HIGH RESOLUTION TPC BASED ON OPTICALLY READOUT GEM

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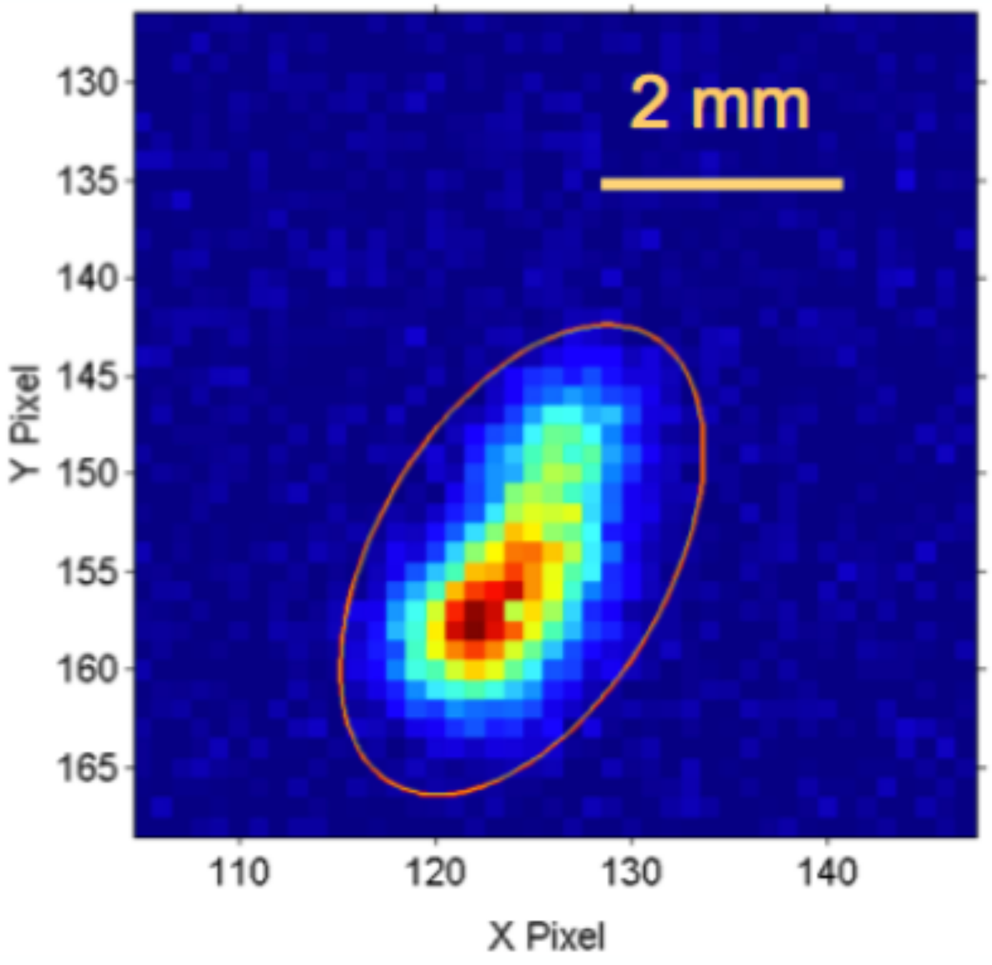
WHY TPC?

Time projection chambers provide:

- 3D tracking (position and direction);
- total released energy measurement;
- dE/dx profile (pid, head-tail);
- reduced readout channel number;

Nuclear recoil in gas



Gas represents an interesting target:

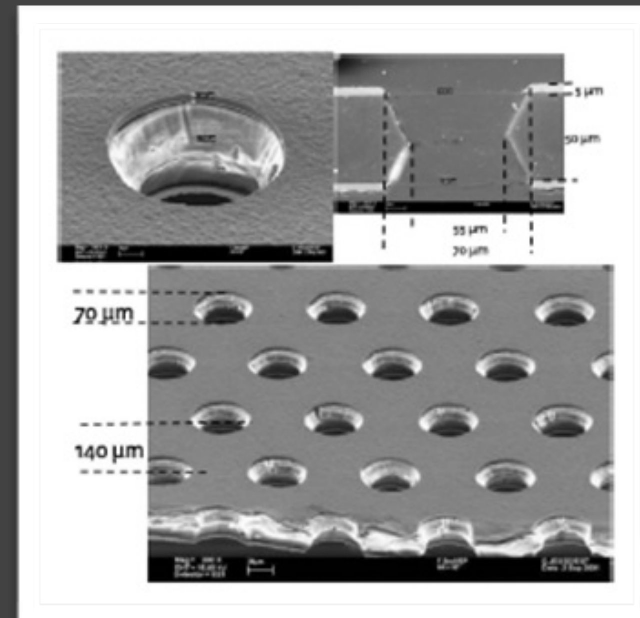
- Nuclei free path can be long enough to be reconstructed;
- Low mass gases allow an efficient momentum transfer from light DM;

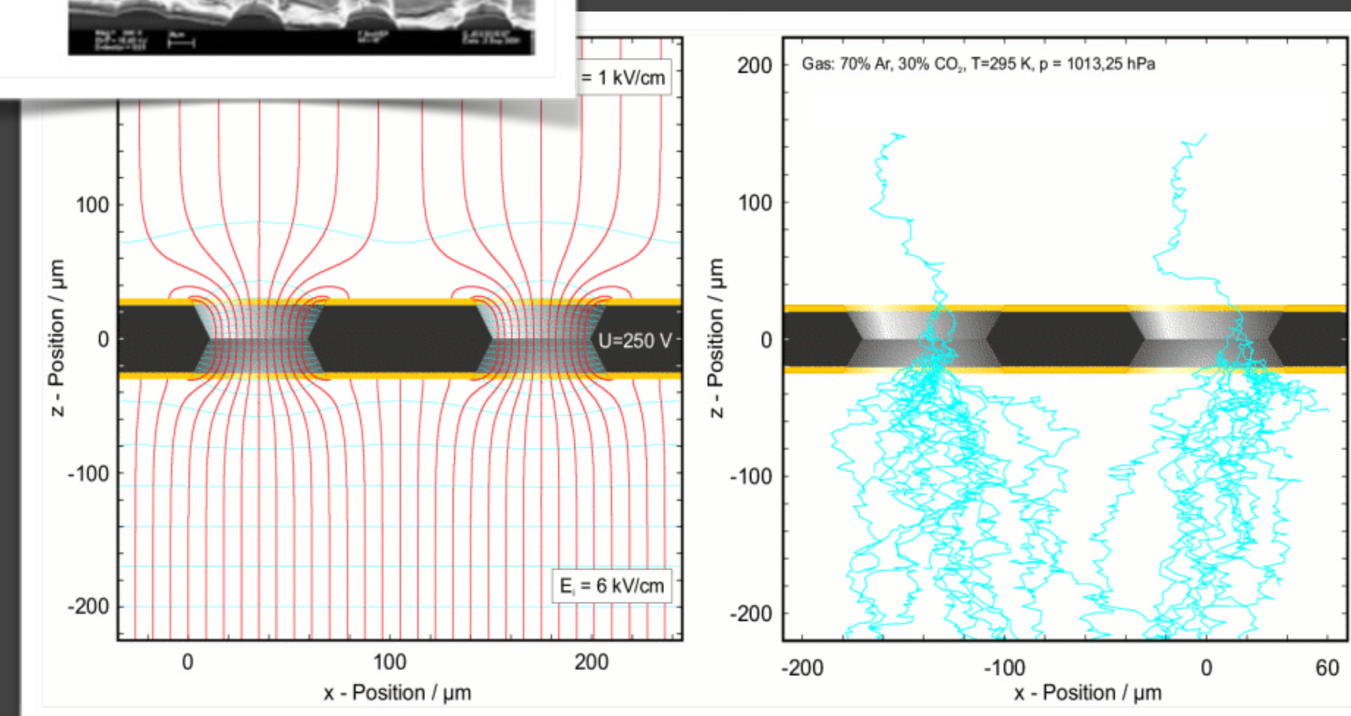
- Avalanche mechanism allows a sensitivity to single primary electrons (i.e. energy release of 30-40 eV);

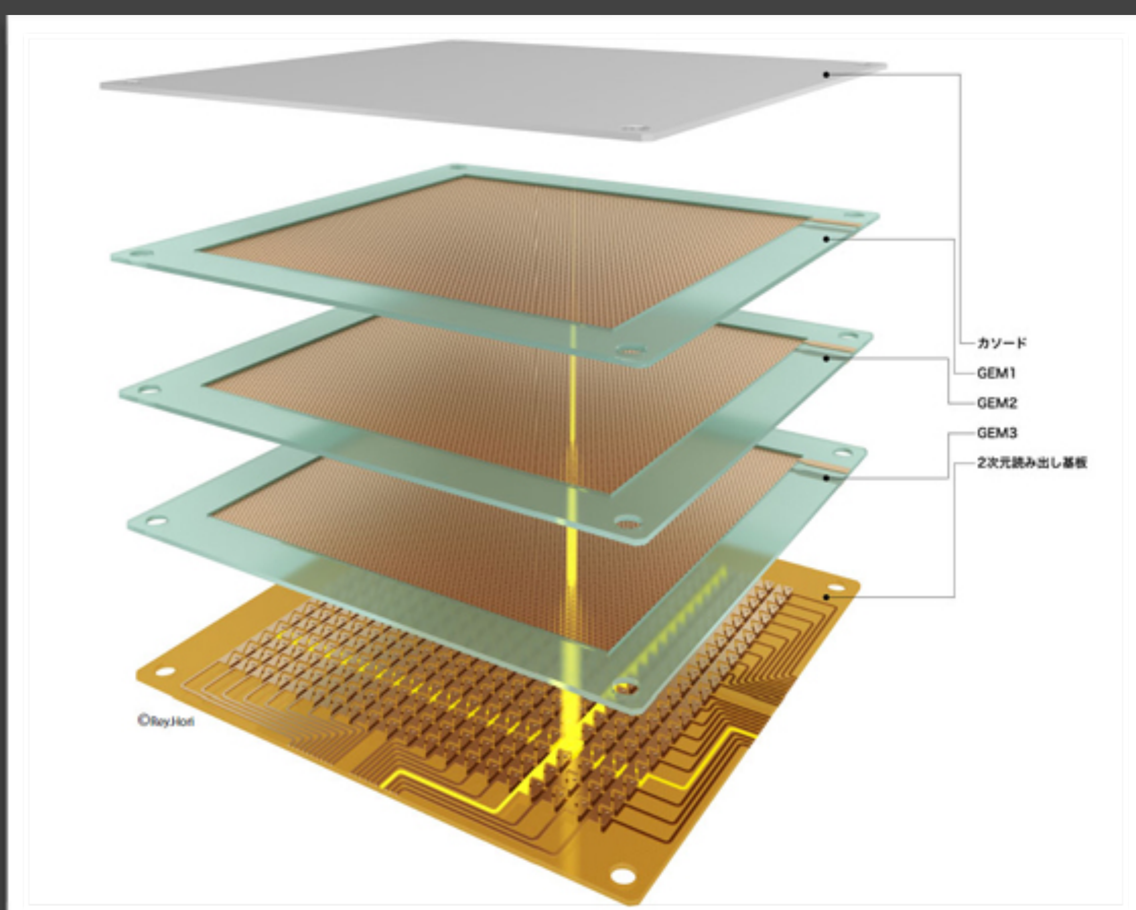
GEM: PRINCIPLE OF OPERATION

Two external electric fields:

- make primary electrons drift toward the GEM;
- extract secondary electrons from the multiplication channels.





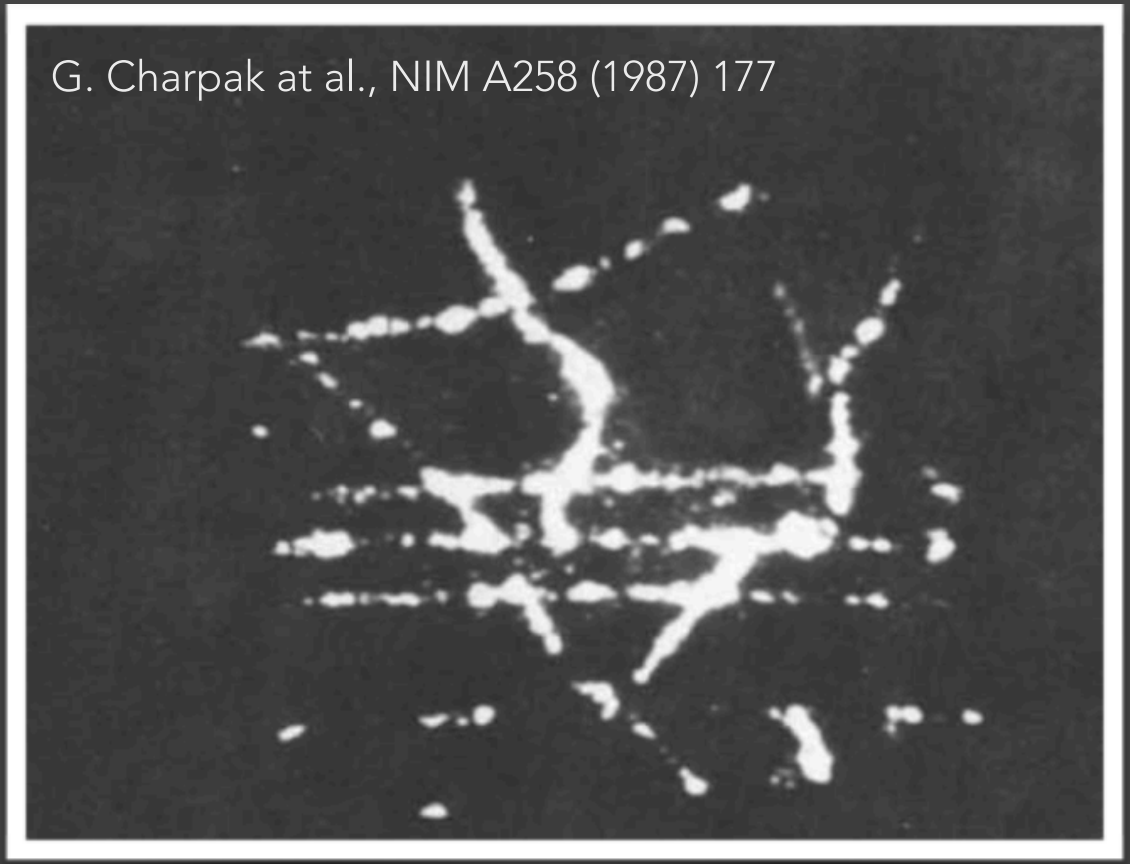


Multiple GEM structures can be used to share the gain and make more stable detectors.

LIGHT: A CHANGE OF PARADIGM

During the multiplication process, photons are produced along with electrons by the gas through atomic and molecular de-excitation;

We propose to readout the light instead of electric signal.



Optical readout of gas detectors offers several advantages:

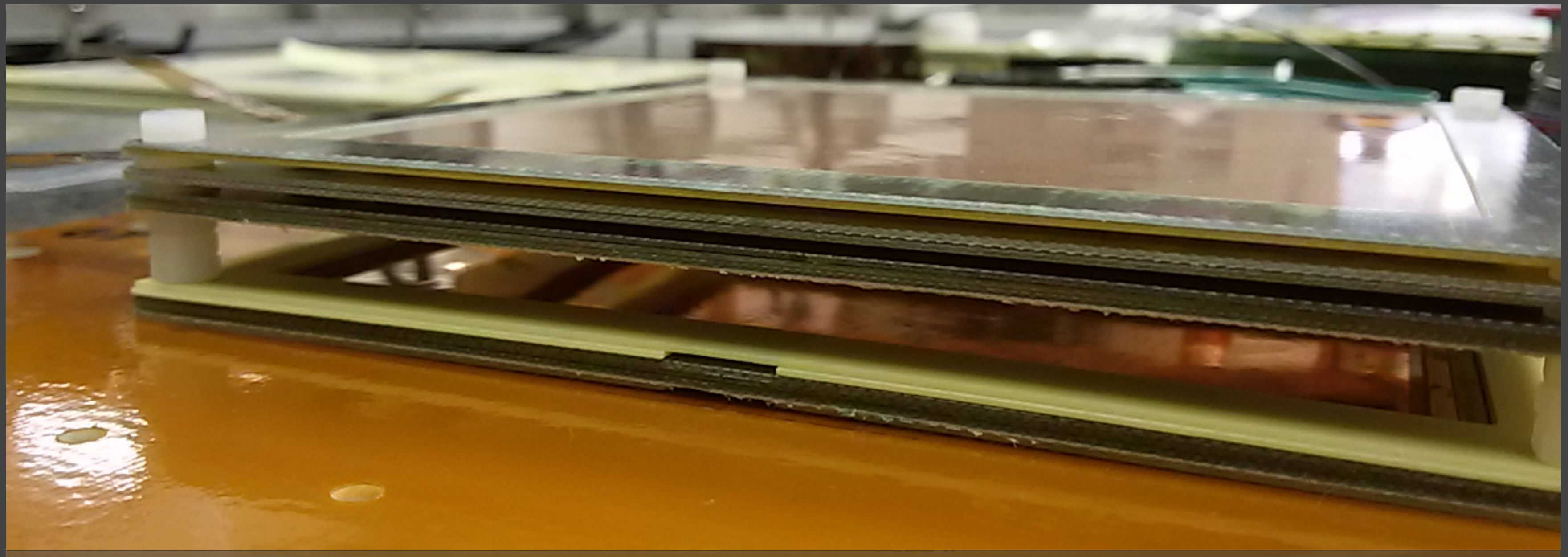
- optical sensors are able to provide high granularities along with very low noise level and high sensitivity;
- optical coupling allows to keep sensor out of the sensitive volume (no interference with HV operation and lower gas contamination);
- suitable lens allow to acquire large surfaces with small sensors;

ORANGE

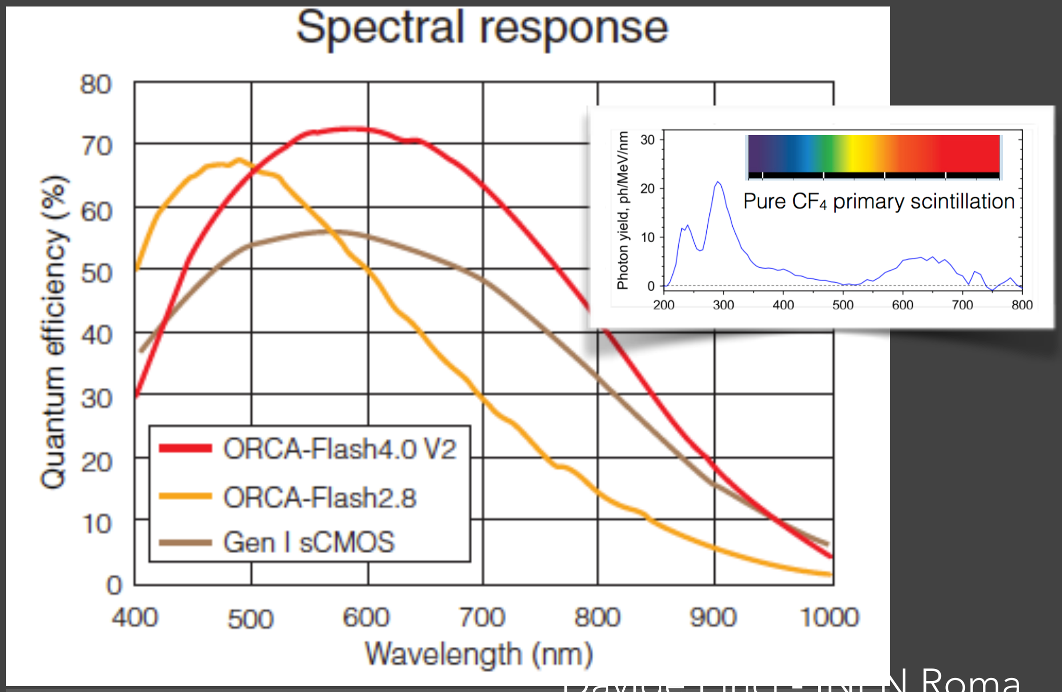
An Optically ReAdout GEM (ORAnGE) device was assembled in 2015;

Triple GEM structure ($10x10\ cm^2$) with 1 cm sensitive gap.

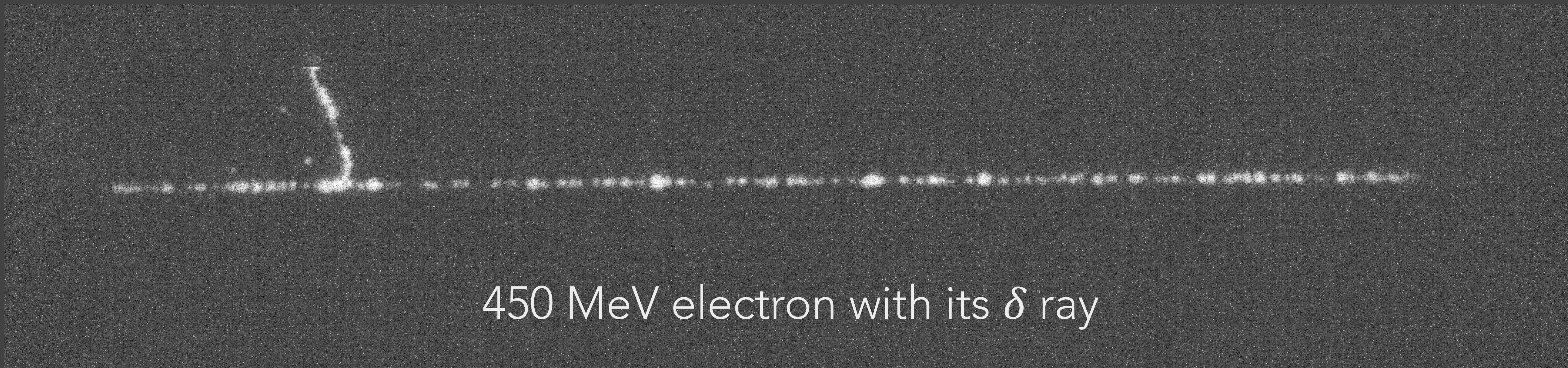
An He/CF_4 (60/40) mixture was used.

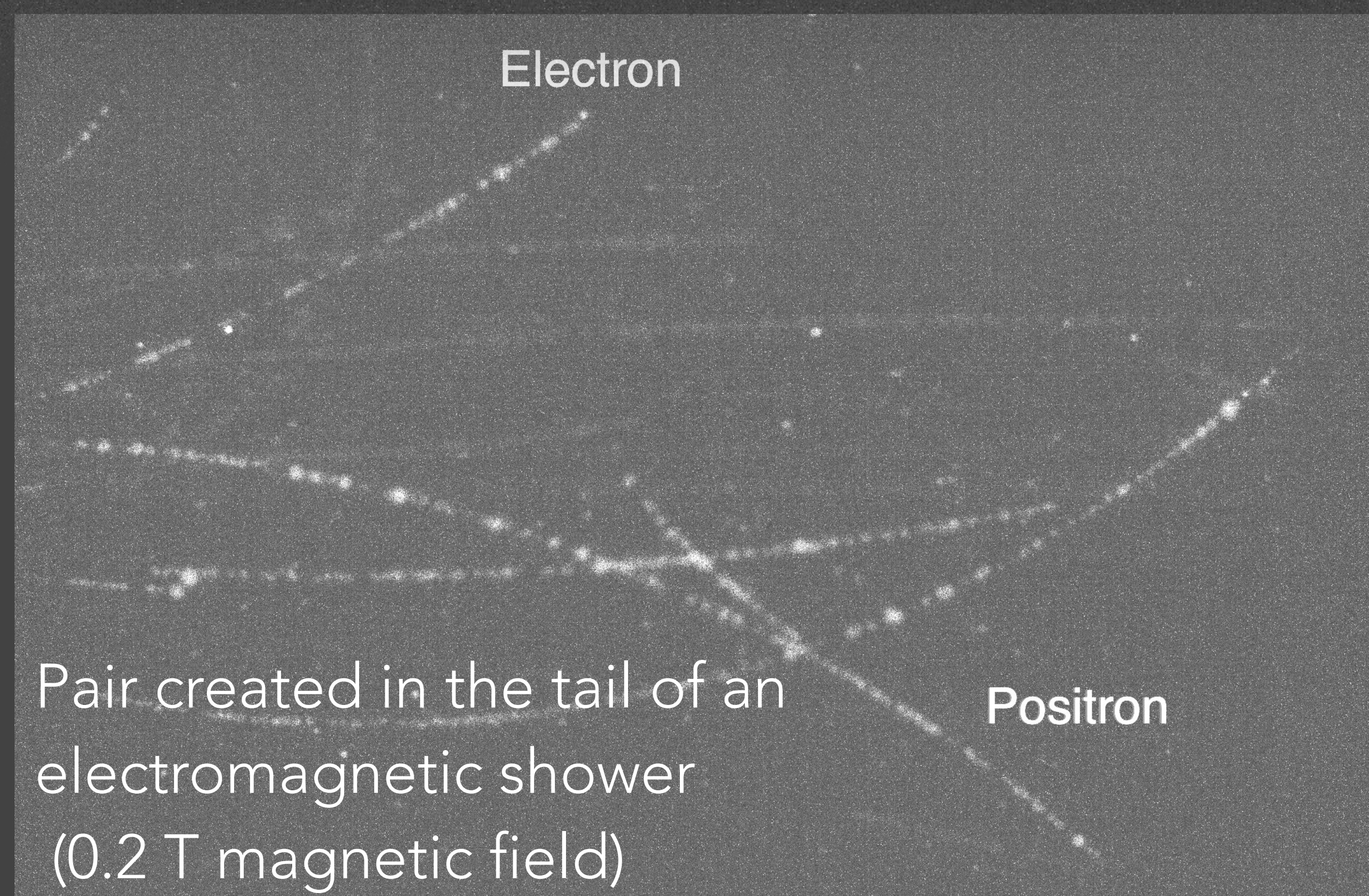


sCMOS sensors provide very low noise and high granularity and sensitivity

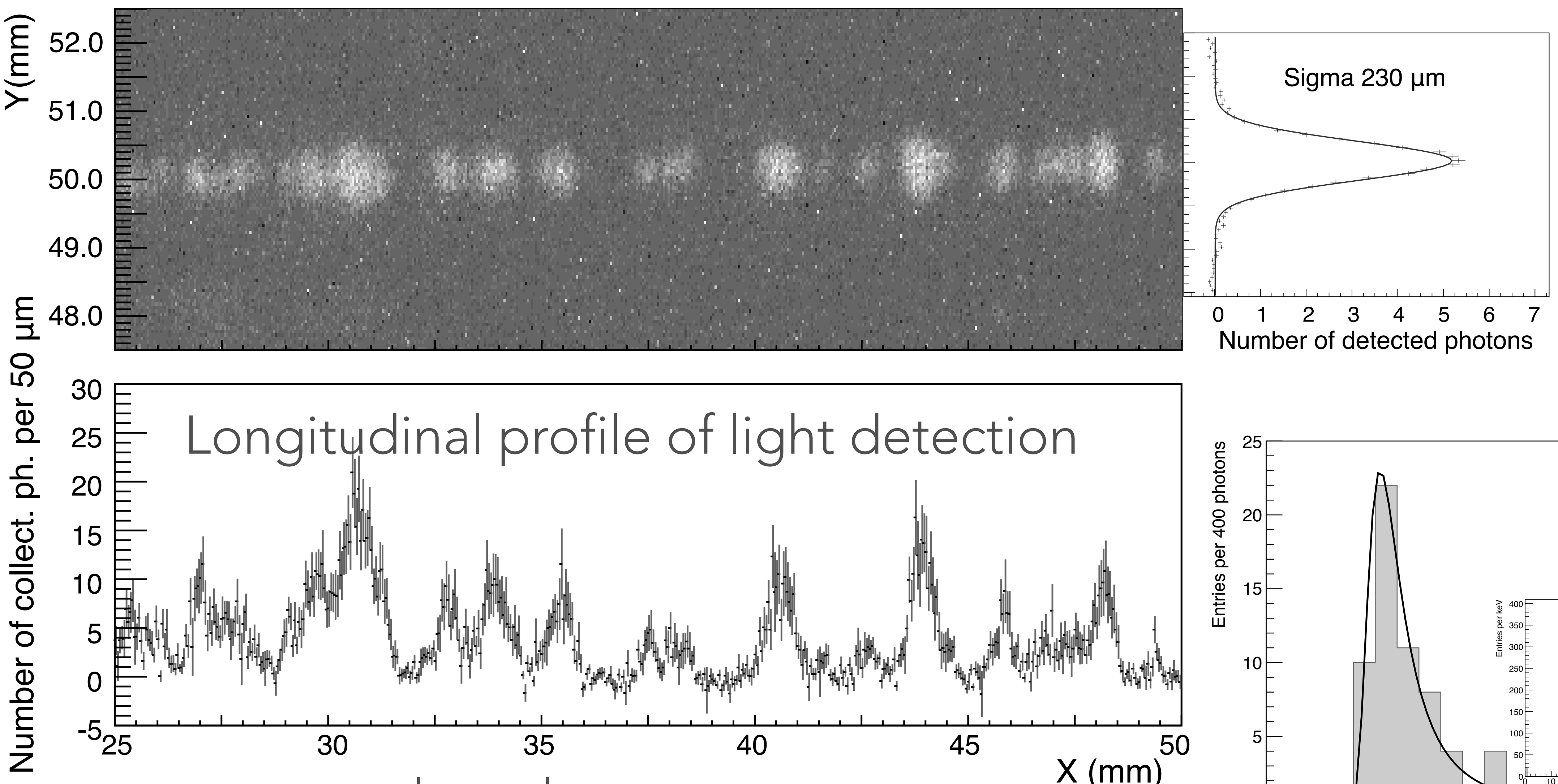


PARTICLE TRACKS



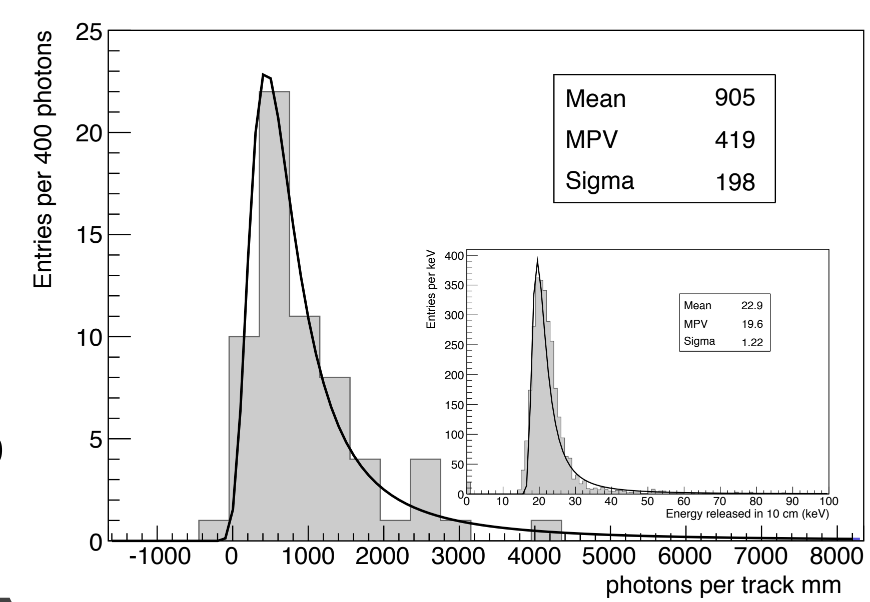


TRACKING PERFORMANCE



Longitudinal profile of light detection

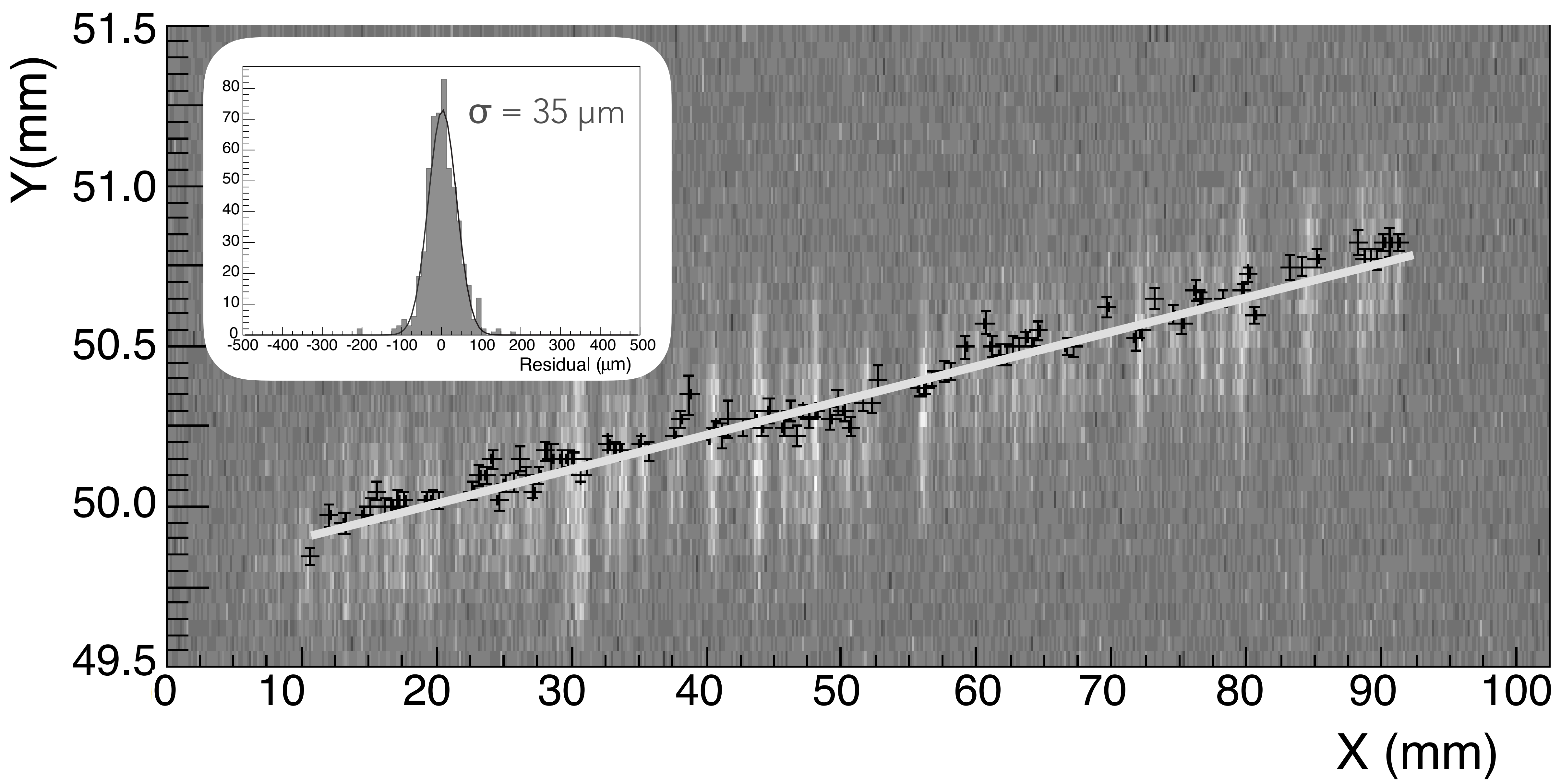
clear cluster structure



About 1000 detected photons per track millimetre (i.e. 230 eV).

In average, 7 primary electrons are ionized per mm: i.e. 150 ph/el.

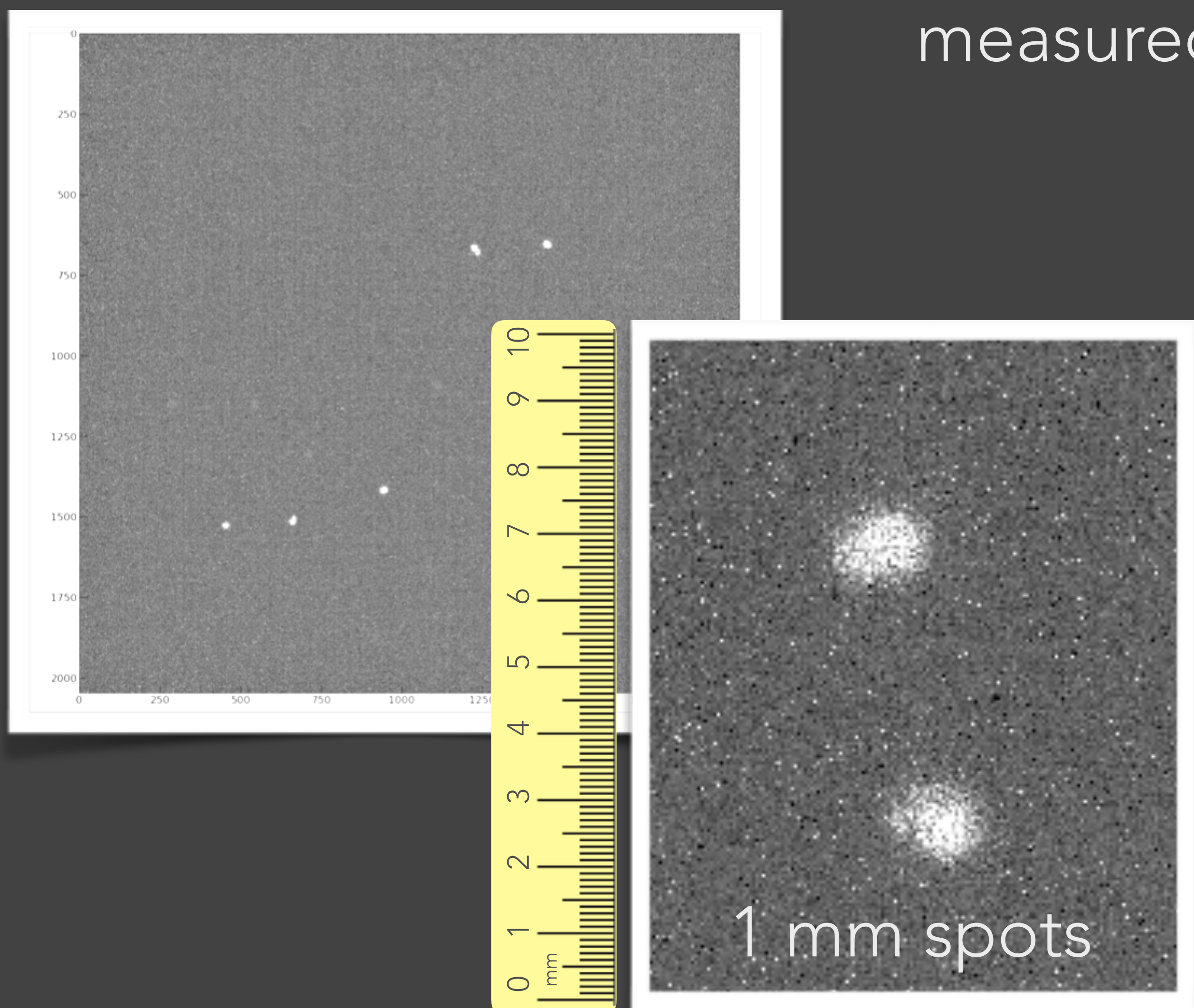
TRACKING PERFORMANCE

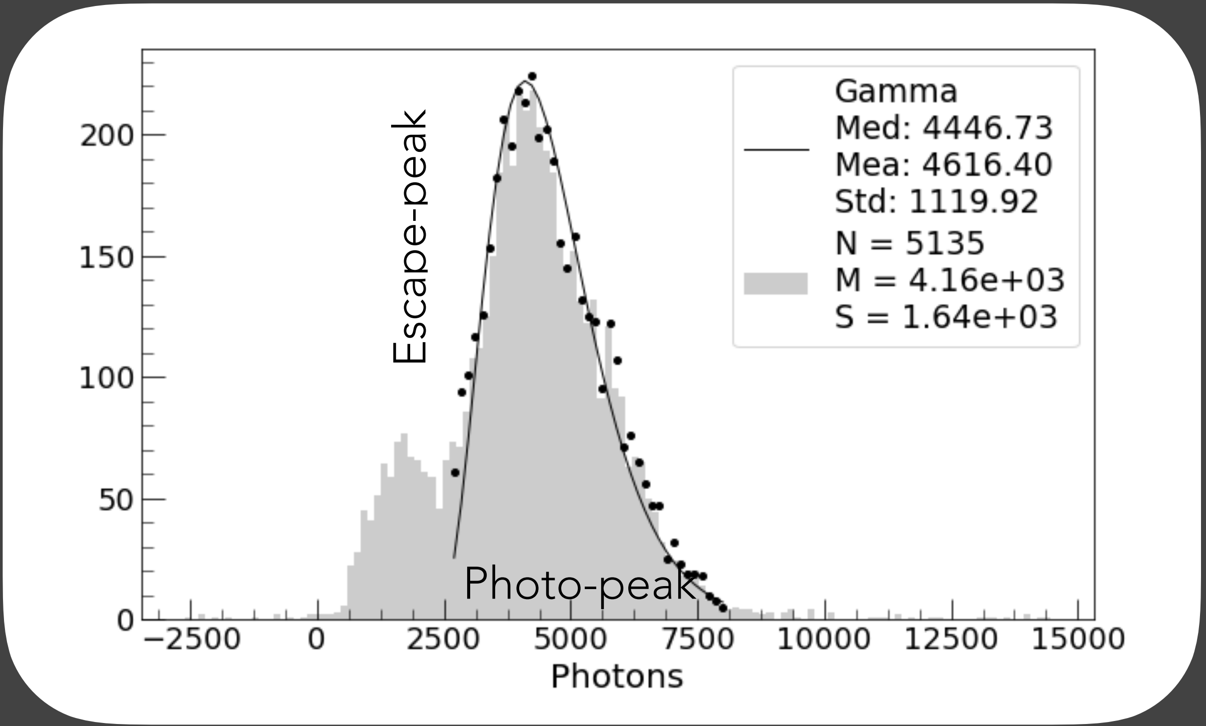


Space resolution of about 35 μm was evaluated from track cluster residuals.

X-RAYS FROM A ^{55}FE SOURCE

The light response to 5.9 keV photons from a ^{55}Fe was measured for several He/CF_4 mixtures.



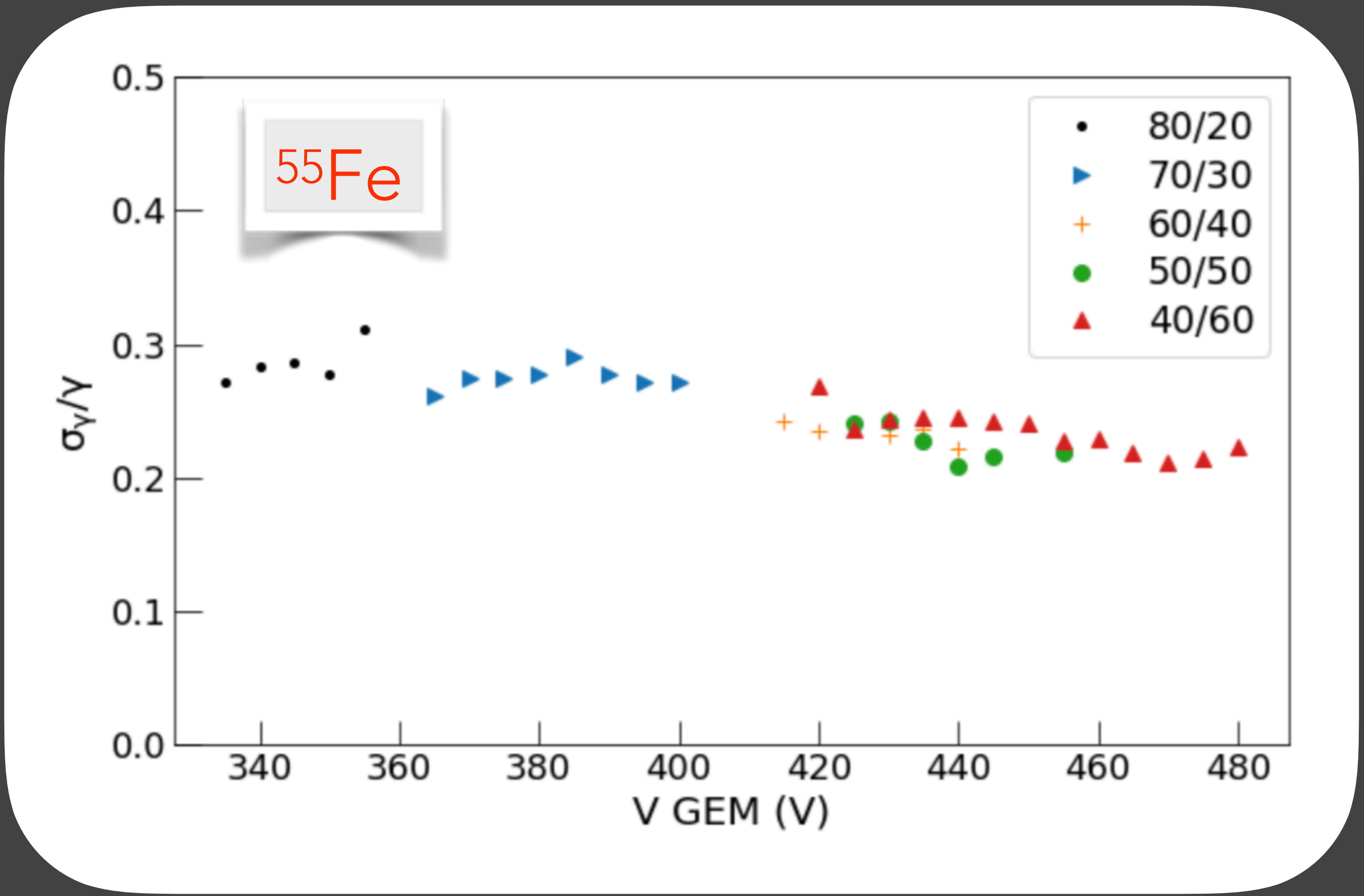


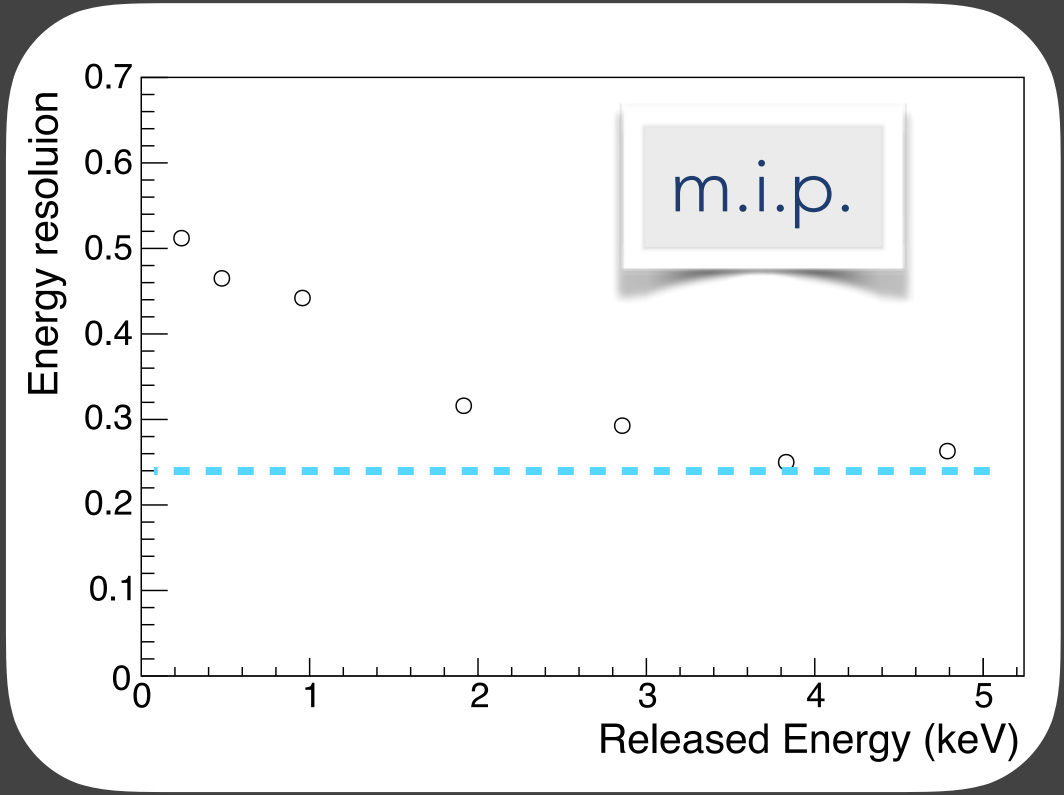
Peak positions and widths were evaluated by a Polya fit

We used a Hough transform to individuate spots and measure their dimension and light yield.

ENERGY RESOLUTION

An energy resolution between 20% and 30% is achieved for releases of 5.9 keV;



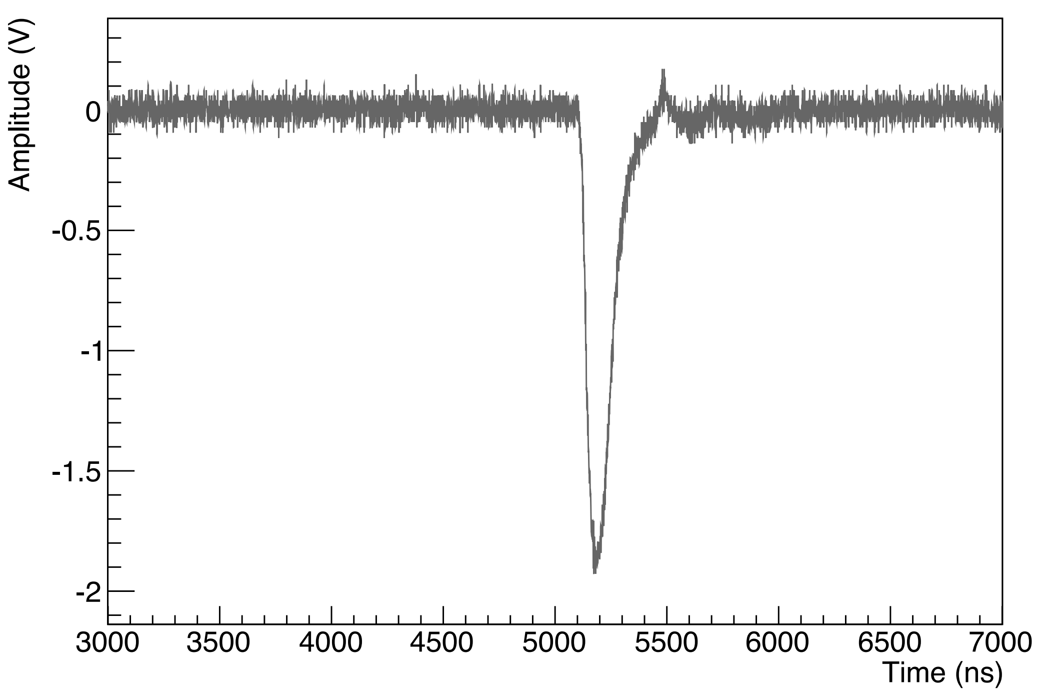


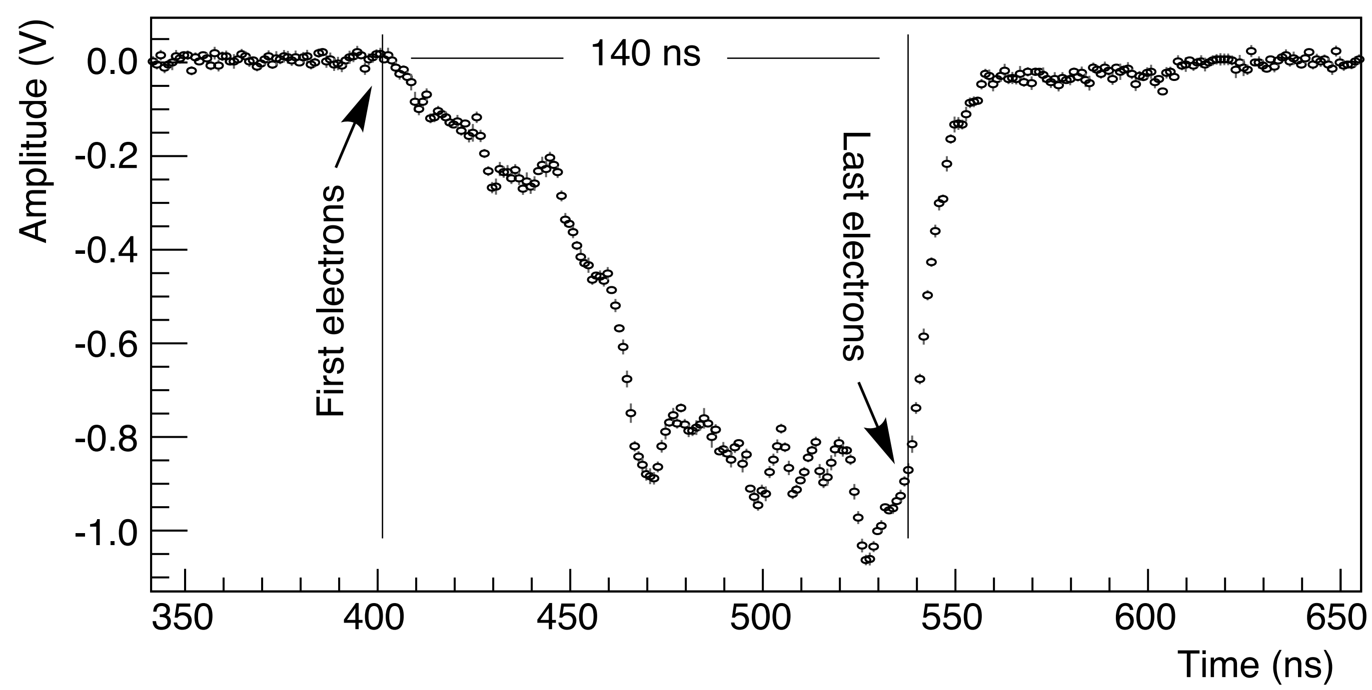
This result is in good agreement with what was evaluated subdividing mip tracks in "slices" of various widths (1 mm - 2 cm) with an released energy simulated by Garfield of 2.4 keV/cm;

COMBINED LIGHT READOUT

Sensitive gap parallel to the beam

Sensitive gap tilted w.r.t. the beam



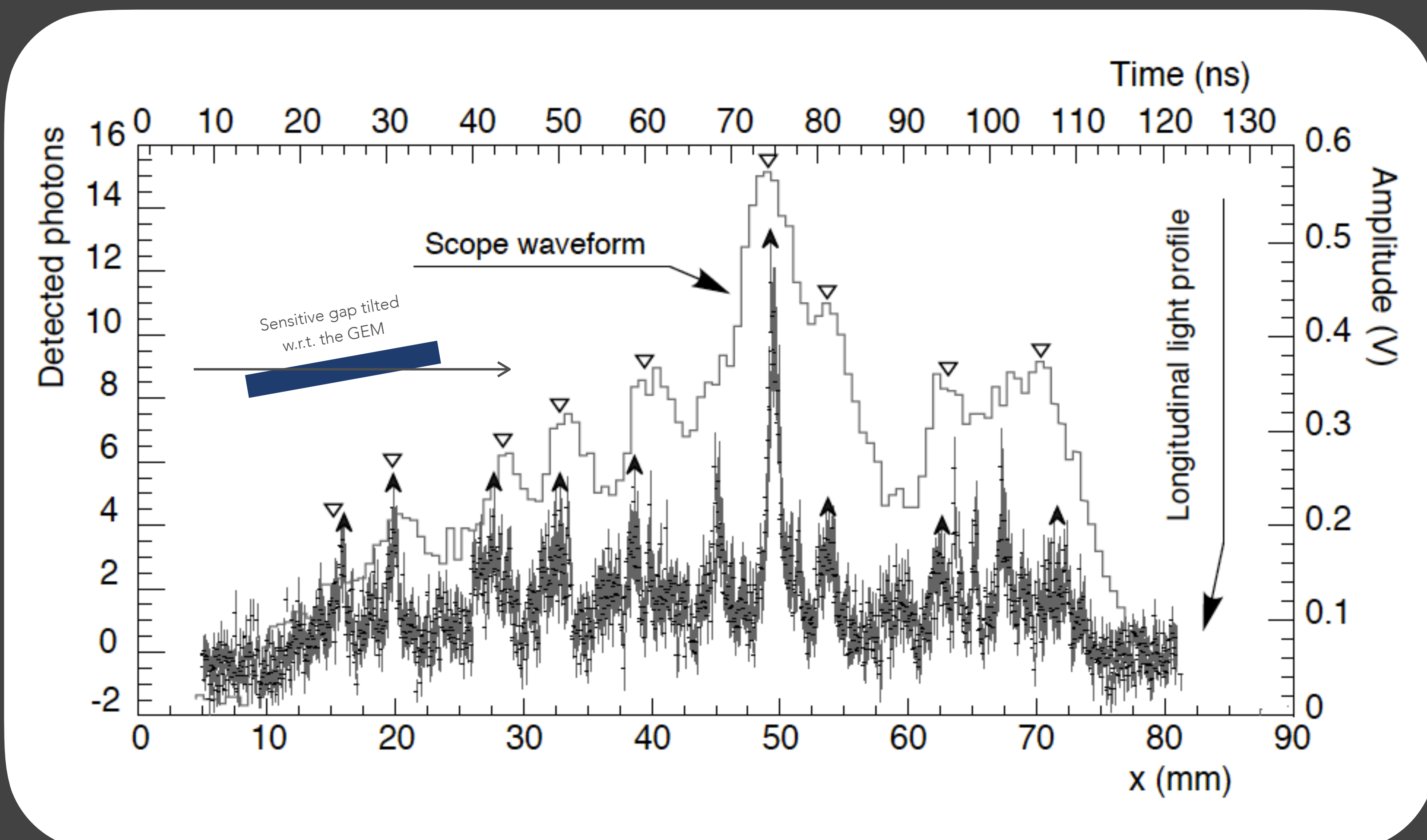


1 cm in 140 ns => drift velocity 7.2 cm/μs in agreement with Garfield expectation of 7.3 cm/μs.

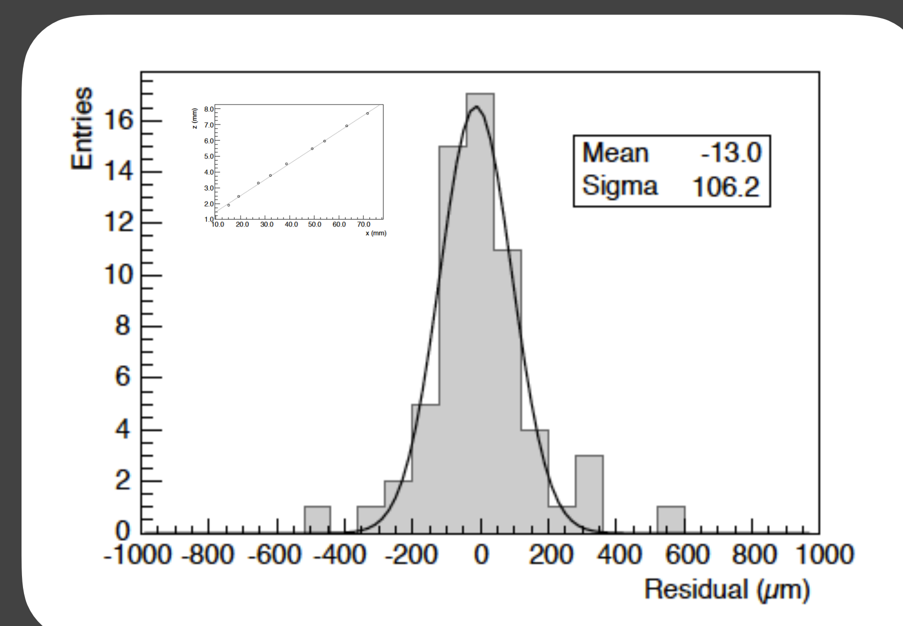
PMT+CMOS COMBINED READOUT

Single cluster 3D position reconstruction can be obtained by comparing the light profile along the track (X, Y) and the PMT waveform (t);

A peak finding algorithm was used to highlight the main cluster signals;



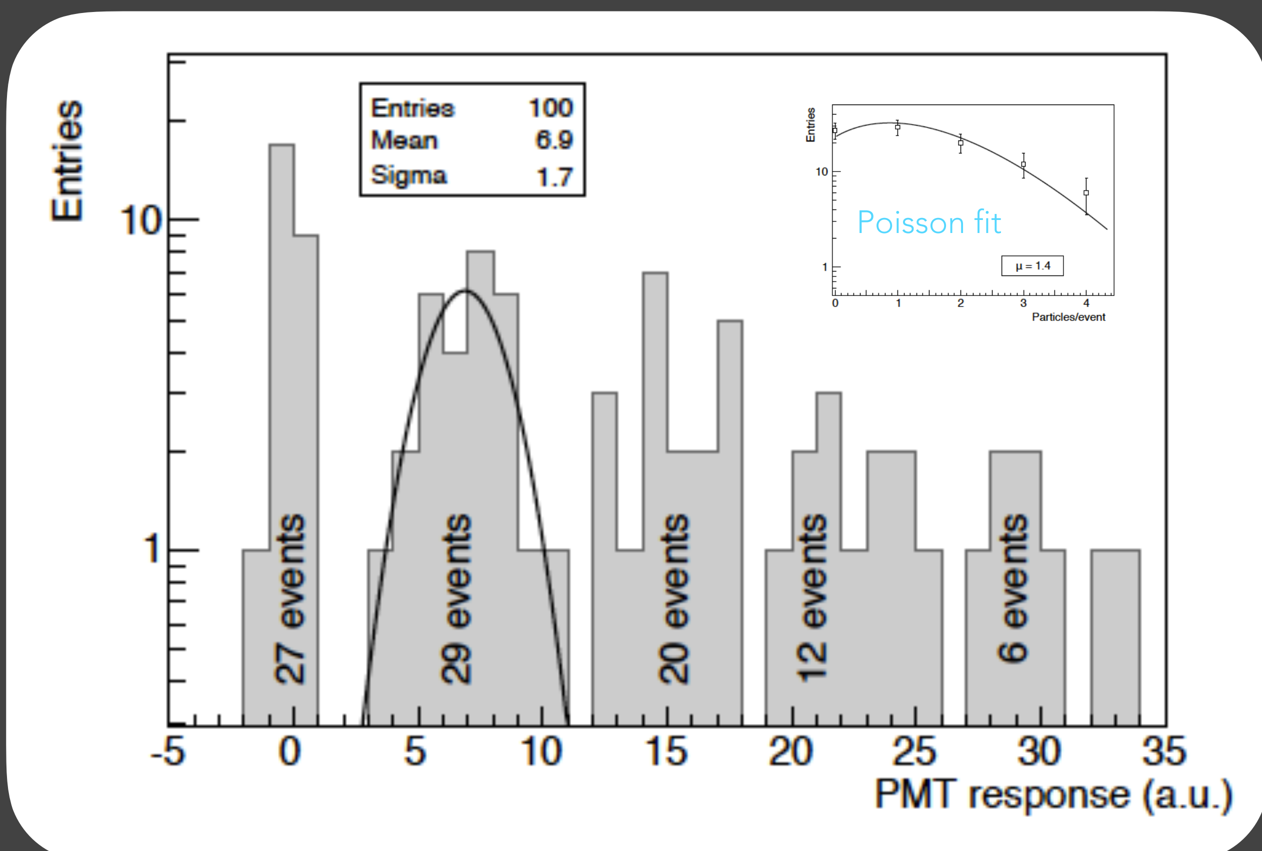
By means of the measured drift velocity, Z coordinate was evaluated;



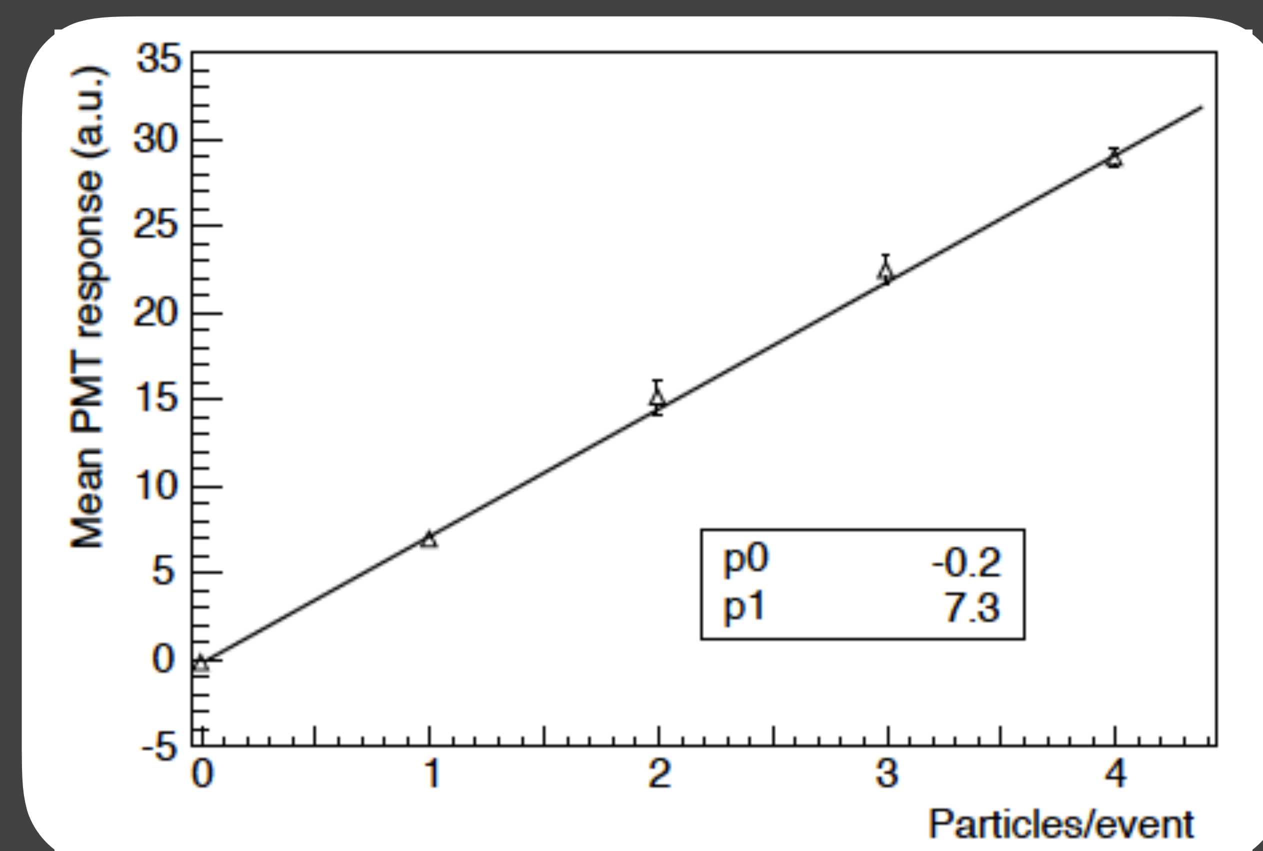
Residual distribution to a 3D fit allows to compute a resolution on Z of 100 μm.

PMT READOUT: ENERGY RESOLUTION

By studying the PMT response, it was possible to easily individuate the different number of particle in each event.



PMT readout is able to provide a resolution on the total released energy (23 keV) of 26 %



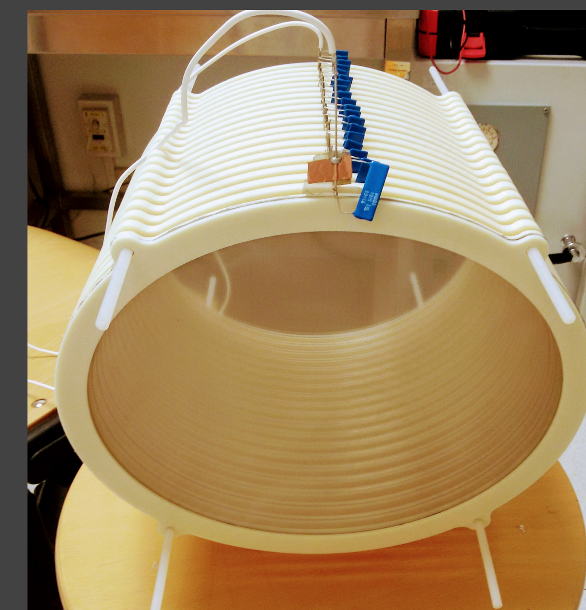
A very good linearity was found.

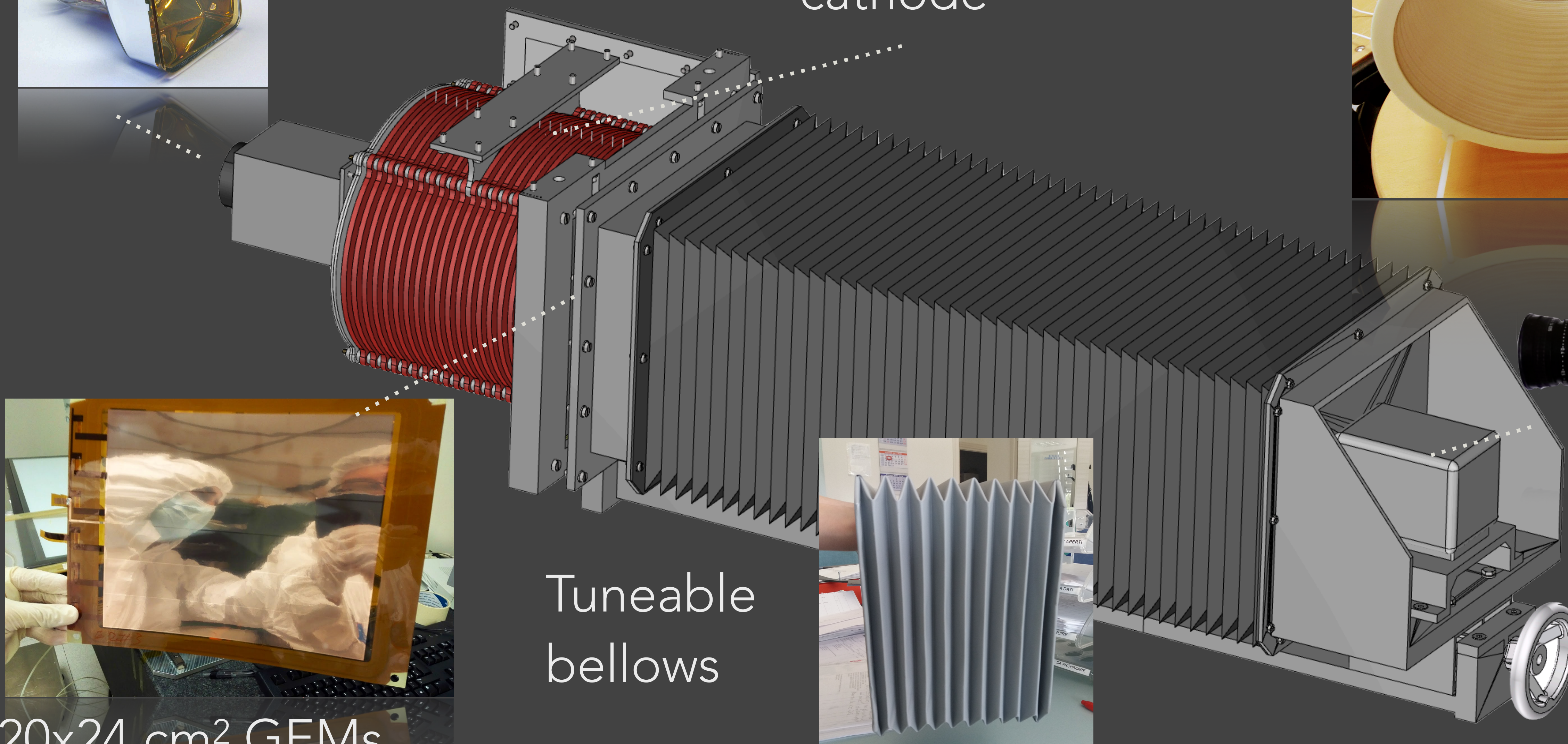
LARGE PROTOTYPE

A new prototype with 7 litre sensitive volume (LEMOn: Large Elliptical Module Optically readout) was built in 2017 tested on electron beam in July.

7x7 cm^2 PMT

Elliptical field cage with semi-transparent cathode



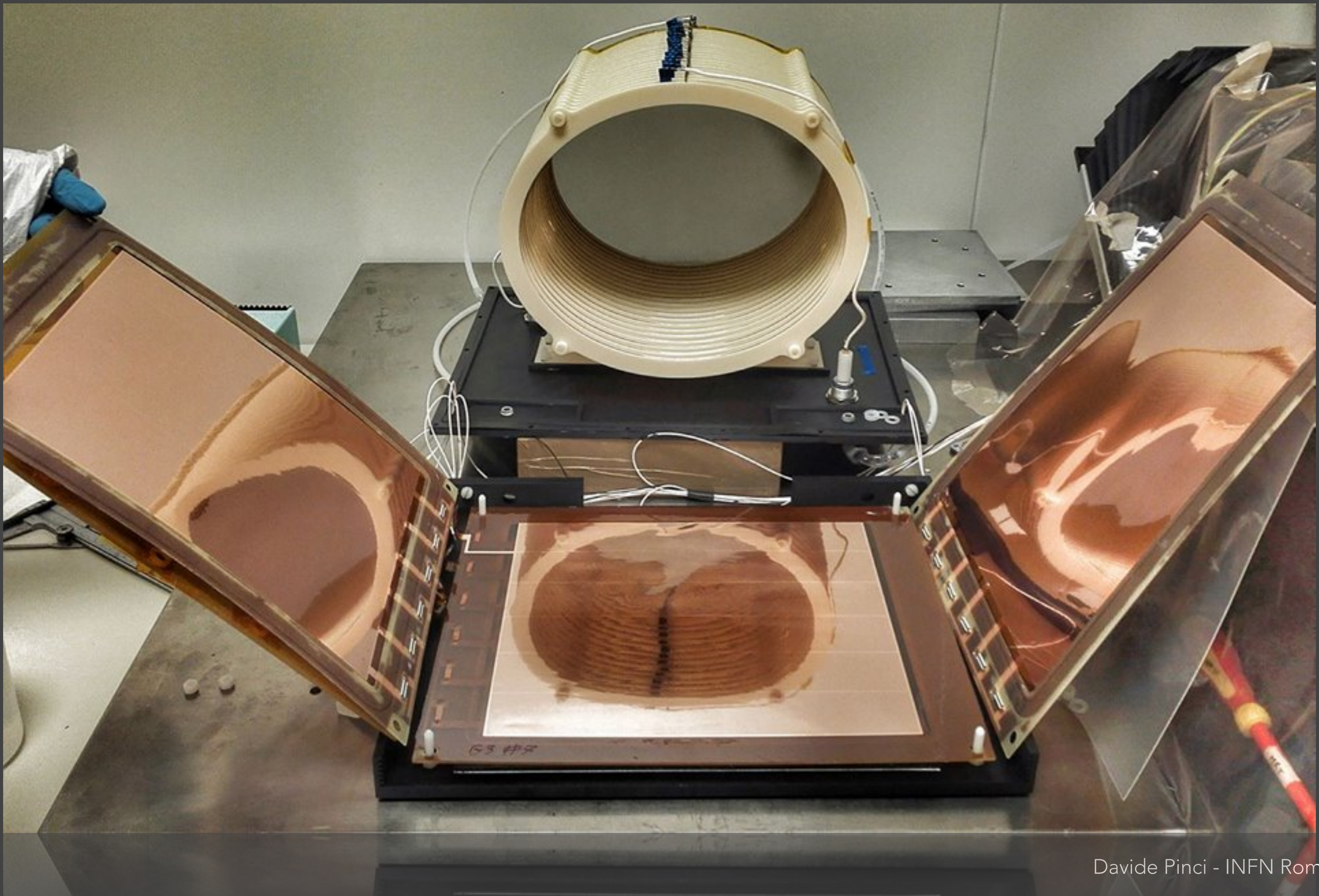


Tuneable bellows

CMOS camera

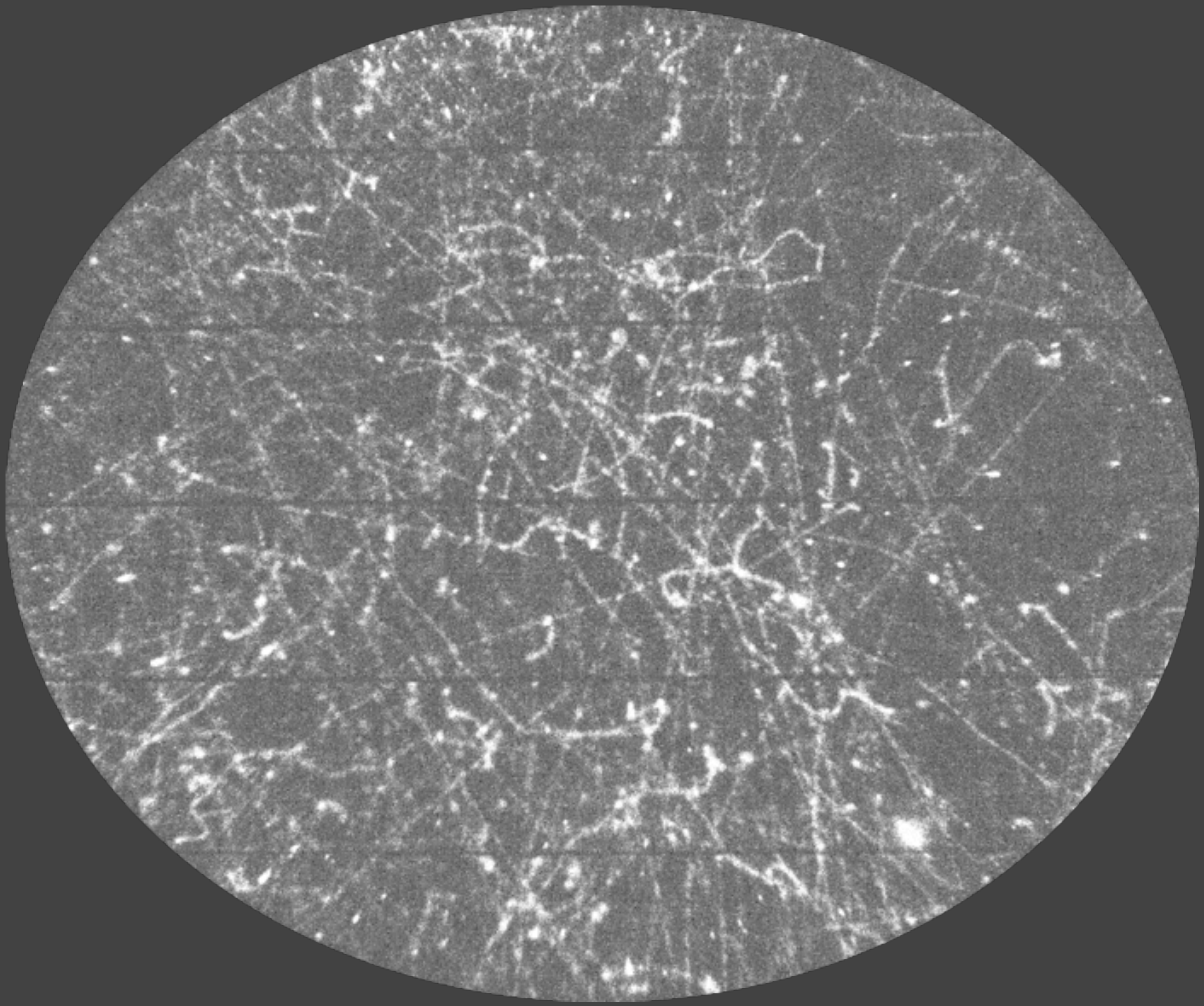
20x24 cm^2 GEMs

INSIDE THE LEMON PROTOTYPE



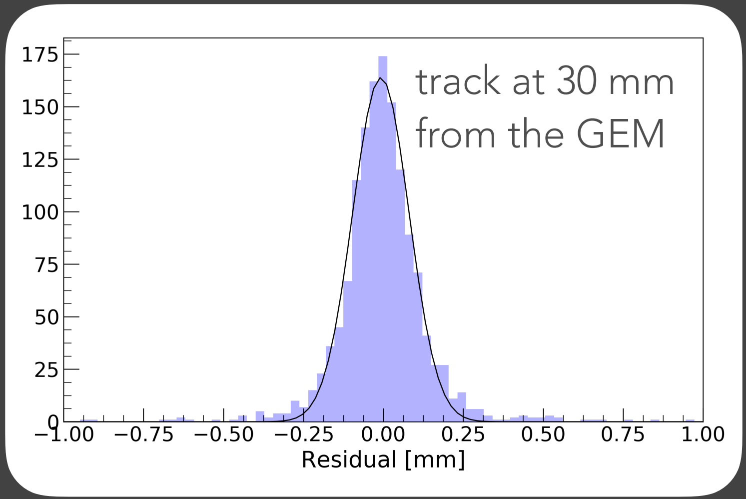
LEMON: FIRST RESULT

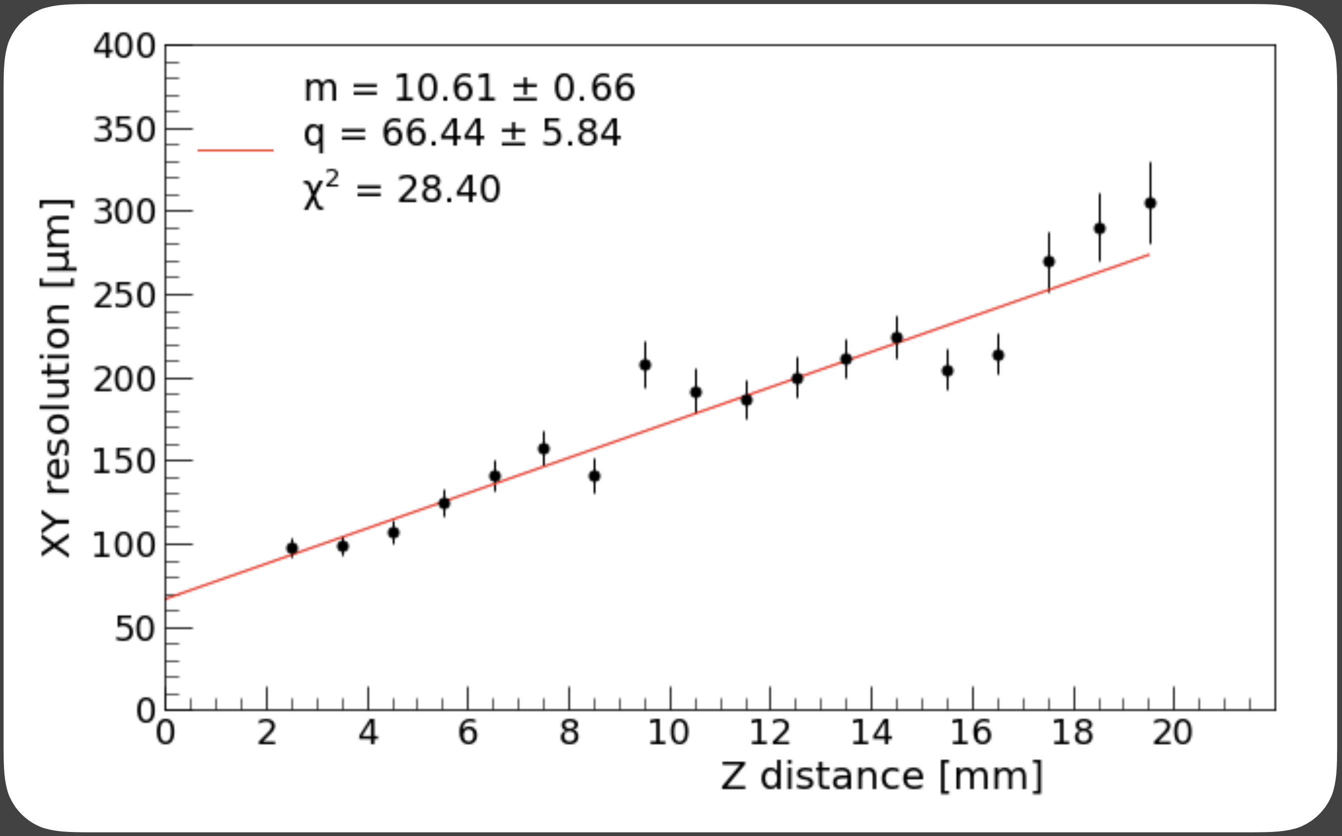
5 sec of natural background



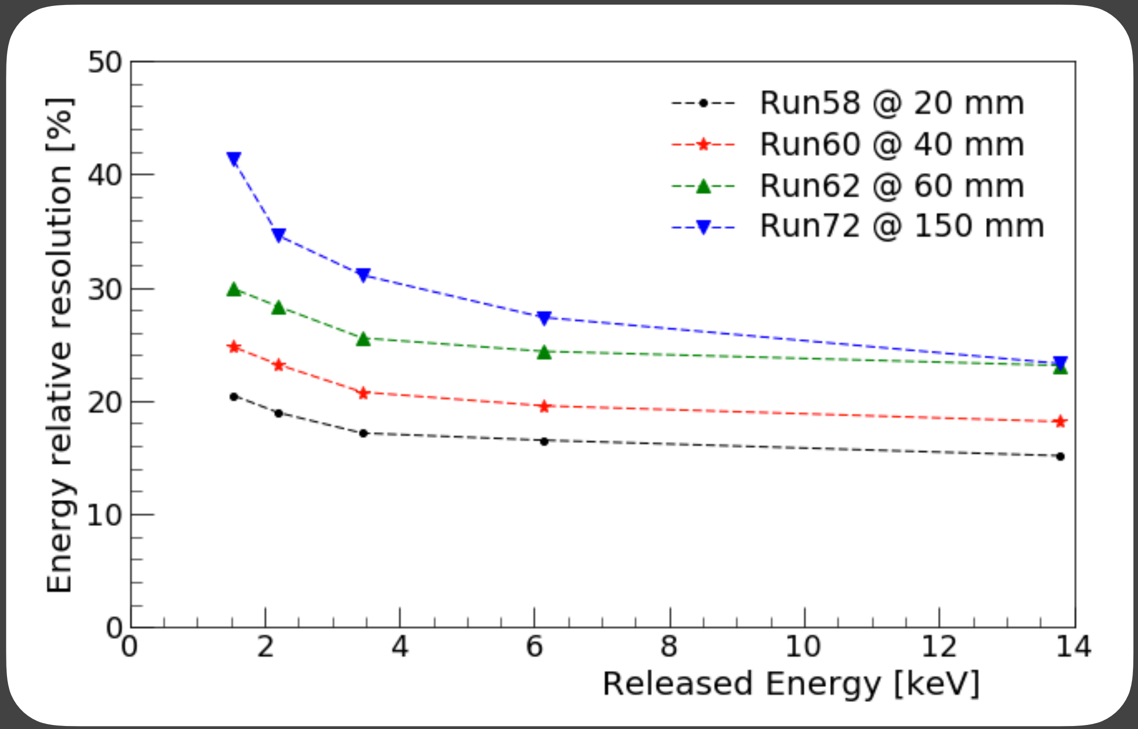
SPACE AND ENERGY RESOLUTION (X,Y)

The space resolution was evaluated as a function of the distance of the track from the GEM, by studying the distribution of the residuals to a linear fit;





Energy resolution was studied at different depths (Z).



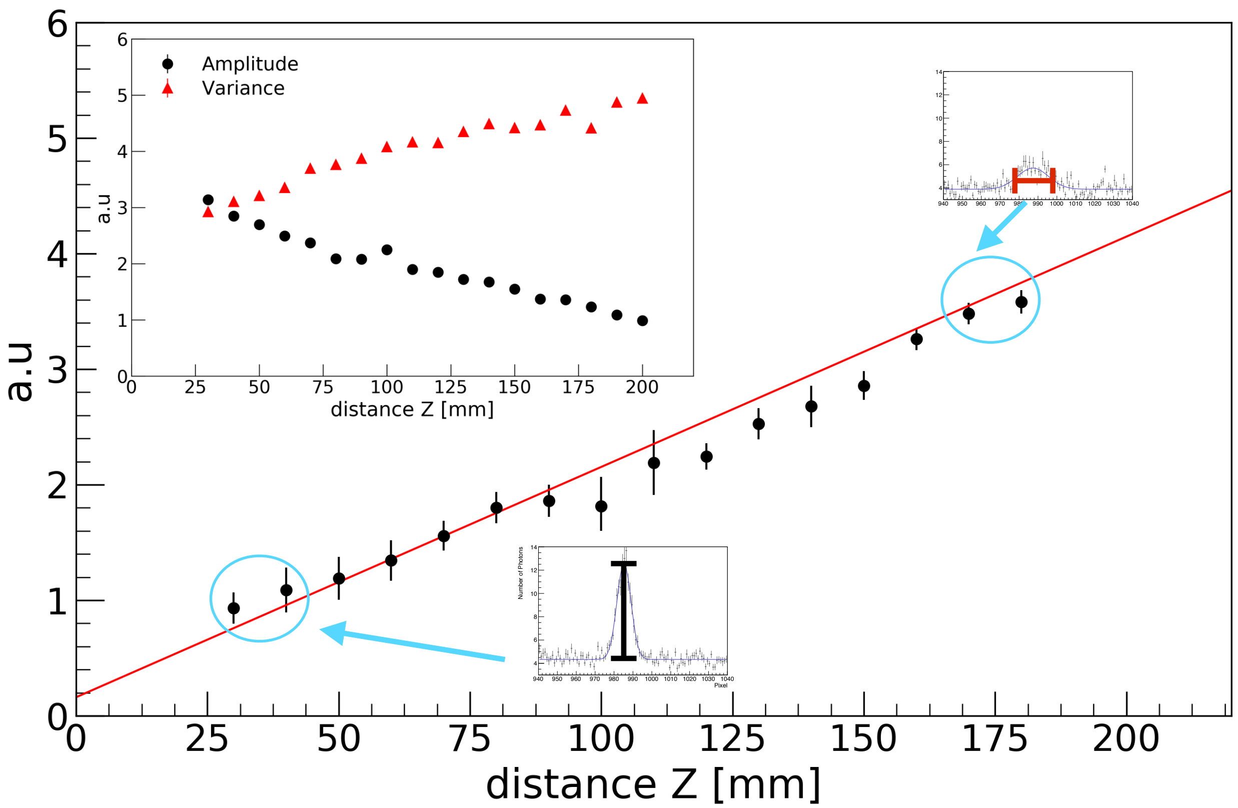
In the few keV region a relative resolution of 20%-30% is achieved

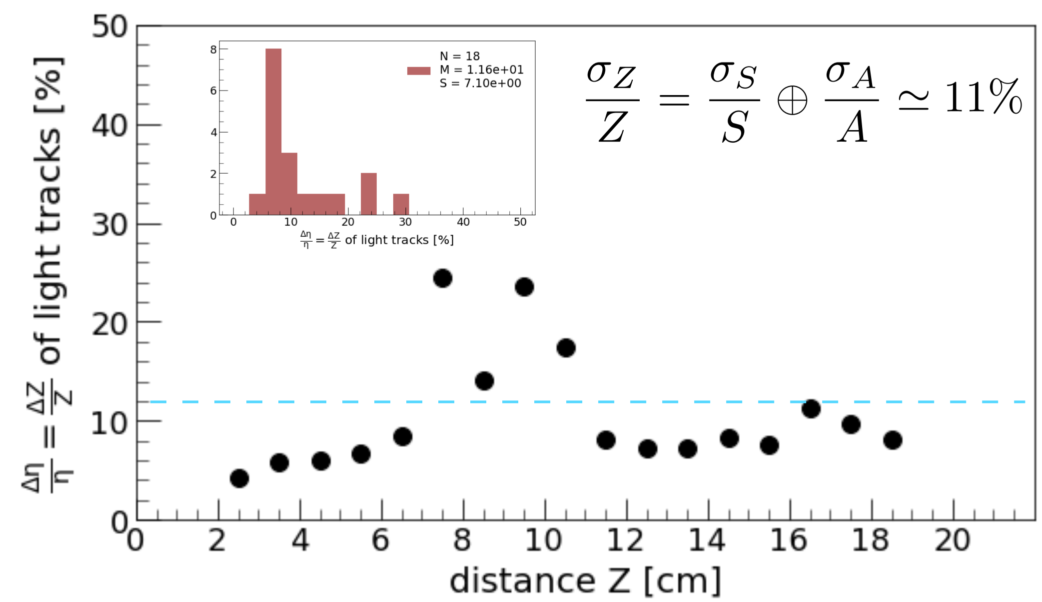
Z RESOLUTION

Electron transversal diffusion in the drift gap can be exploited to extract information for evaluating the Z of the event in applications without an external time reference (e.g. DM search);

The transverse light profile is expected to become lower and larger as long as the track is far from the GEM;

Since the amplitude (A) decreases and the width (S) increases with Z, their ratio η = S/A increases (independently from the amount of produced light);

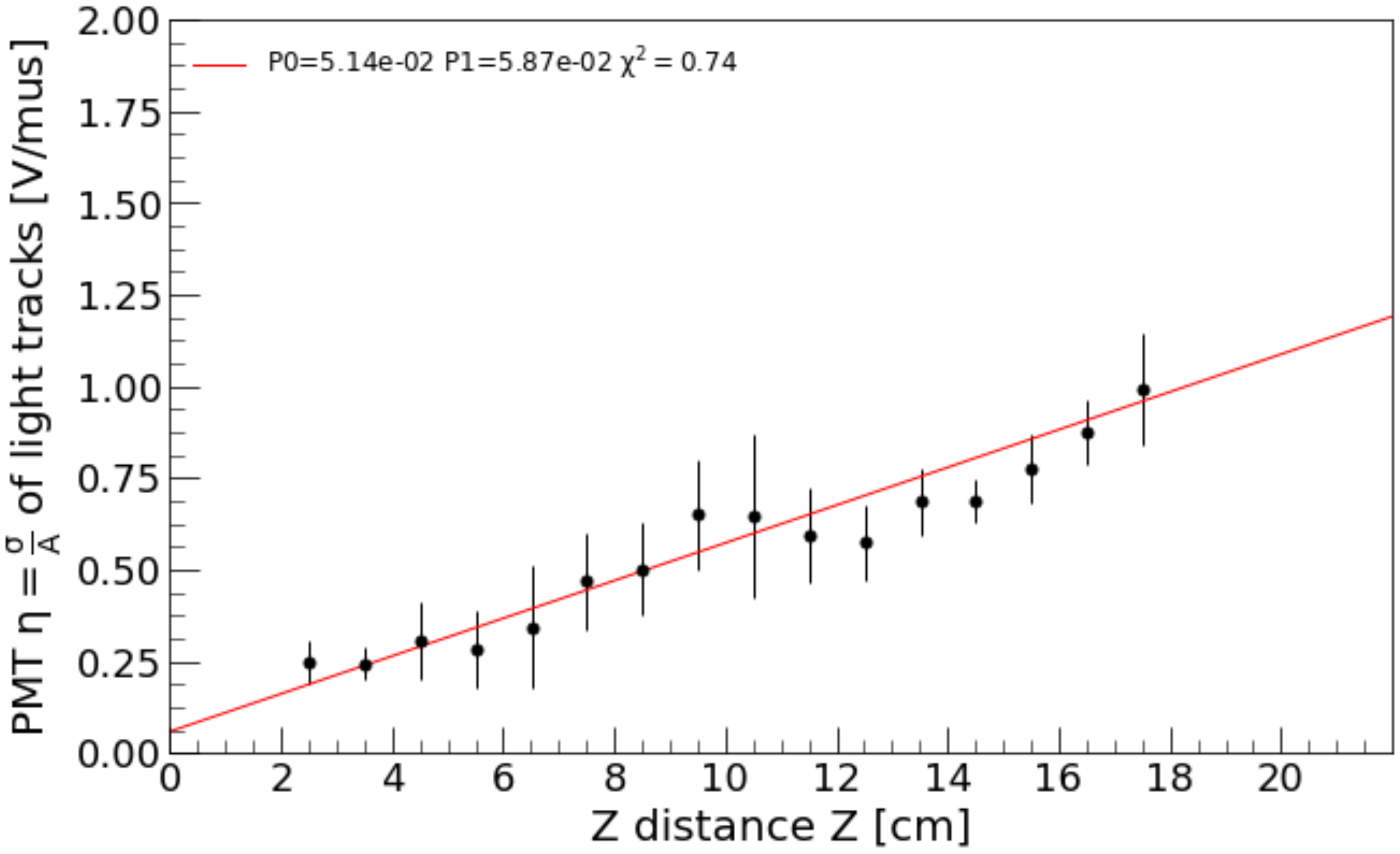


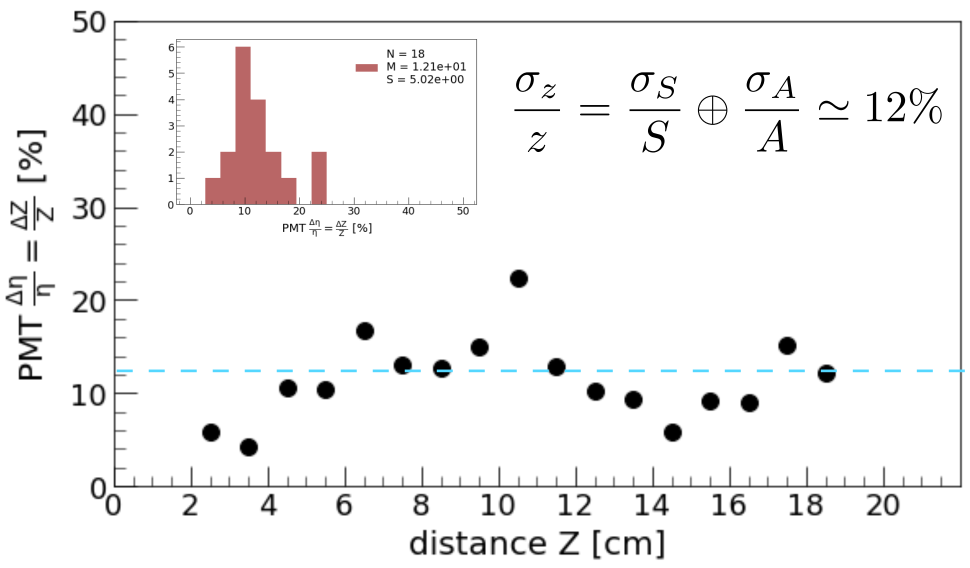


σz~ 2-3 cm @ 20 cm

Z RESOLUTION

The longitudinal electron diffusion modifies the structure of the PMT signal;
Also in this case, the signal amplitude (A) and width (S) are expected to depend on the track Z and their ratio η_{PMT}=S/A is expected to increase with Z



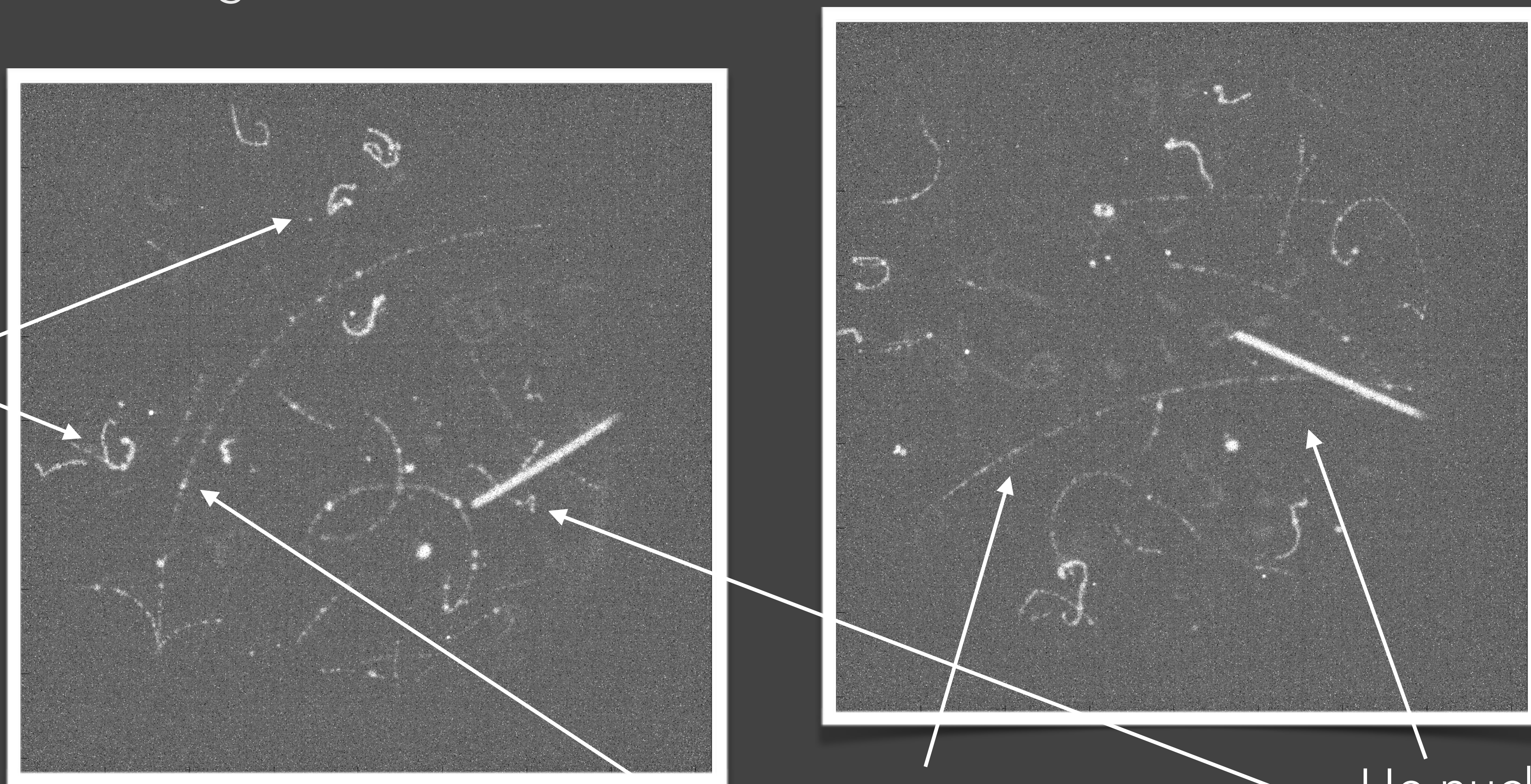


$$\frac{\sigma_z}{z} = \frac{\sigma_S}{S} \oplus \frac{\sigma_A}{A} \simeq 12\%$$

σz~ 2-3 cm @ 20 cm

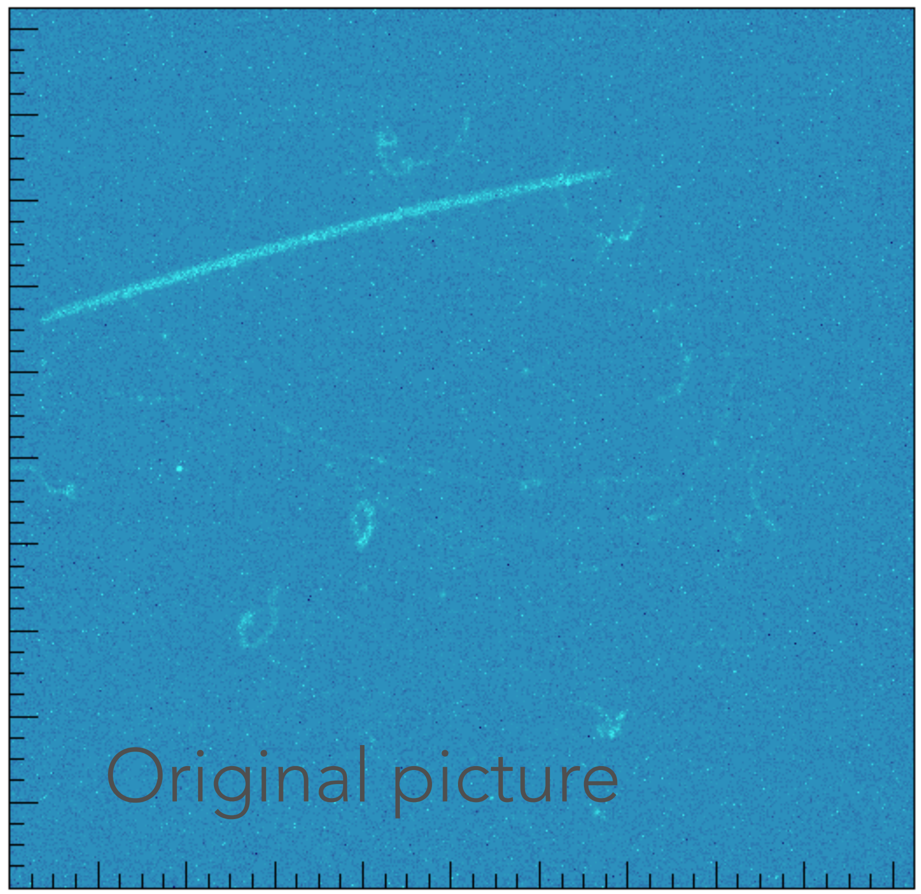
MEASUREMENTS WITH NEUTRONS

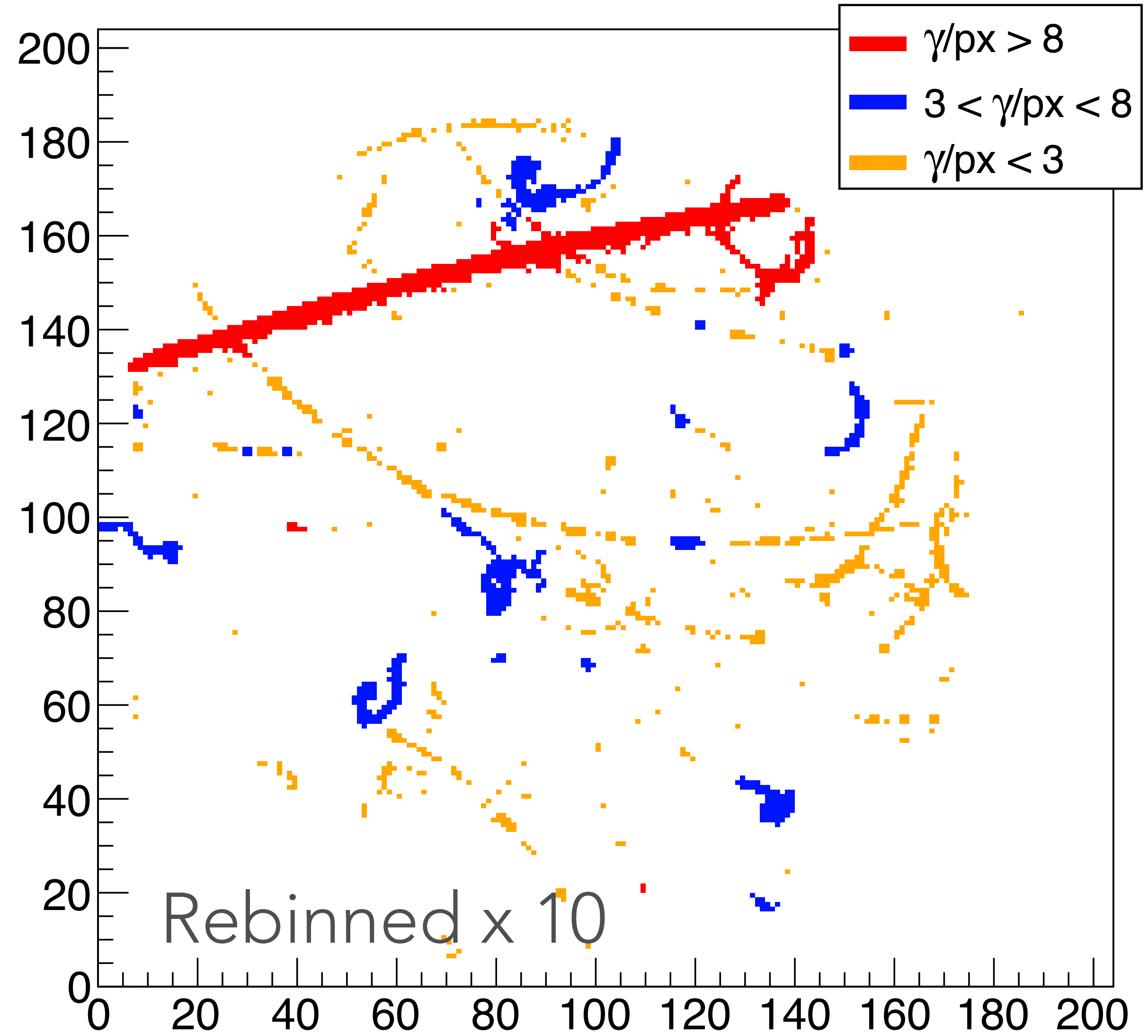
A small prototype was exposed to an AmBe source, providing 1-10 MeV neutrons along with 4 MeV and 60 keV photons.
A 0.2 T magnetic field was present within the drift field provided by a permanent magnet.



PARTICLE IDENTIFICATION

Specific ionisation allows a fast particle identification.



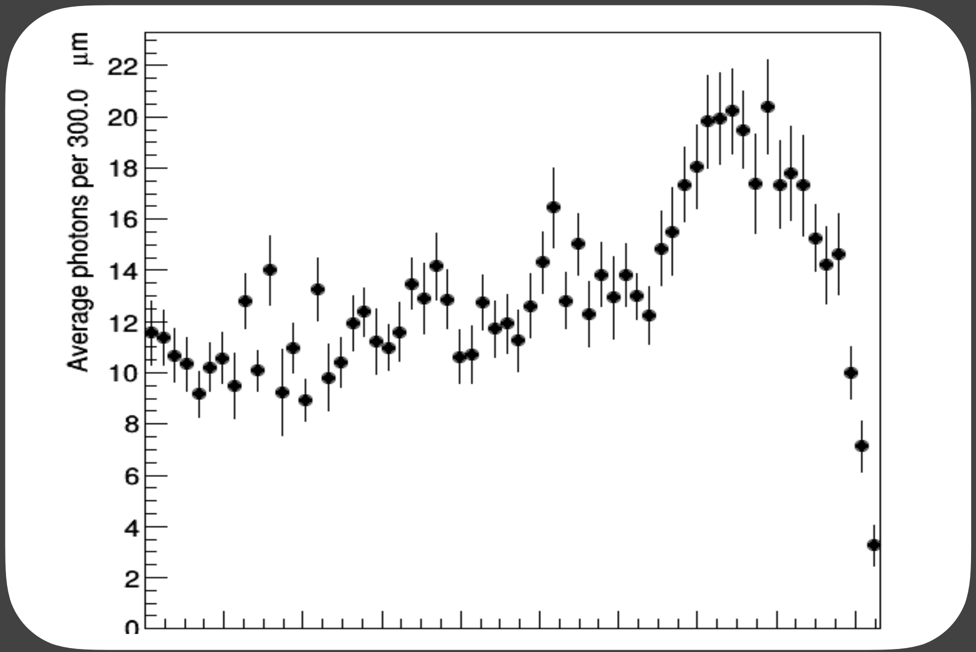


By simply assigning different colours to identified clusters as a function of their average light density, the three species are almost completely separated.

FNG: NEUTRON GUN AT ENEA

LEMOn was tested with 2.45 MeV neutrons at Frascati Neutron Generator

Nuclear recoil tracks are clearly visible among background induced by soft photons.



Longitudinal light profile shows a typical Bragg peak shape

CONCLUSION

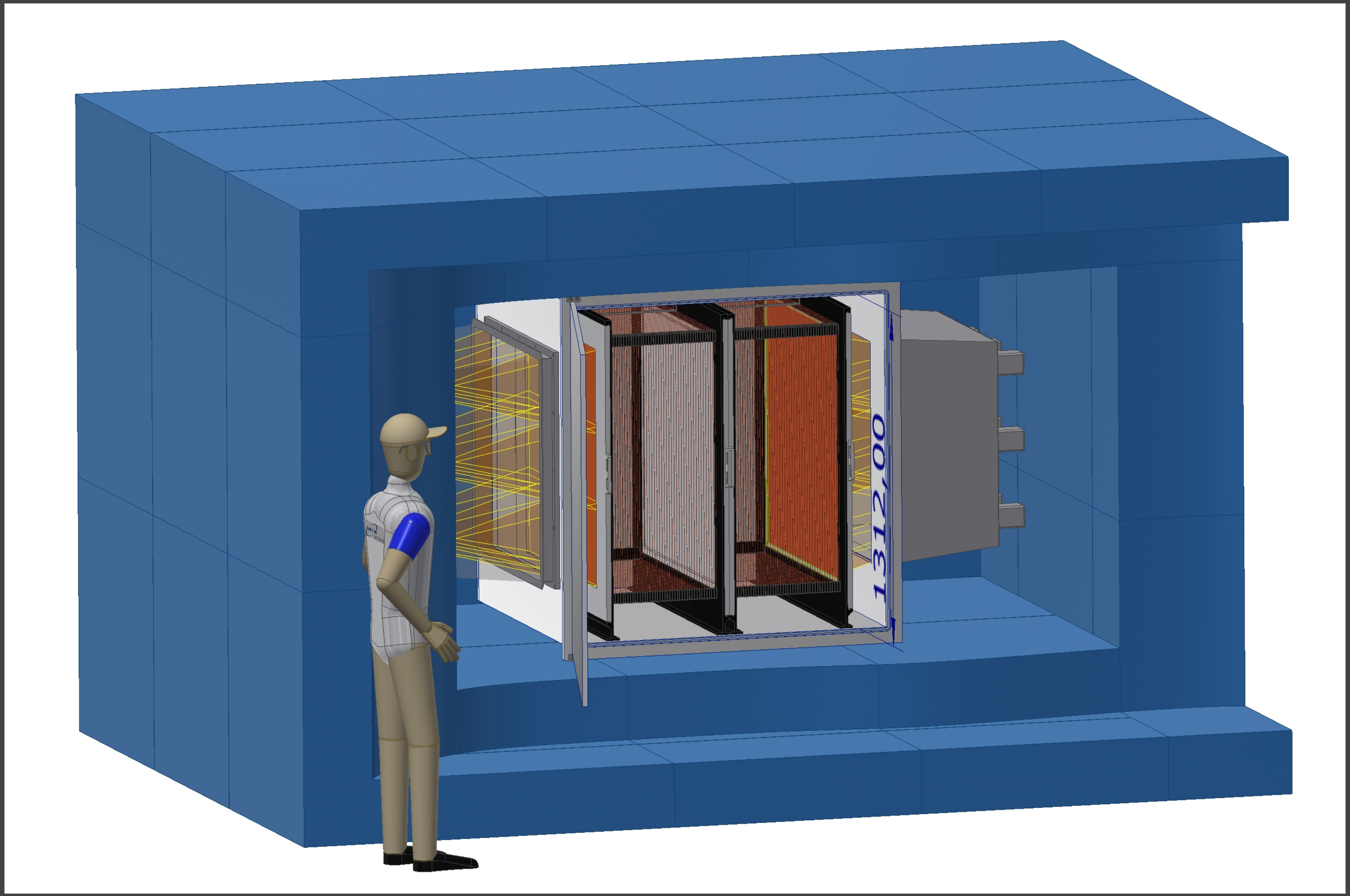
TPC based on GEM combined optical readout demonstrated very interesting performance:

- X-Y resolution around 100 μm;
- effect of electron diffusion can be exploited to determine the track depth with a 10% uncertainty;
- 20%-30% precision on the evaluation of released energy already in the keV range;
- first analysis with neutrons is providing promising results on nuclear recoil detection and identification.

We think this technology showed to be really promising for developing a detector for directional light Dark Matter search.
We are proposing to CSN2 to finance the production of a TDR and the construction of a 1 m^3 demonstrator;

CYGNO

Study not only the detecting performance on larger volume but also all aspects related to intrinsic background induced by radioactivity of the material, apparatus shielding, gas circulation and purification.

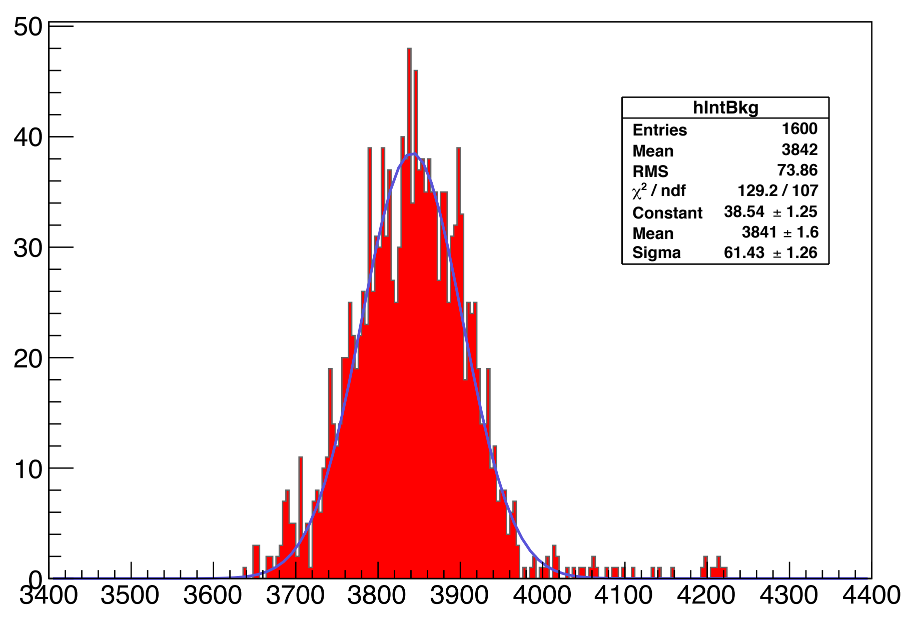


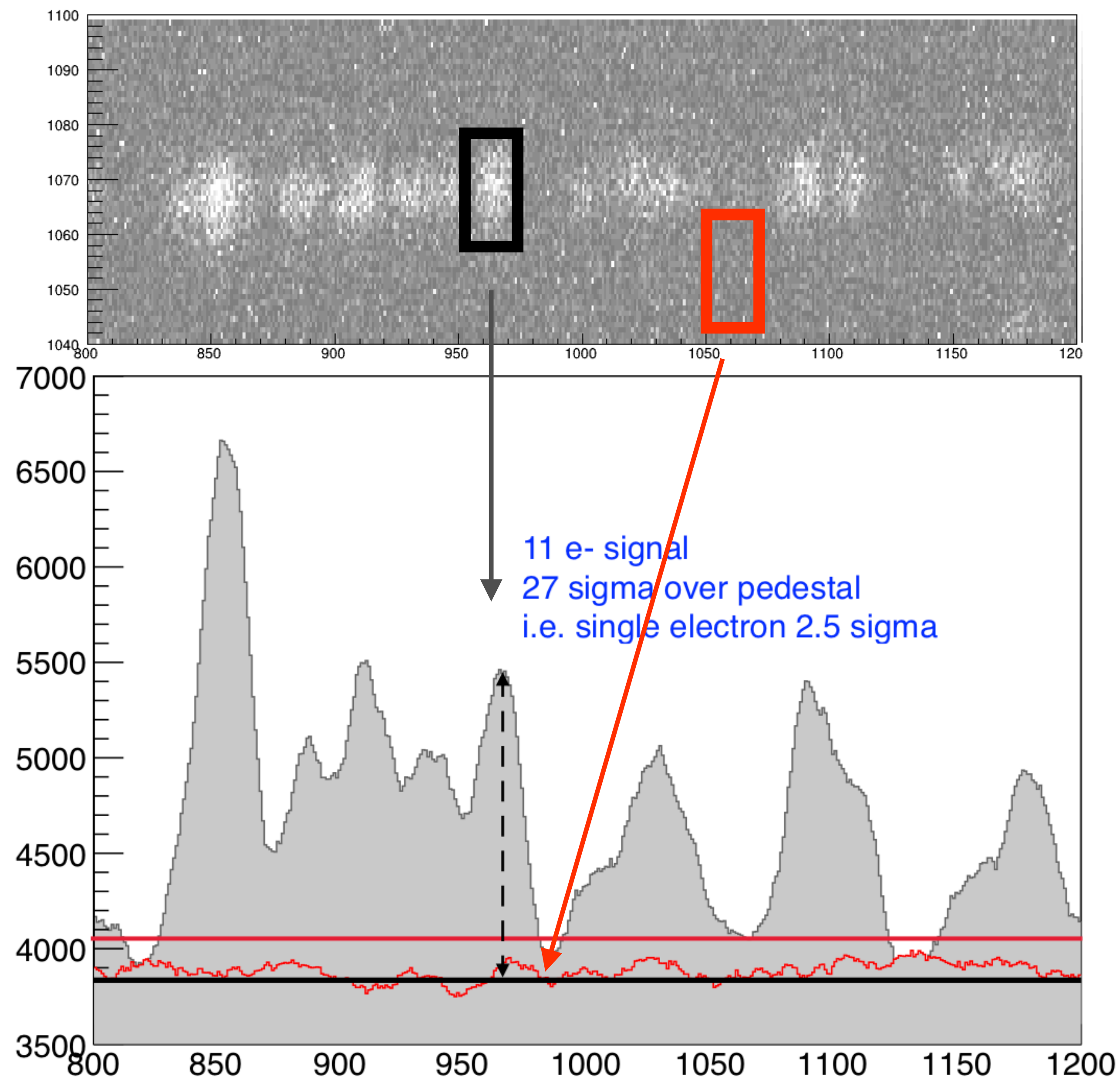

Thank you

BACKUP

SIGNAL TO NOISE

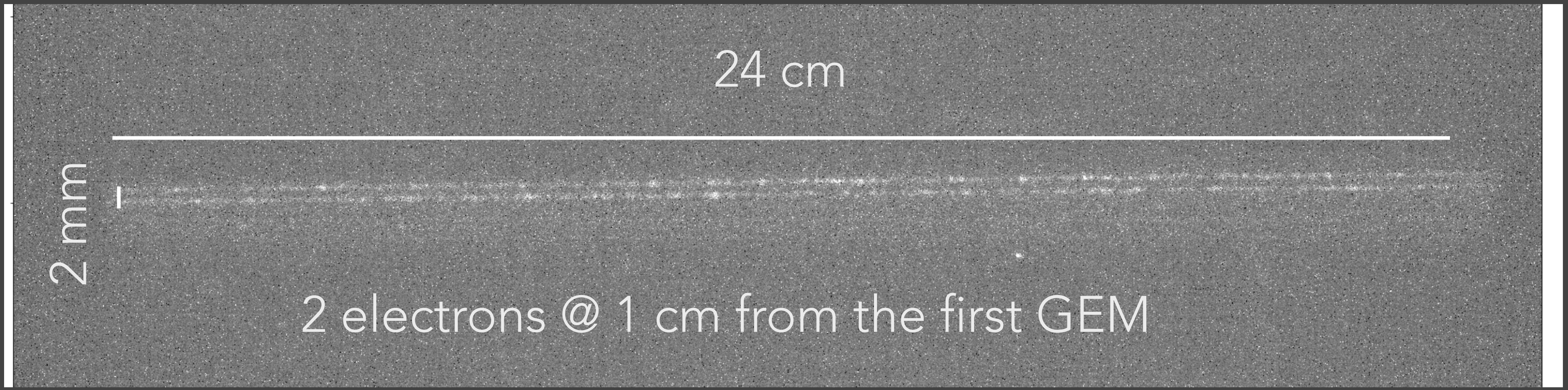
To get an idea about the signal to noise ratio, detected light was integrated in 20x20 pixel box along the track and on the background.

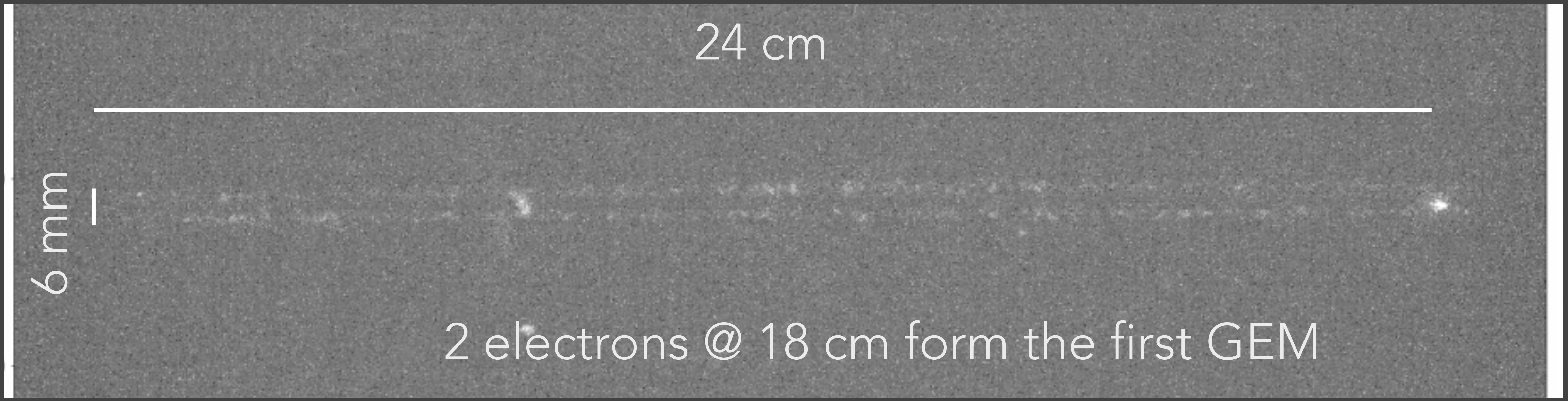




Pedestal has a jitter of 60 ph. Therefore a single electron has a sig/noise = 2.5;
A blob with 1650 detected photons (i.e. 11 el) is 27 sigma over the pedestal

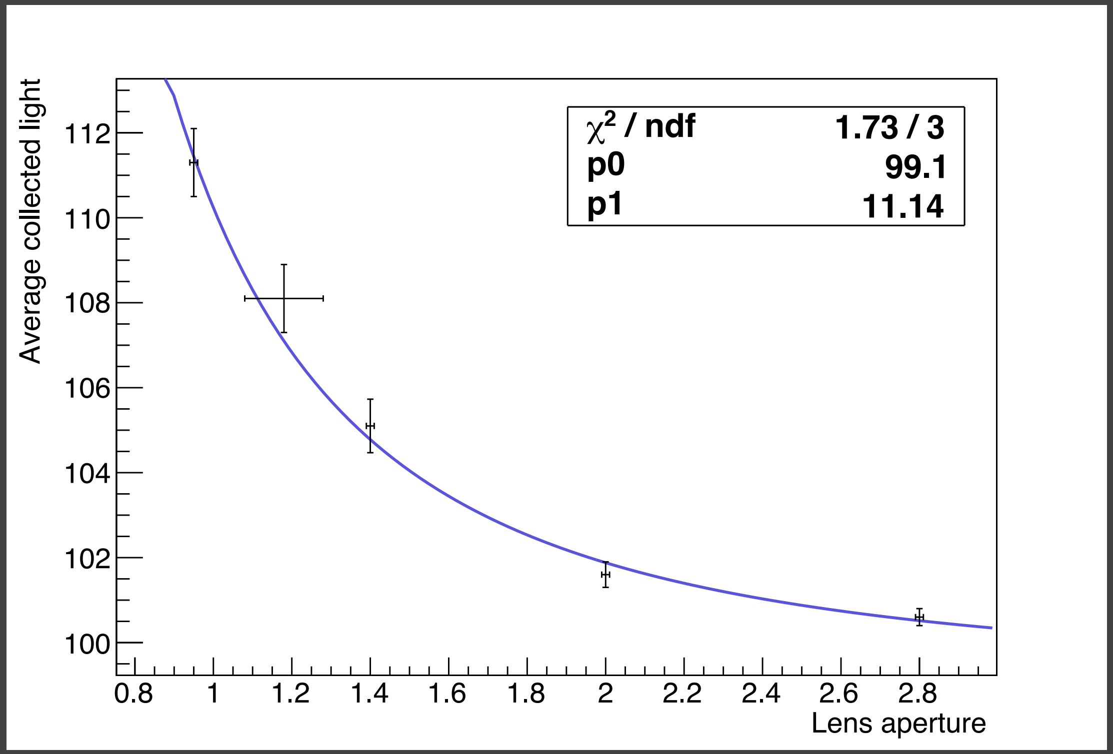
LEMON: TRACK SEPARATION

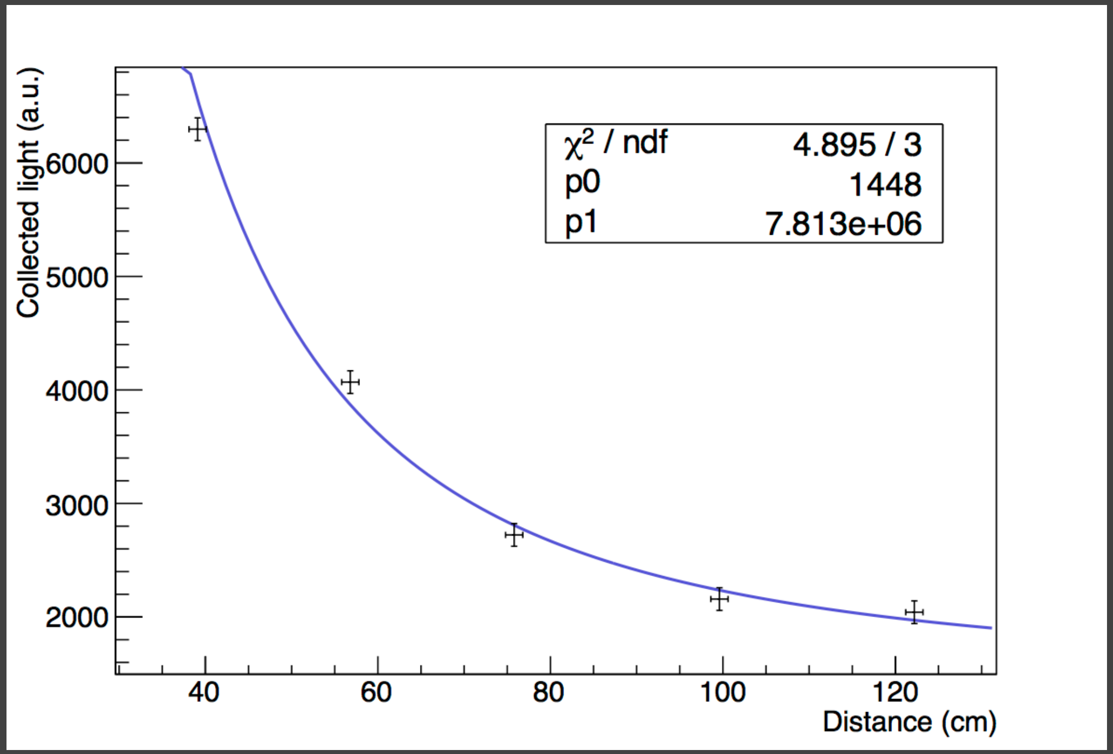




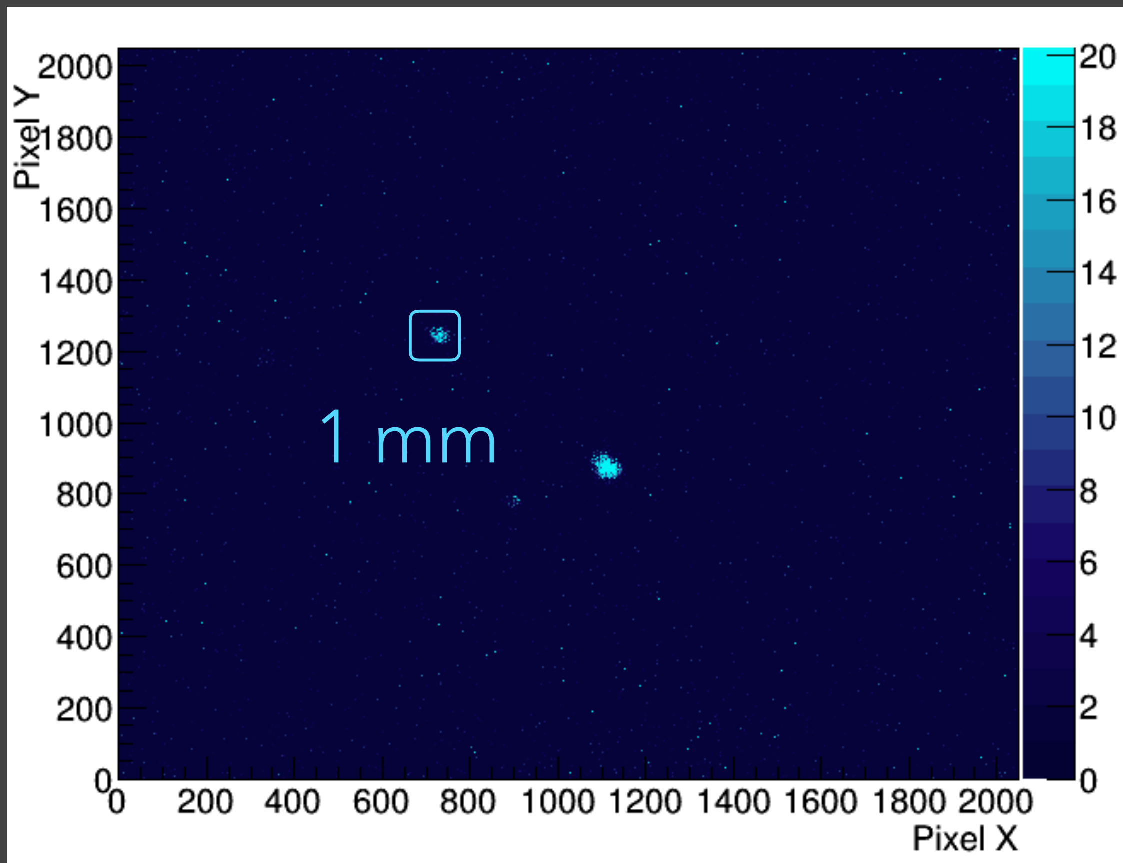
LIGHT EMISSION ISOTROPY

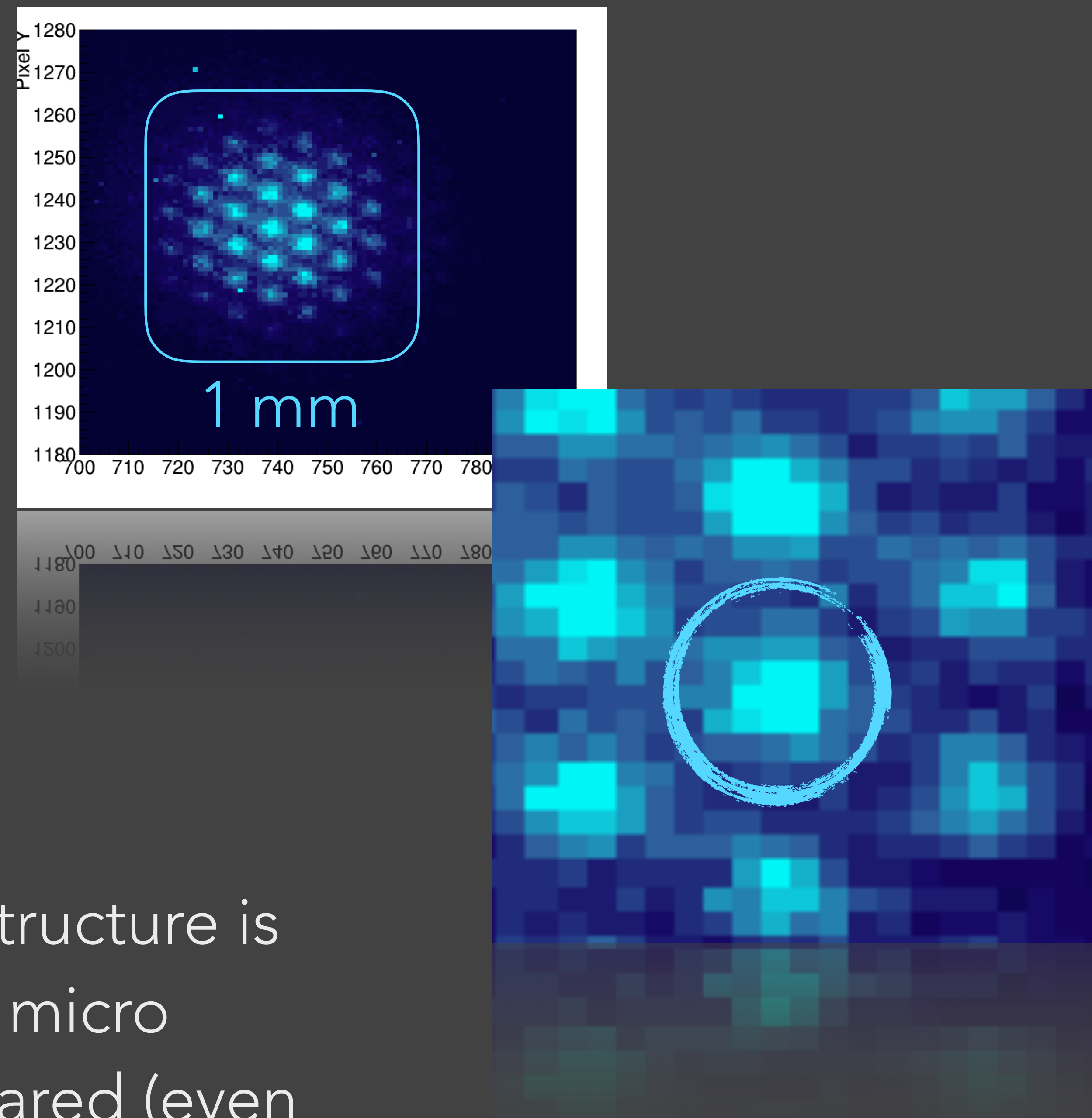
aperture and distance light emission demonstrating that the emission is isotropic





FIRST MEASUREMENTS



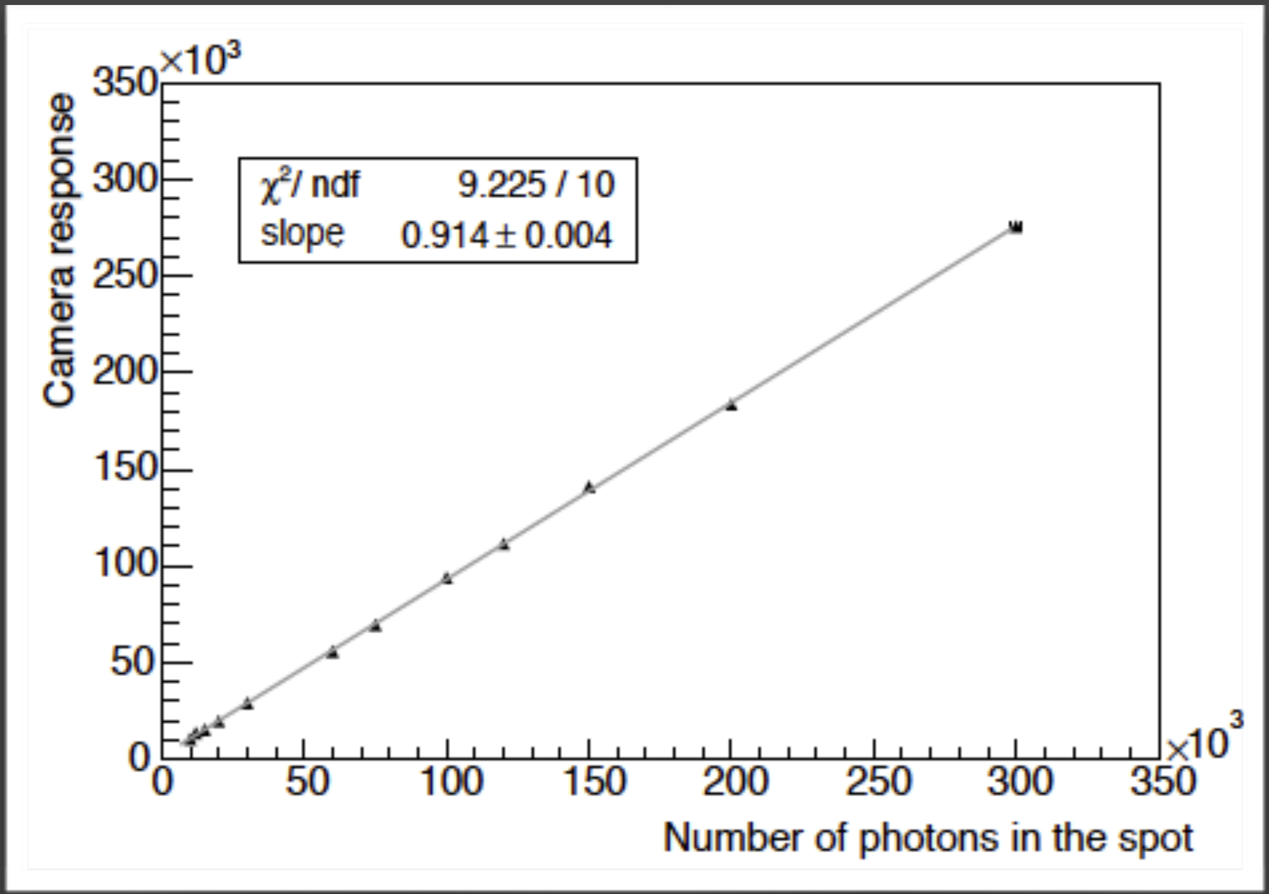


Once the high voltage to the GEM structure is turned ON, several hot spots due to micro discharges within the channels appeared (even without a sizeable current being drawn);

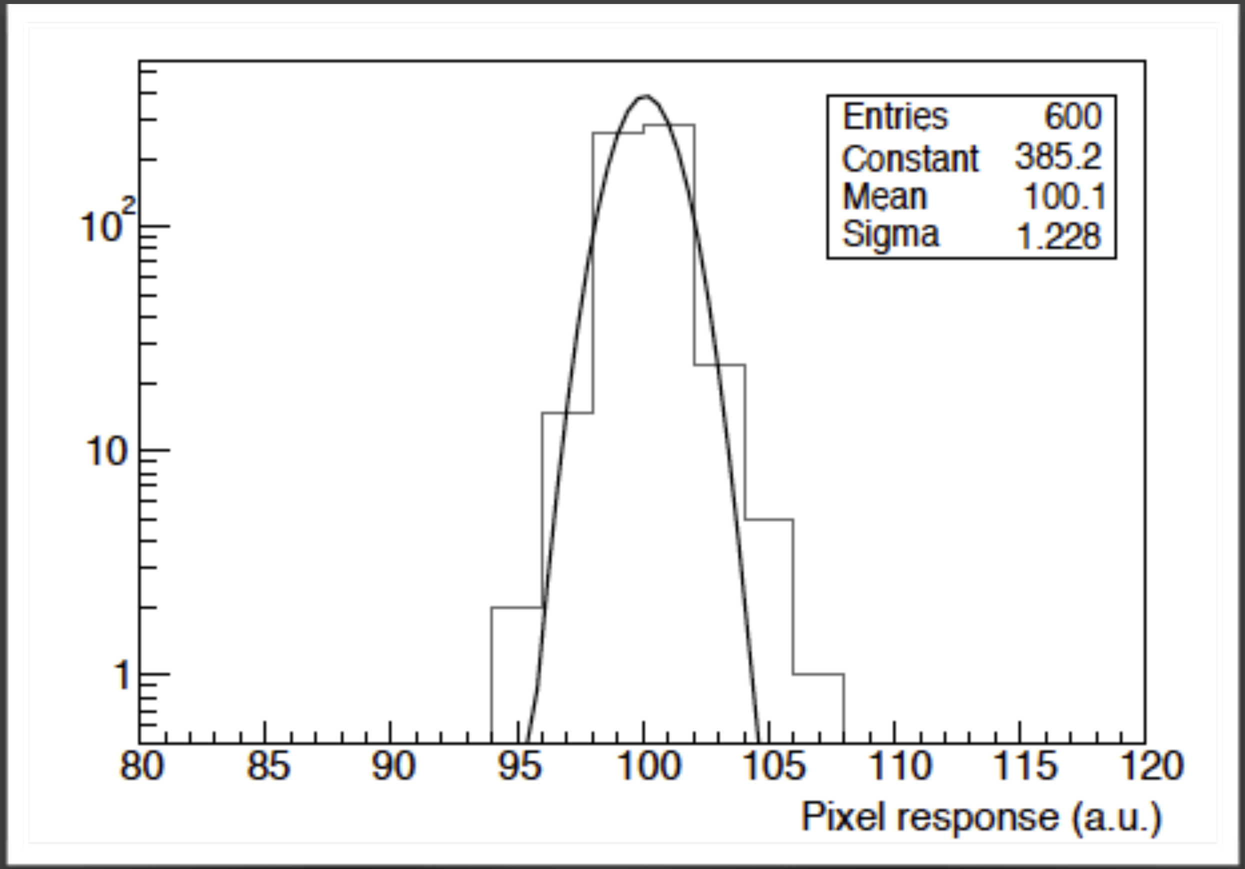
The hole texture is clearly visible.

CAMERA PERFOMANCE

The photo-sensor was studied by means of a calibrated light source;



The camera behaviour is well linear in the whole studied range with a response of 0.91±0.01 counts per photon



Fluctuations of the pedestal are lower than 2 counts, i.e. lower than two photons per pixel in good agreement with the expectations