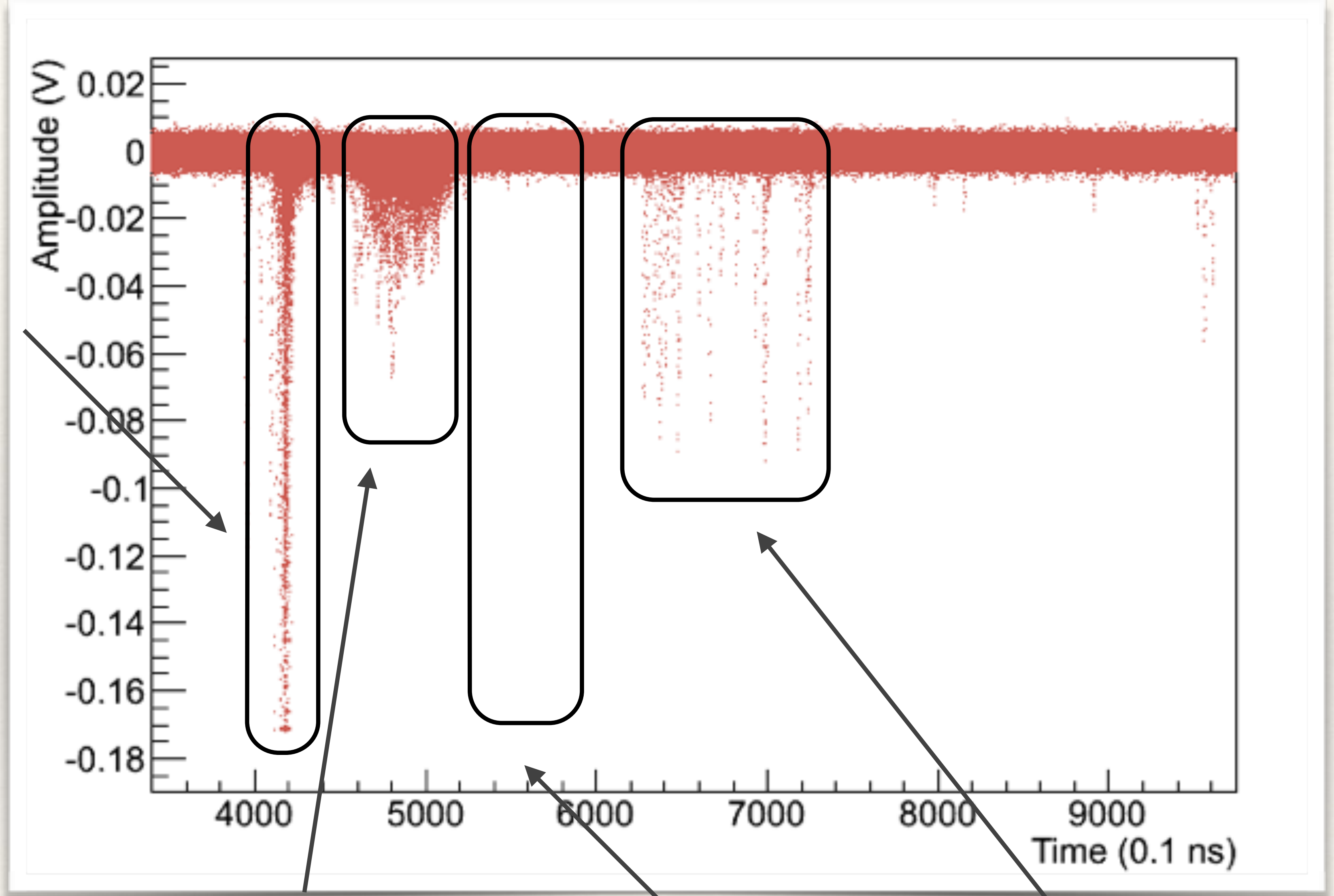
Charge released between the first and the second GEM and thus amplified only by two GEMs (bi-GEM effect)

Main signals due to the triple-GEM amplification

Echos of the triple-GEM signals arriving more than 200 ns later.

Bi-GEM effect

To confirm the bi-GEM effect, a run was taken with the first GEM off.



These spikes are always there

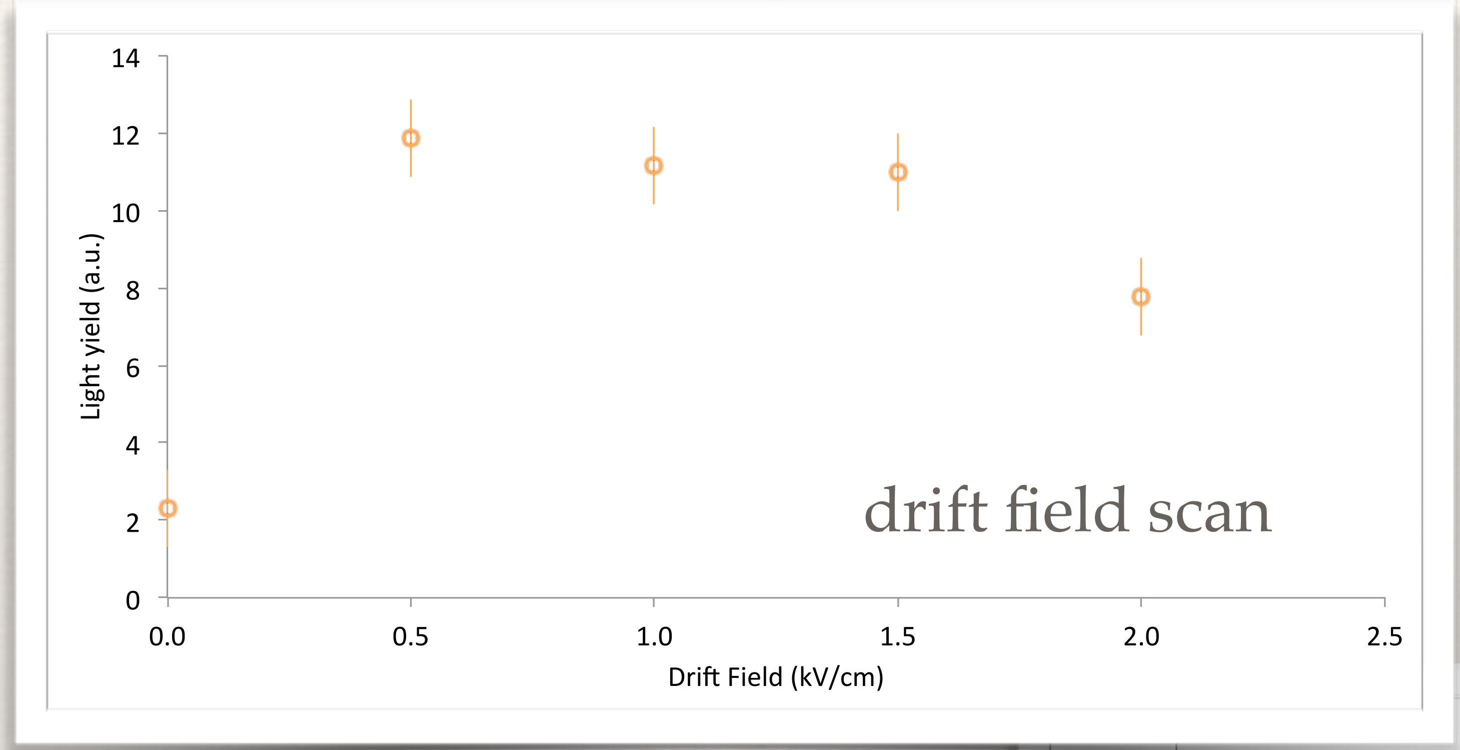
Charge released between the first and the second GEM and thus amplified by two only GEMs (bi-GEM effect)

Nothing there…

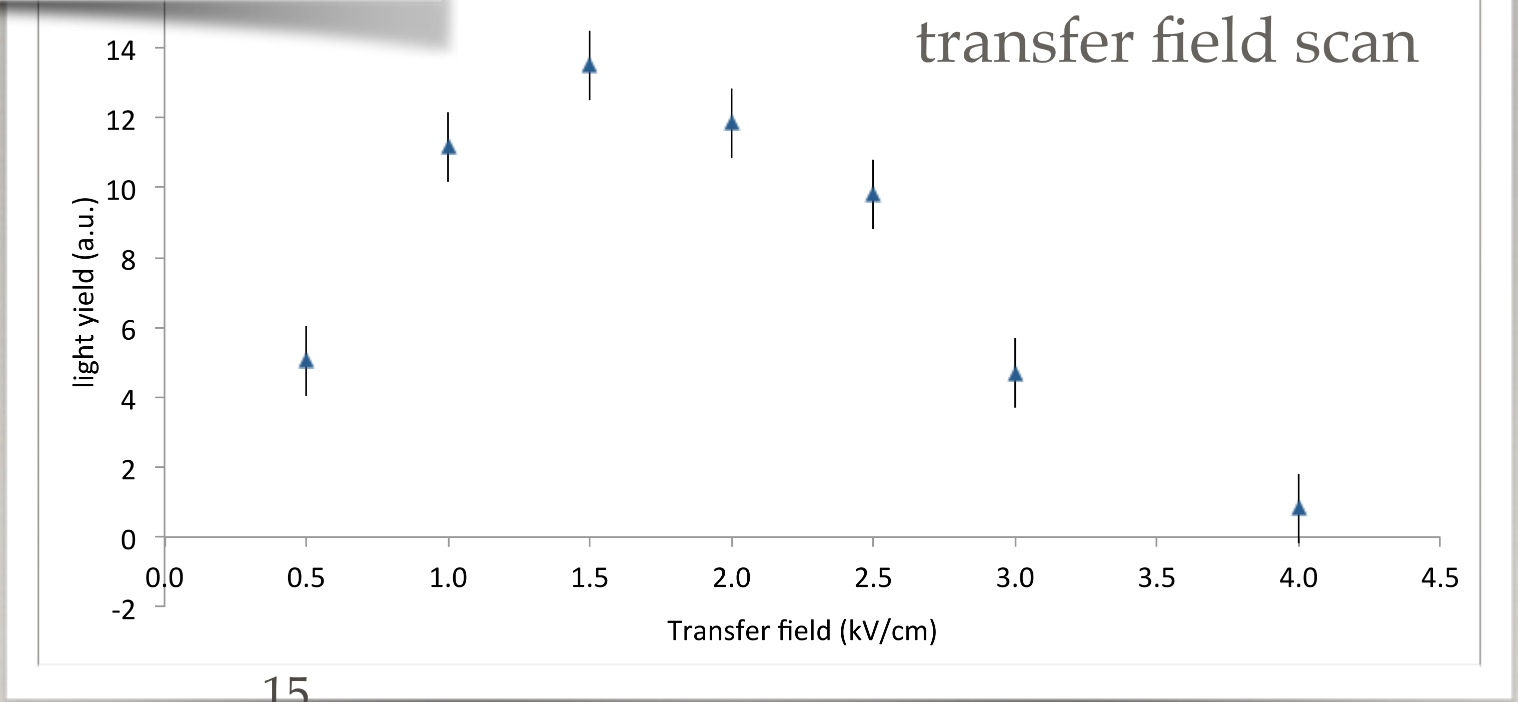
Echos of the bi-GEM signals arriving 150 ns later.

Optimization of the electric fields

The electric field values have been scanned in order to optimize the charge collection and extraction in the GEM channels and thus to maximise the system light yield;



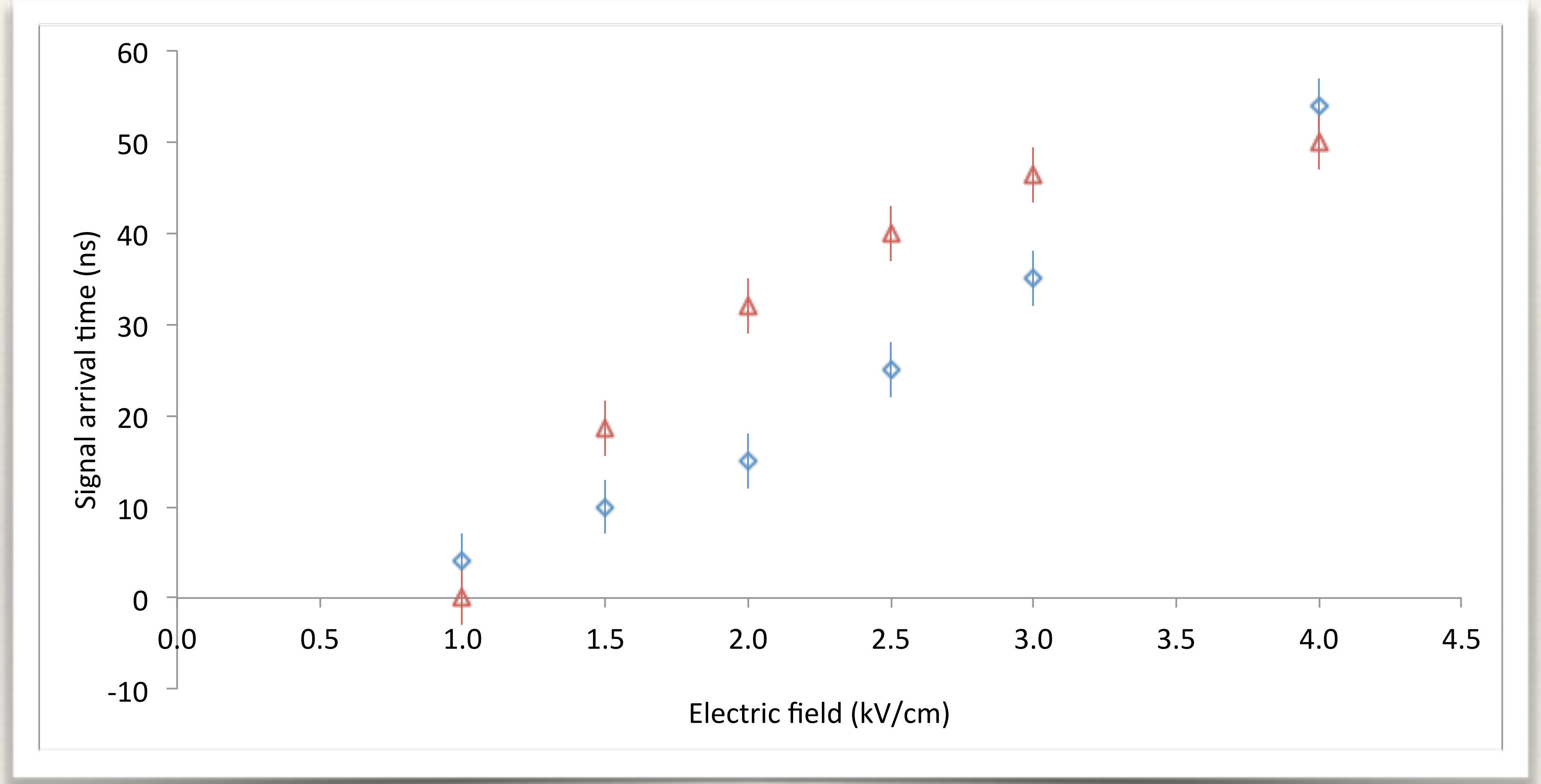
The amount of light is almost stable for drift field values in the range 0.5 - 1.5 kV/cm



A transfer field around 1.5 kV/cm maximises the light collection.

Signal arrival time

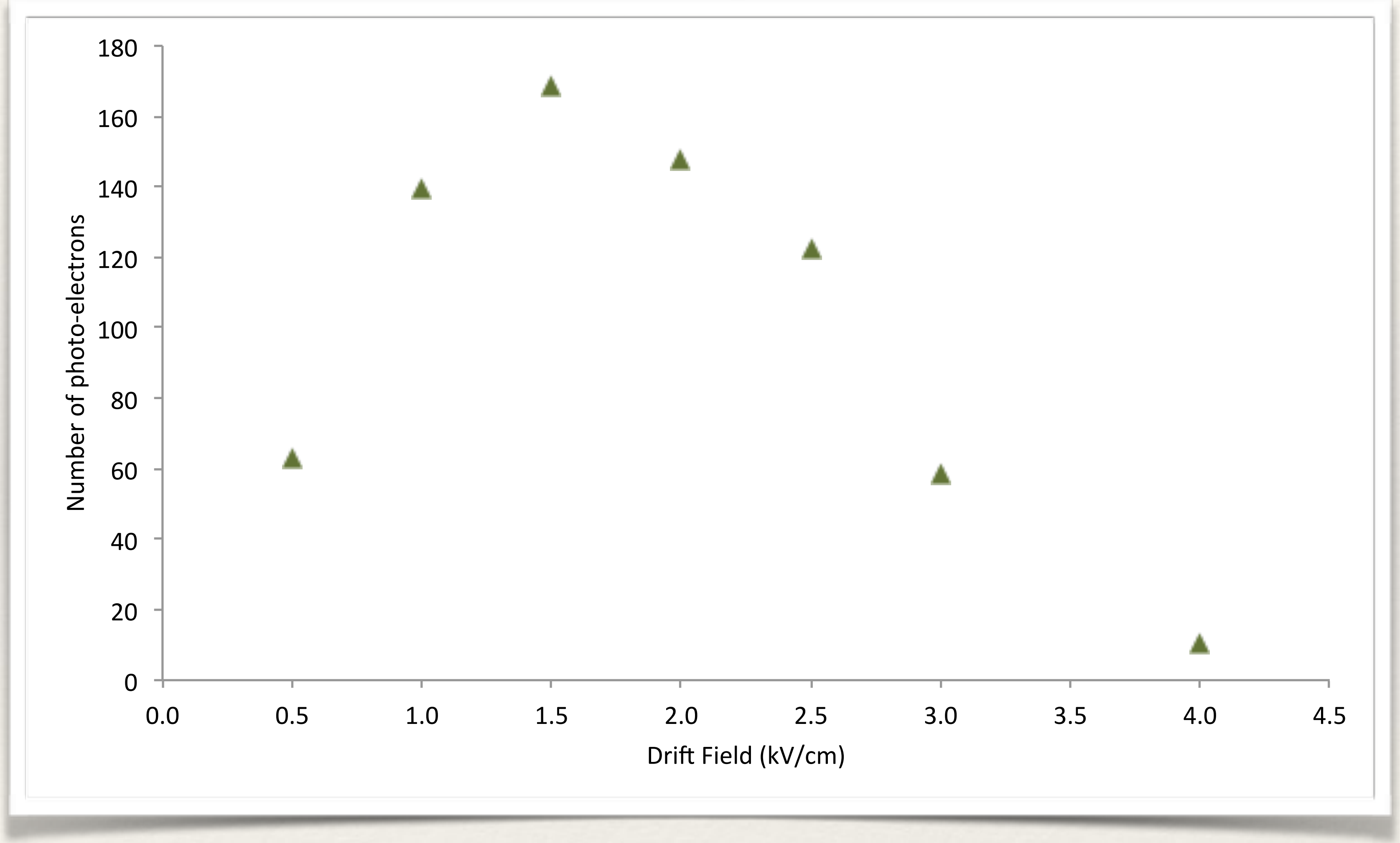
In order to check the results of the simulation, the measured signal arrival times for different drift fields are compared with the ones evaluated by using the calculated drift velocity.



Altough the agreement is not perfect, the behavior and the order of magnitude of the two studies are the same.

Light yield measurement

The average charge provided for a single photo-electron for this PMT was measured to be 0.16 +- 0.05 pC;



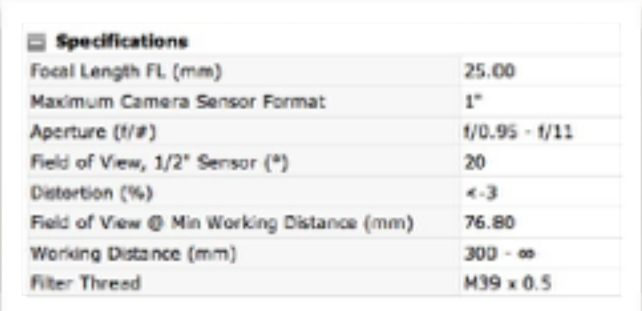
By means of this calibration the number of produced photoelectrons was evaluated;

In the optimized field condition more than 160 p.e. were collected;

The CMOS-Camera

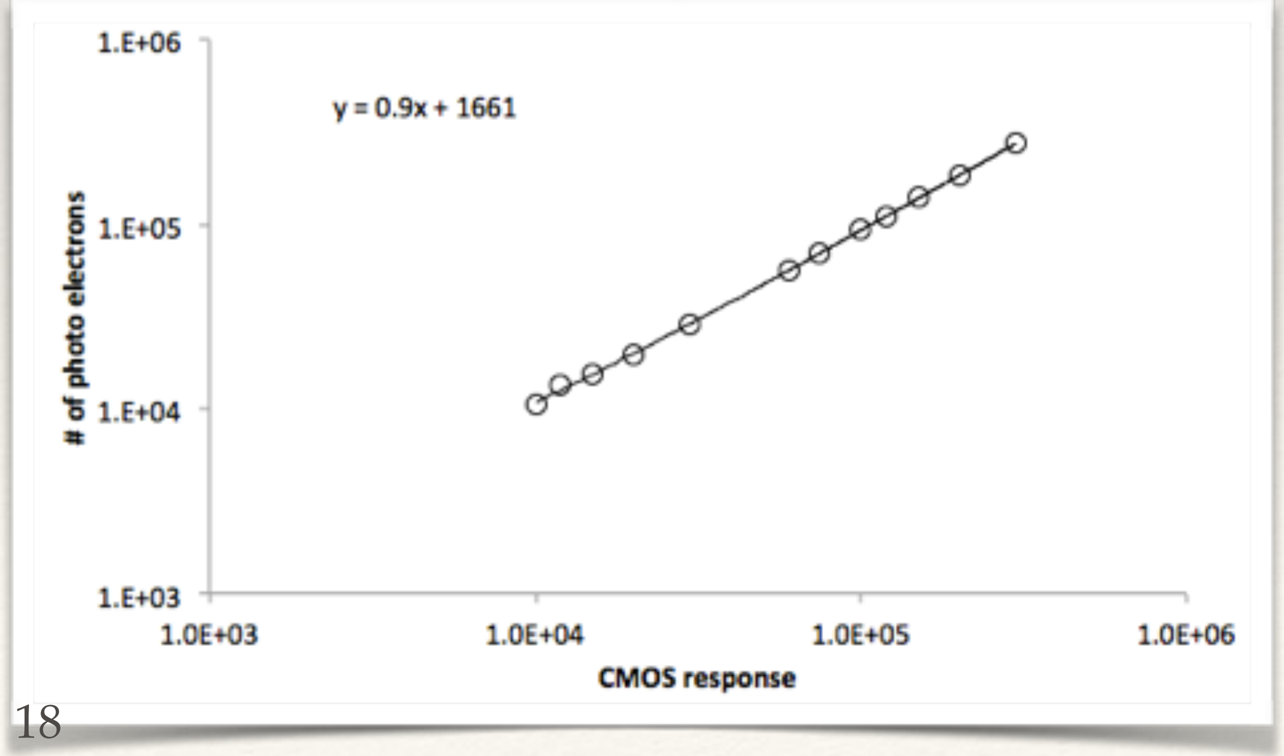
Once the light production was studied and maximised, the PMT was replaced by a CMOS camera with a suitable lens;

Hamamatsu provided us, for a few weeks test, an ORCA flash 4.0 camera that we instrumented with a Schneider bright lens

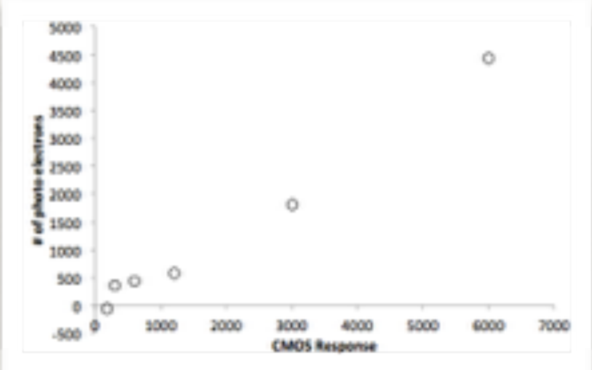


Specifications	
Focal Length FL (mm)	25.00
Maximum Camera Sensor Format	1"
Aperture (f/#)	f/0.95 - f/11
Field of View, 1/2" Sensor (°)	20
Distortion (%)	<-3
Field of View @ Min Working Distance (mm)	76.80
Working Distance (mm)	300 - ∞
Filter Thread	M39 x 0.5

This system was tested by means of a calibrated light pulse

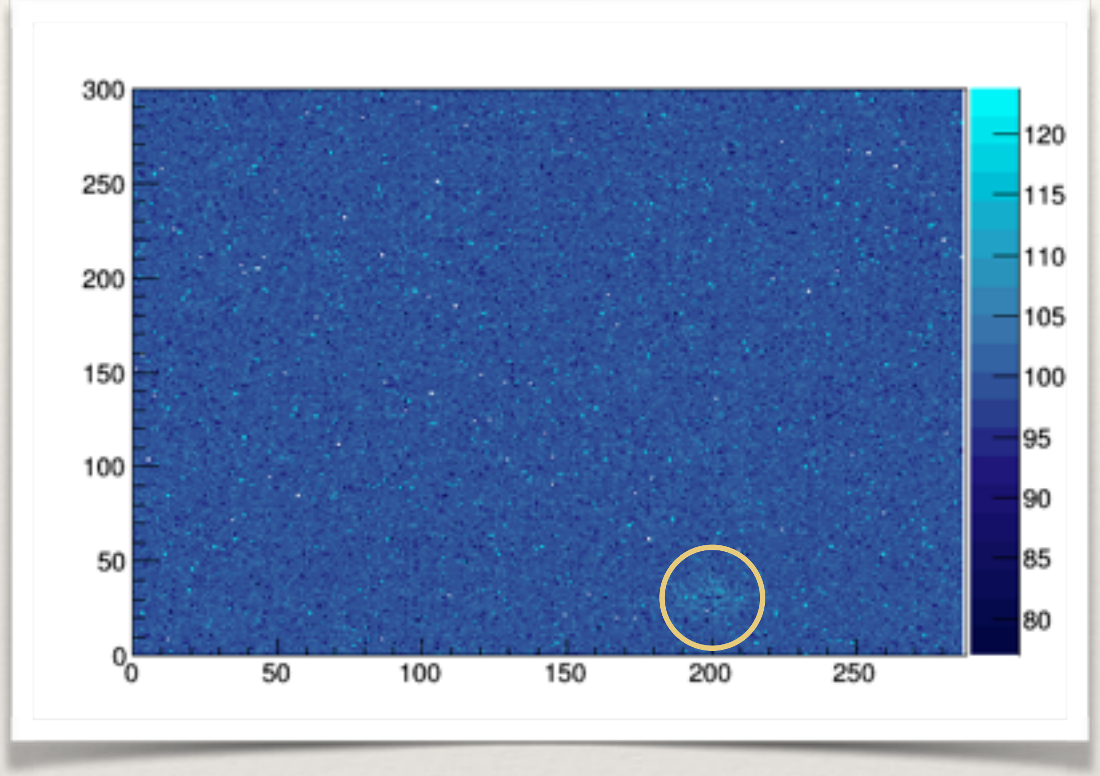


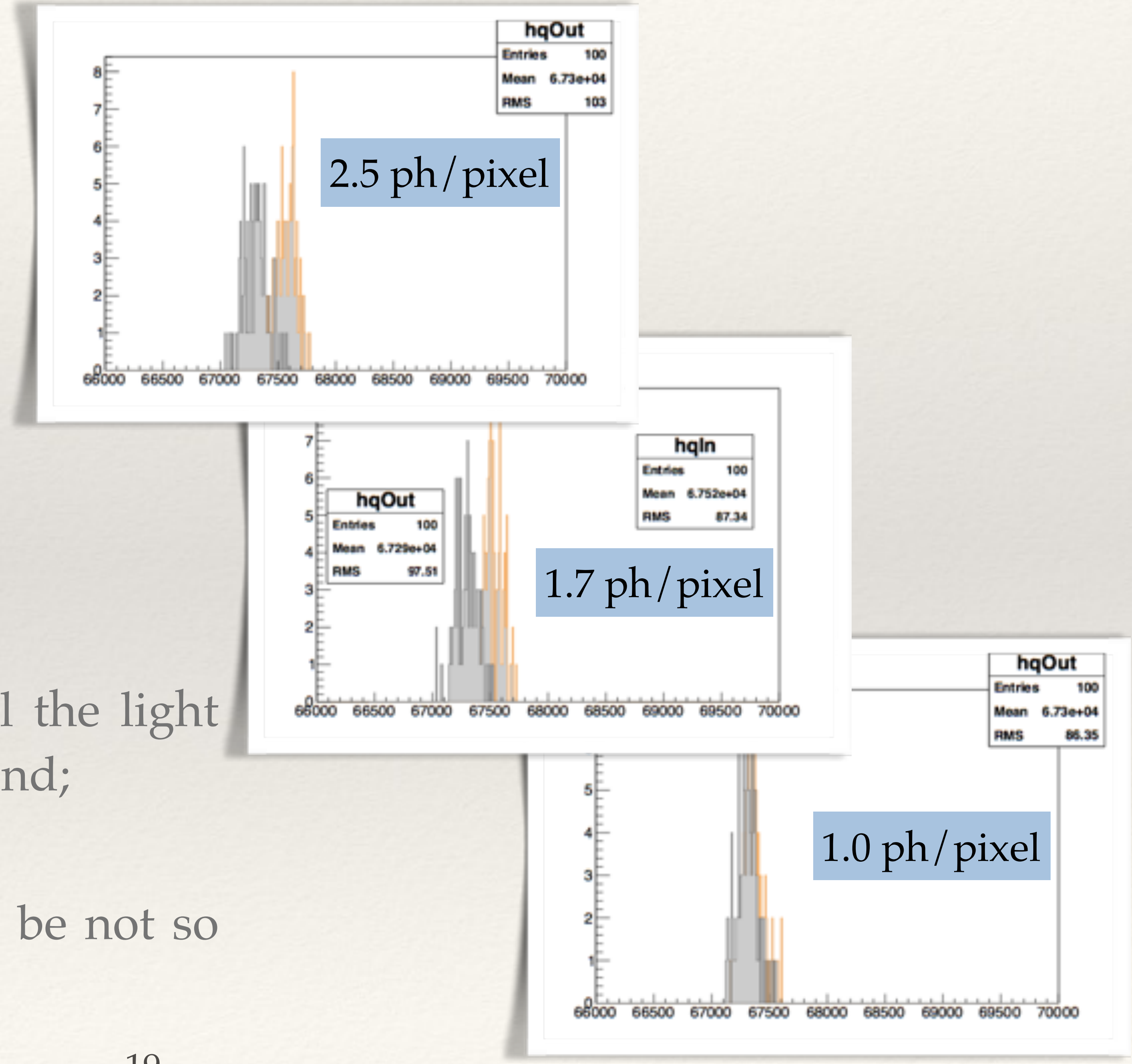
The response linearity is quite good over a large range except for a threshold behavior for small amount of photons



The CMOS-Camera

In order to test the sensitivity of this camera to a very small amount of photons, light in two identical regions in and out of the spot was measured for 100 times for different pulse instensities.



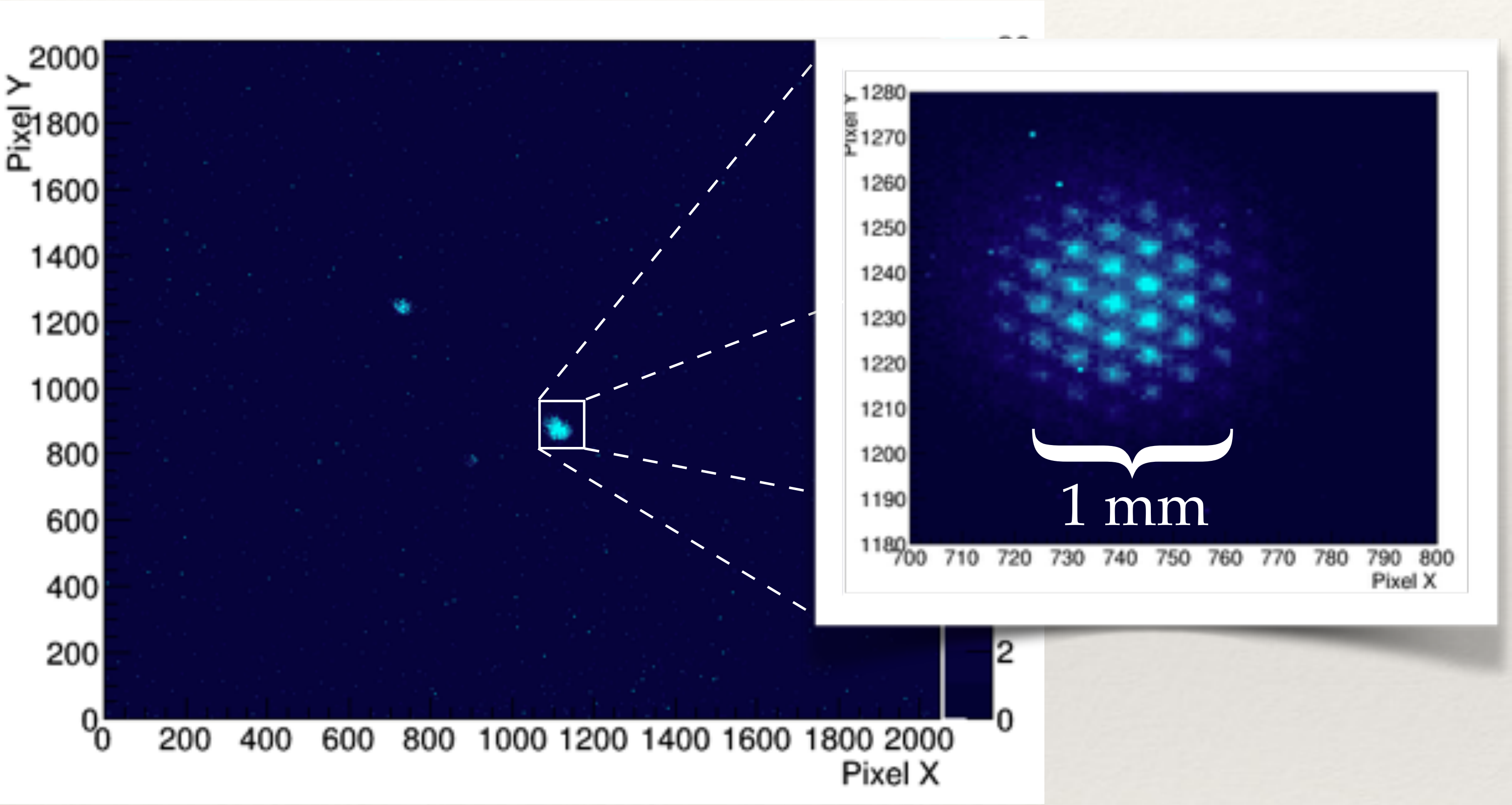


With as few as to 2.5 photons/pixel the light spot is well separated from background;

For fewer light the situation start to be not so clear;

First measurements

By using the camera we've been able to take pictures of several hot spots that appears when the three GEMs reach the high voltage working point, even without drawing a sizable leakage current;



Unfortunately, the Schneider lens broke during the measurements;

We acquired few hundreds of images while illuminating the GEM detector by means of a ^{137}Cs source.

Except from tracks due to direct interactions of photons within the CMOS sensor, so far we were not able to see light signals coming from the triple GEM detector.

Conclusion

The aim of the MONDO project is to provide a neutron dose monitor able to measure the direction and the energy of the neutrons produced during the hadron-terapy;

A detector made by a target of scintillating fibers readout by a high granularity CMOS sensor, via an image intesifier based on a triple GEM detector is under development.

The light yield of a triple-GEM detector was studied and optimised;

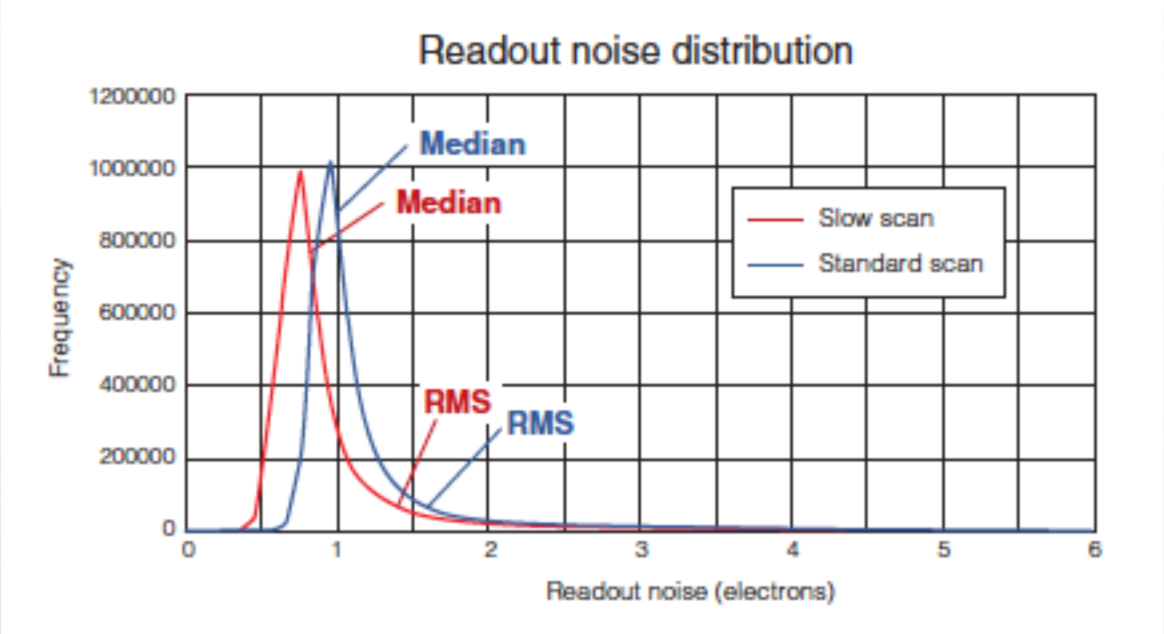
The performance of a CMOS based camera were tested and found to be very promising for our application;

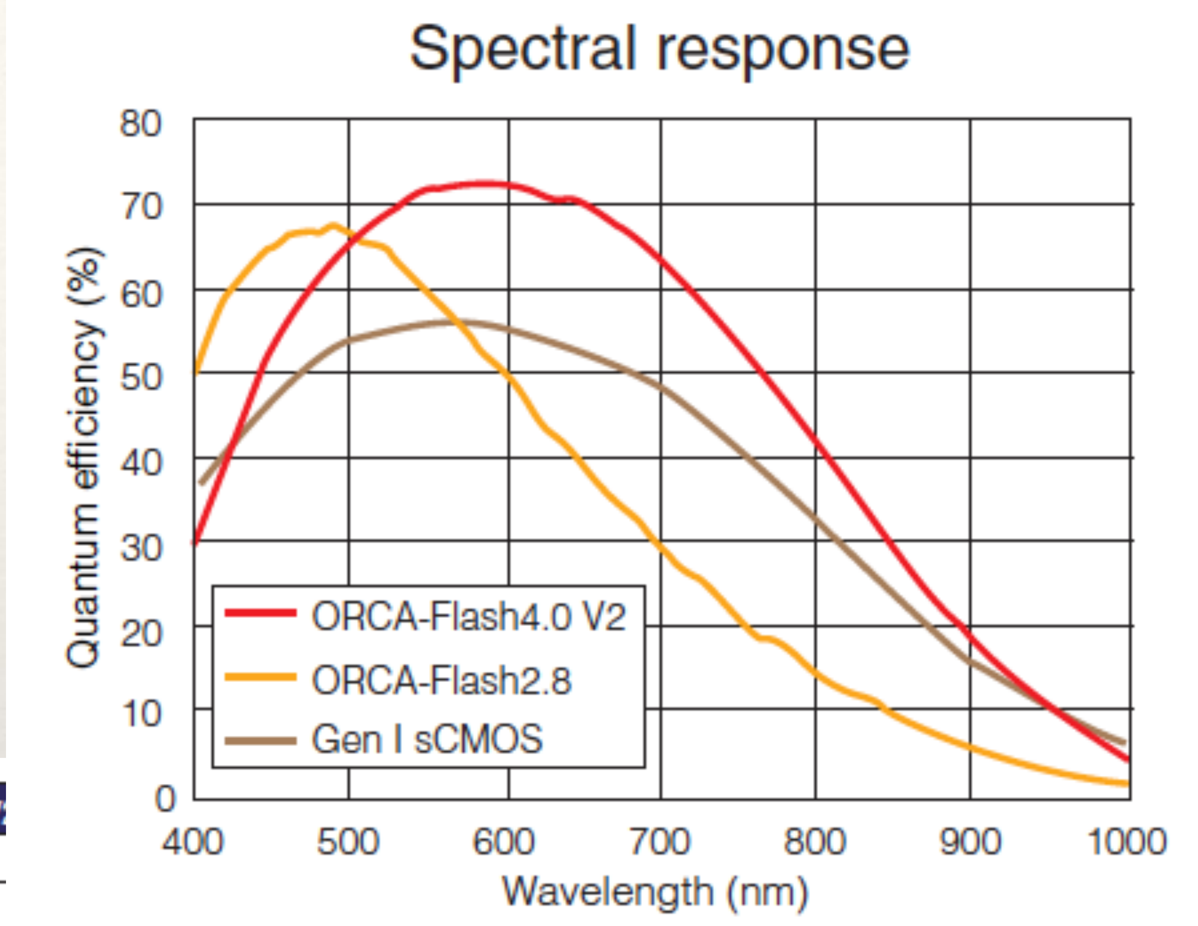
Unfortunately, so far we haven't been able to see signals from this system but the game has just started;

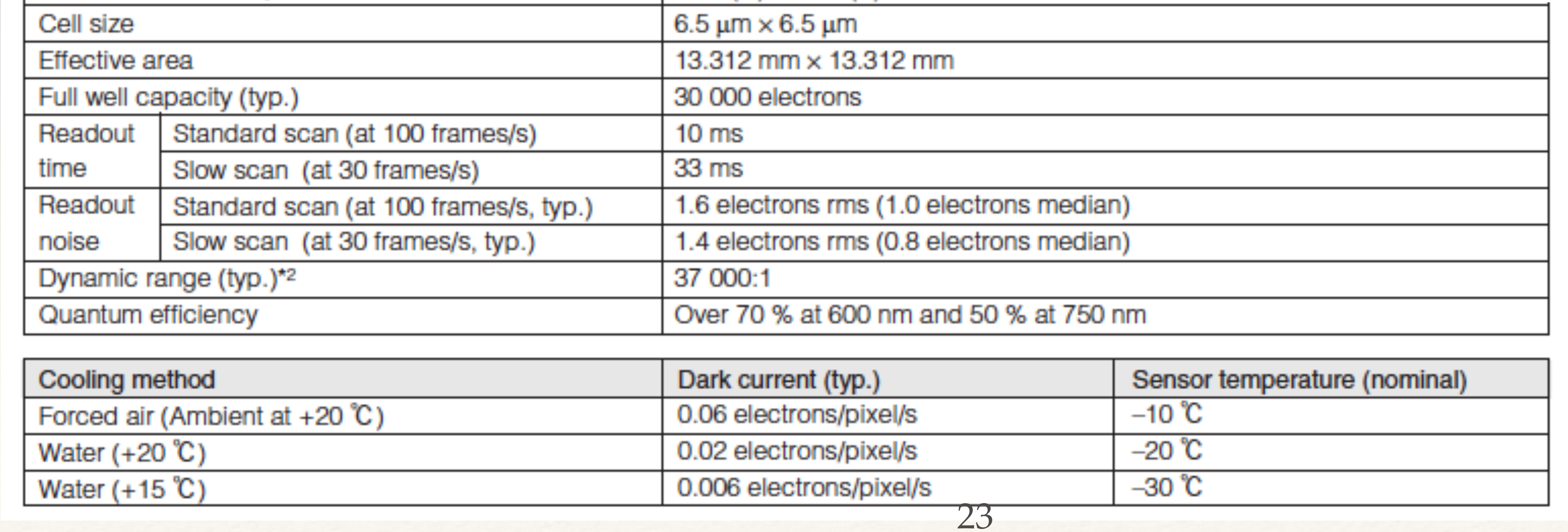
If the light is not enough we'll try to increase the amount of CF_4 in the mixture or to add a fourth GEM to the stack;

Back up

ORCA Flash 4.0







Product number		C11440-22CU (ORCA-Flash4.0 V
Imaging device		Scientific CMOS sensor FL-400
Effective number of pixels		2048(H) × 2048(V)
Cell size		6.5 µm × 6.5 µm
Effective area		13.312 mm × 13.312 mm
Full well capacity (typ.)		30 000 electrons
Readout time	Standard scan (at 100 frames/s)	10 ms
	Slow scan (at 30 frames/s)	33 ms
Readout noise	Standard scan (at 100 frames/s, typ.)	1.6 electrons rms (1.0 electrons median)
	Slow scan (at 30 frames/s, typ.)	1.4 electrons rms (0.8 electrons median)
Dynamic range (typ.)*2		37 000:1
Quantum efficiency		Over 70 % at 600 nm and 50 % at 750 nm

Cooling method	Dark current (typ.)	Sensor temperature (nominal)
Forced air (Ambient at +20 ℃)	0.06 electrons/pixel/s	–10 ℃
Water (+20 ℃)	0.02 electrons/pixel/s	–20 ℃
Water (+15 ℃)	0.006 electrons/pixel/s	–30 ℃

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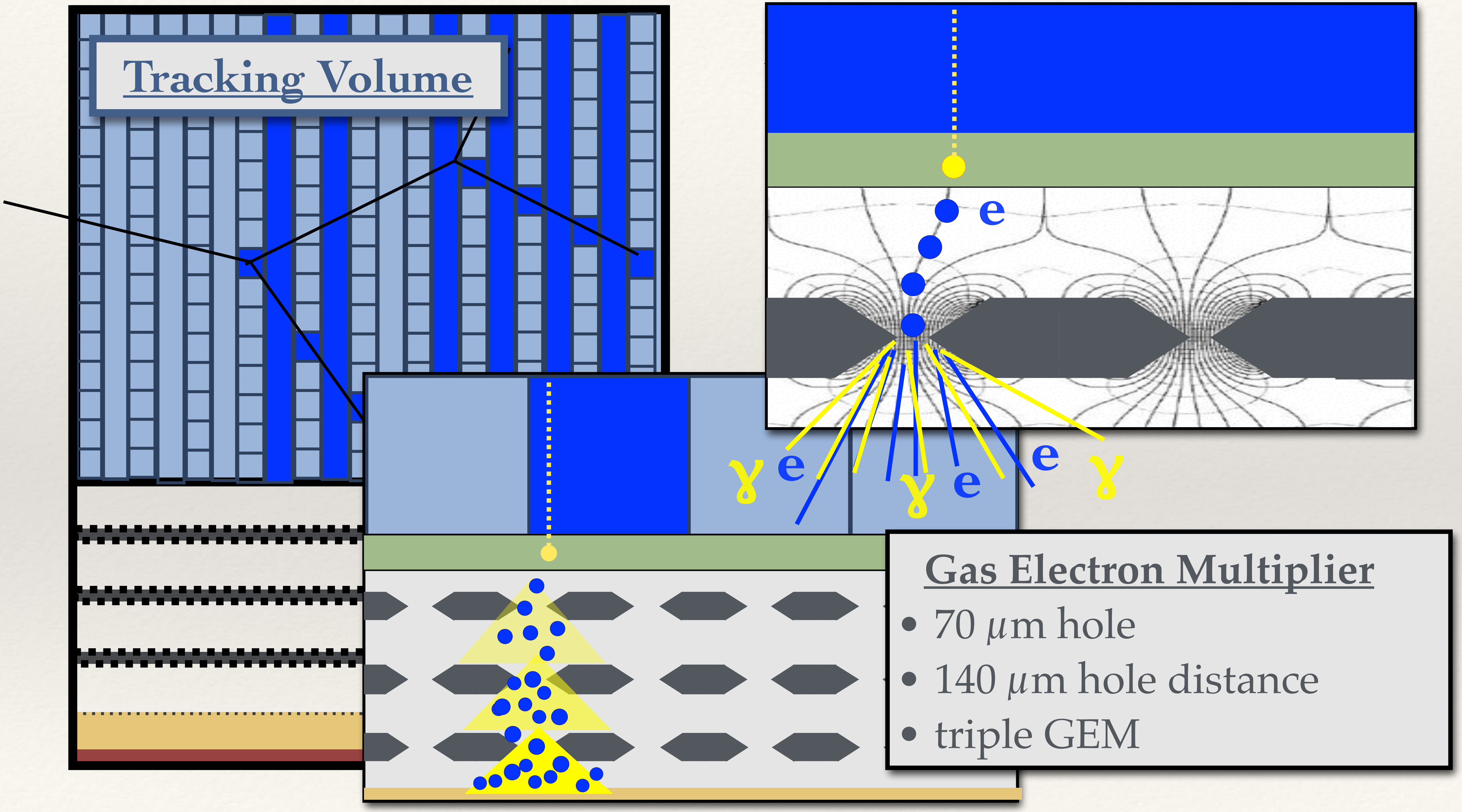
Image Intensifier

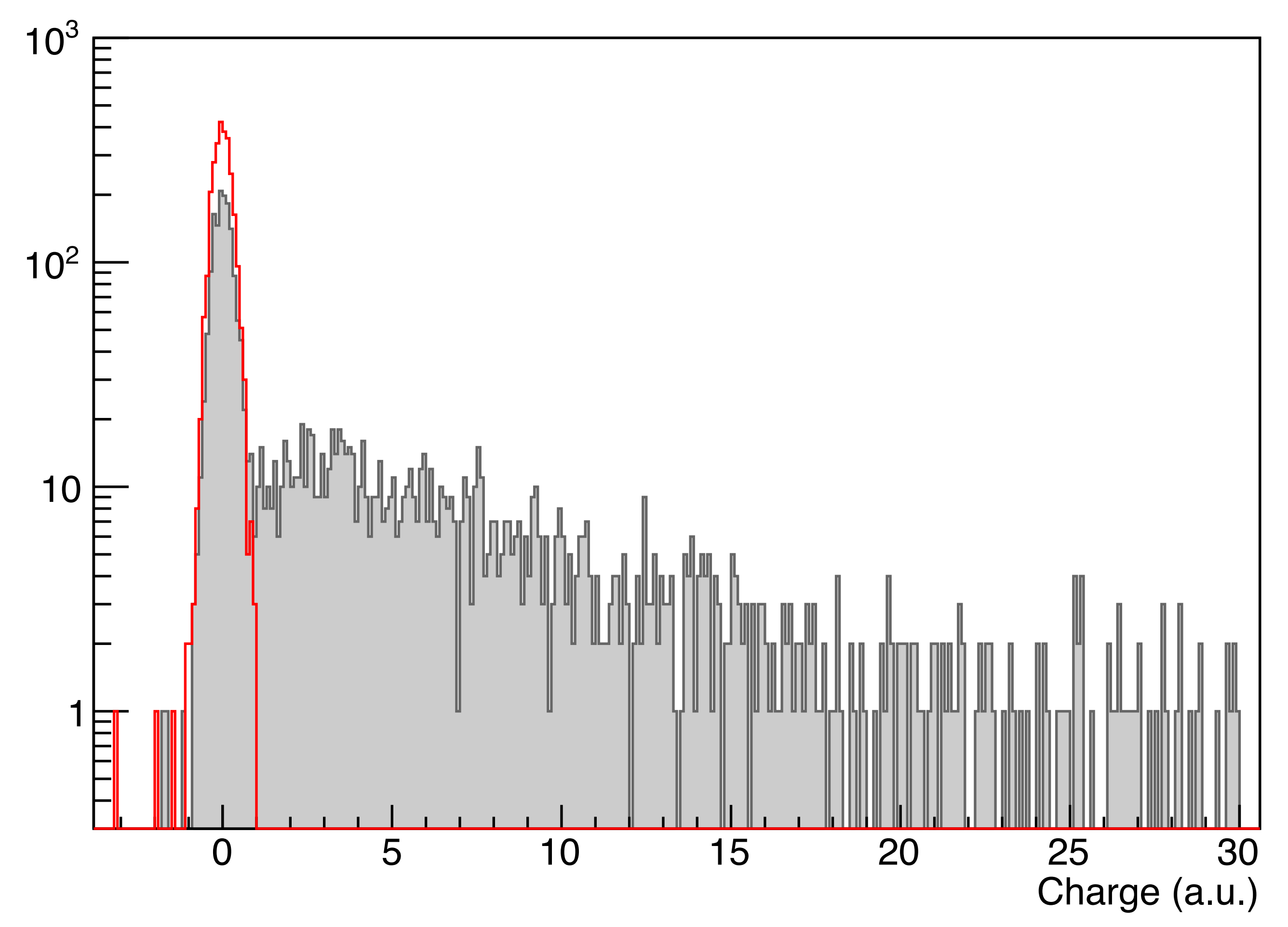


Gas Electron Multiplier

- 70 μm hole
- 140 μm hole distance
- triple GEM

Charge spectra

The waveforms were numerically integrated to evaluate the total collected charge



Example of a charge spectrum obtained with $V_{GEM} = 360$ V;

The pedestal is evaluated in a similar gate before the trigger signal;