HIGH RESOLUTION TPC BASED ON OPTICALLY READOUT GEM

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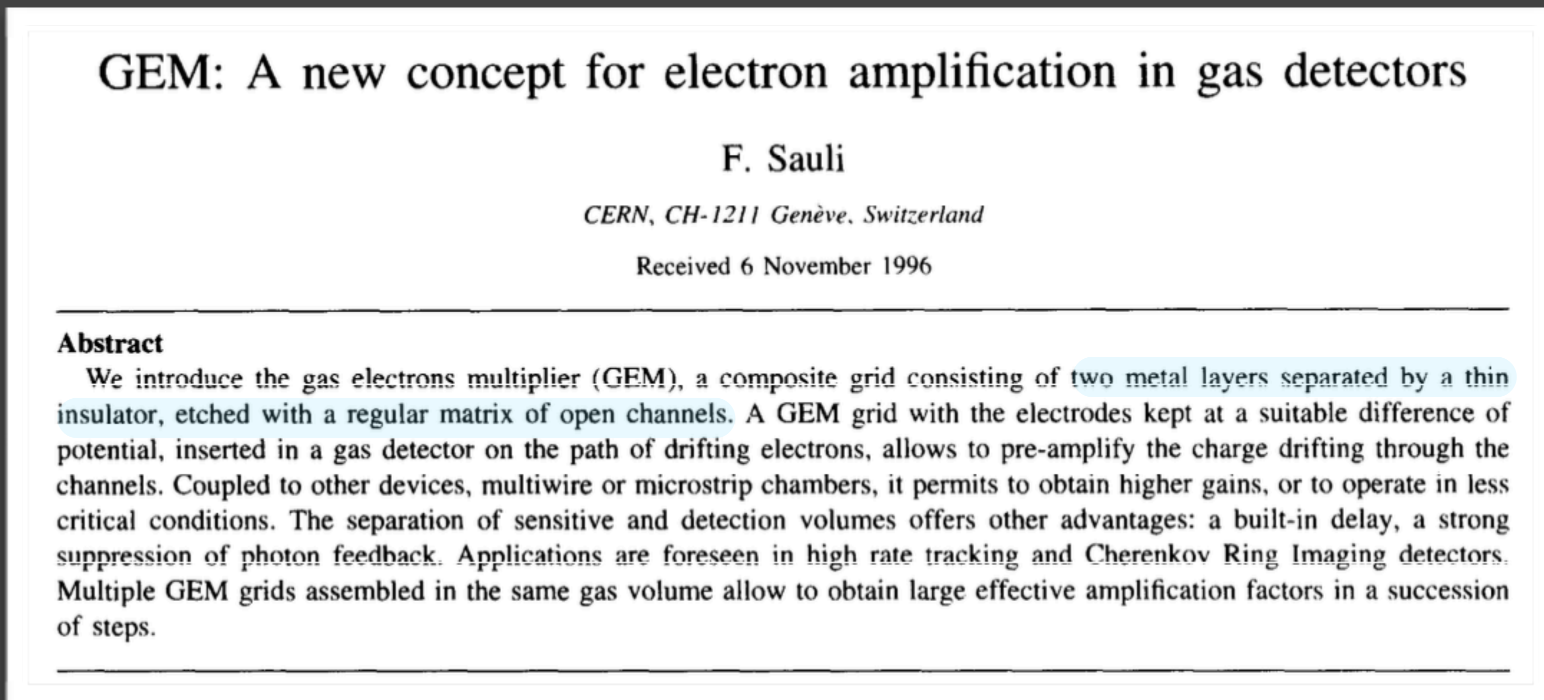
GEM: PRINCIPLE OF OPERATION



GEM: A new concept for electron amplification in gas detectors

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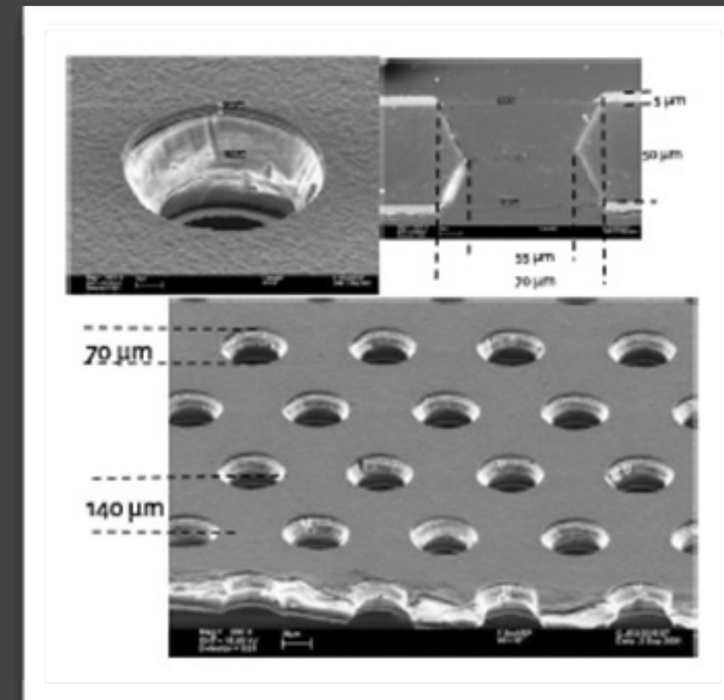
Received 6 November 1996

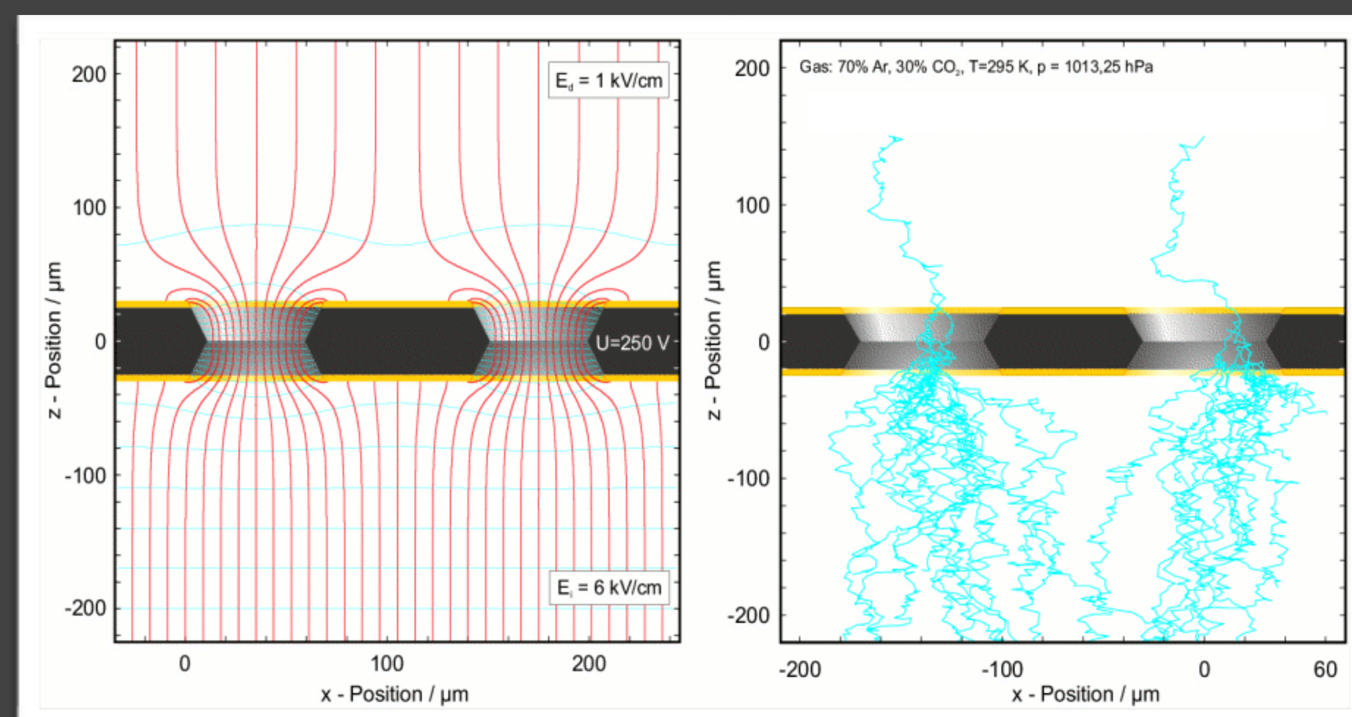
Abstract

We introduce the gas electrons multiplier (GEM), a composite grid consisting of two metal layers separated by a thin insulator, etched with a regular matrix of open channels. A GEM grid with the electrodes kept at a suitable difference of potential, inserted in a gas detector on the path of drifting electrons, allows to pre-amplify the charge drifting through the channels. Coupled to other devices, multiwire or microstrip chambers, it permits to obtain higher gains, or to operate in less critical conditions. The separation of sensitive and detection volumes offers other advantages: a built-in delay, a strong suppression of photon feedback. Applications are foreseen in high rate tracking and Cherenkov Ring Imaging detectors. Multiple GEM grids assembled in the same gas volume allow to obtain large effective amplification factors in a succession of steps.



Two external electric fields:

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

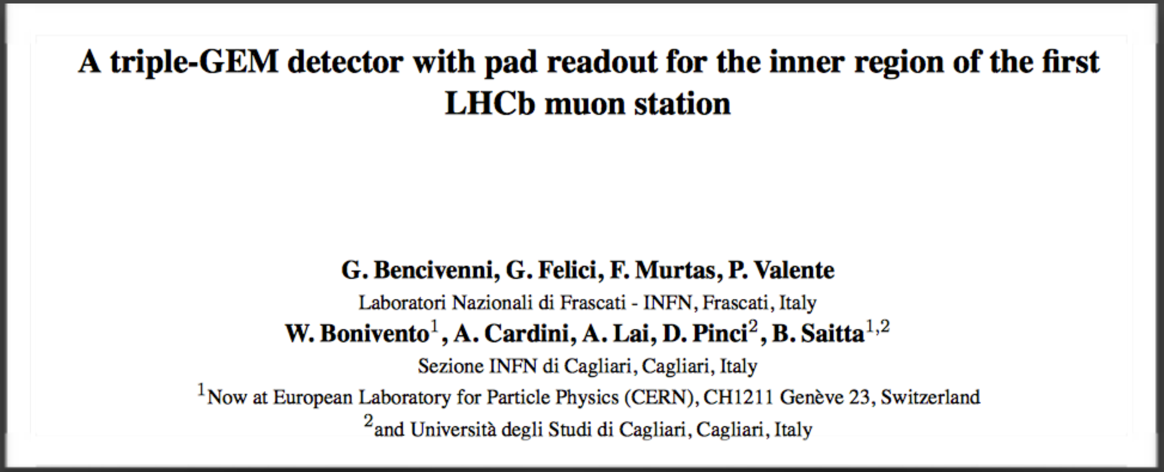


Multiple GEM structures can be used to share the gain and make more stable detectors.

THE TRIPLE GEM DETECTOR

Triple-GEM detectors were invented here!

An R&D was carried out between 2000-2003 and a detector was developed for LHCb Muon System.



A triple-GEM detector with pad readout for the inner region of the first LHCb muon station

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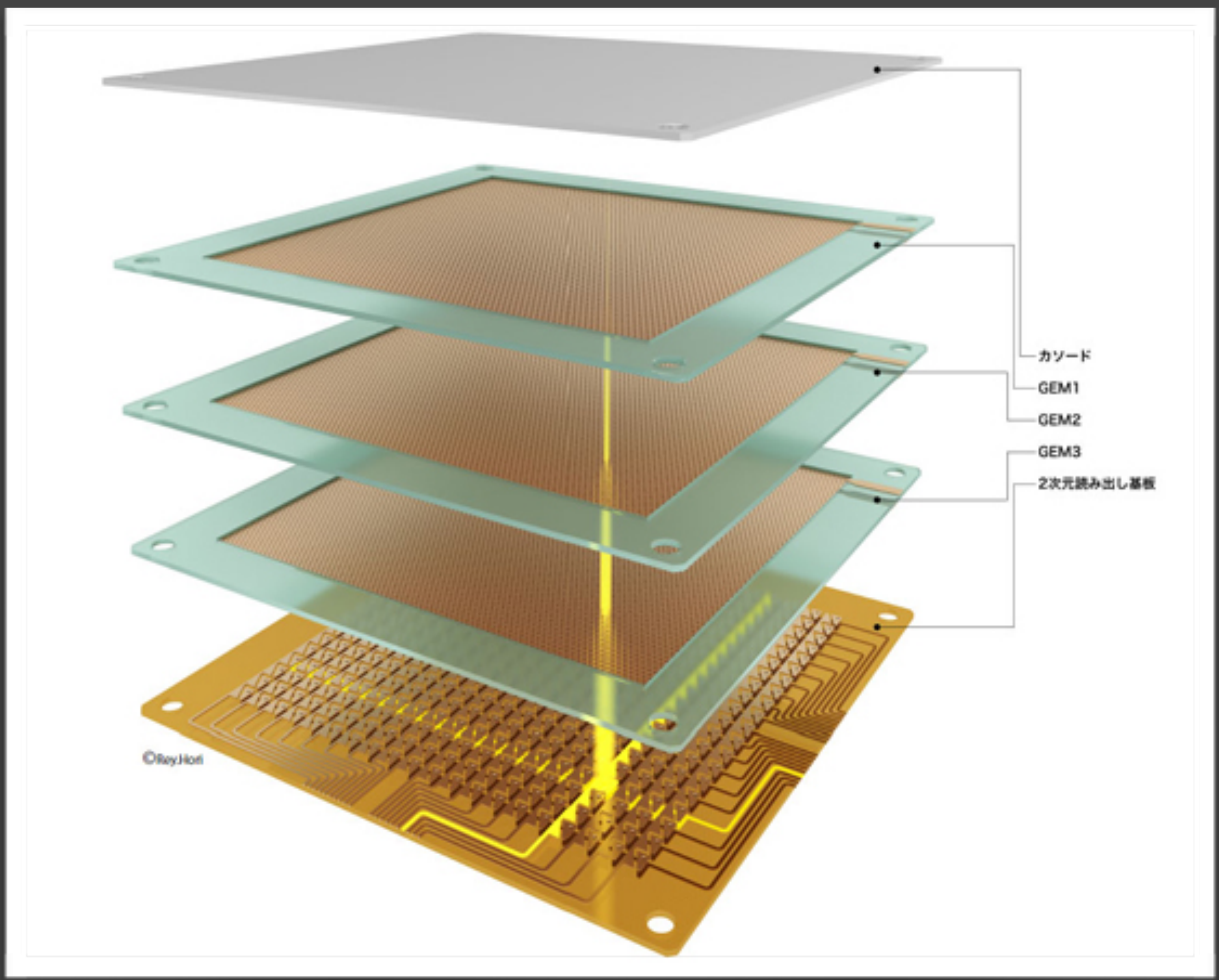


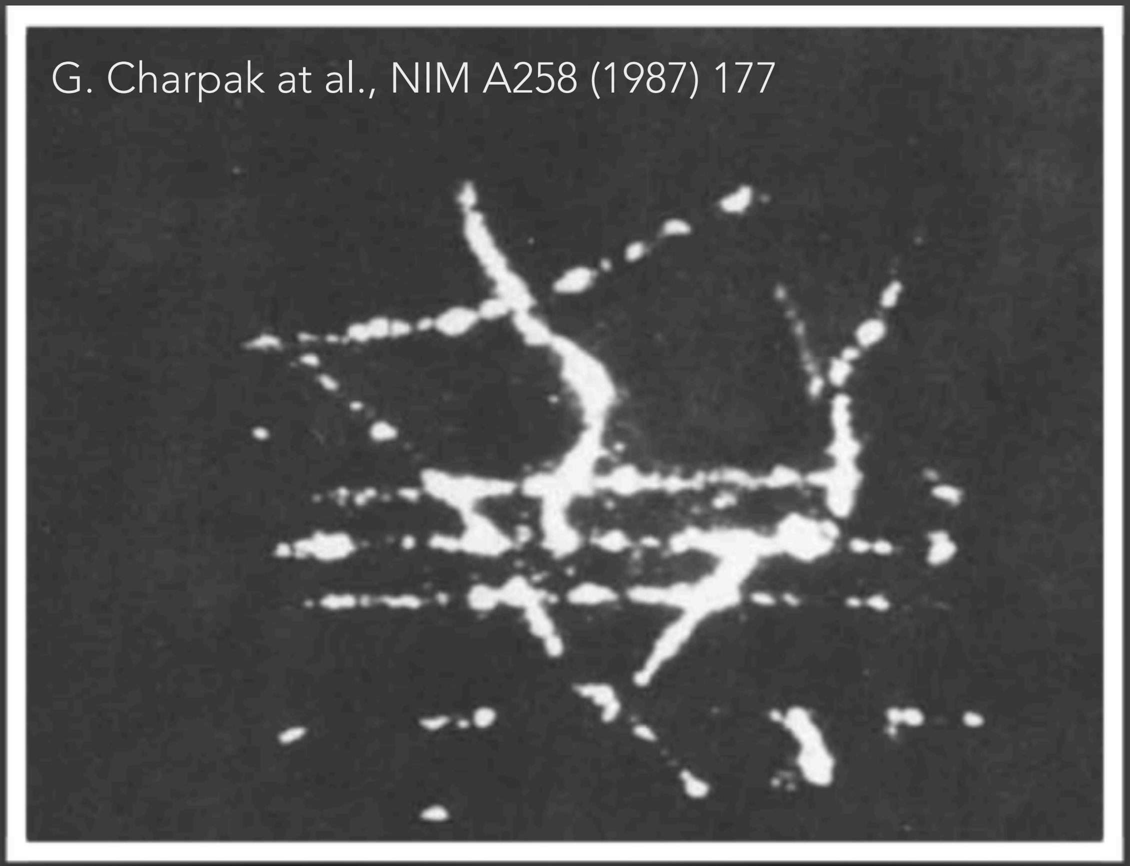
Some of the triple-GEM pioneers during a Test Beam in 2001 (photograph G. Bencivenni).

Since then, a lot of different R&D on triple-GEM have been completed at LNF.

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.



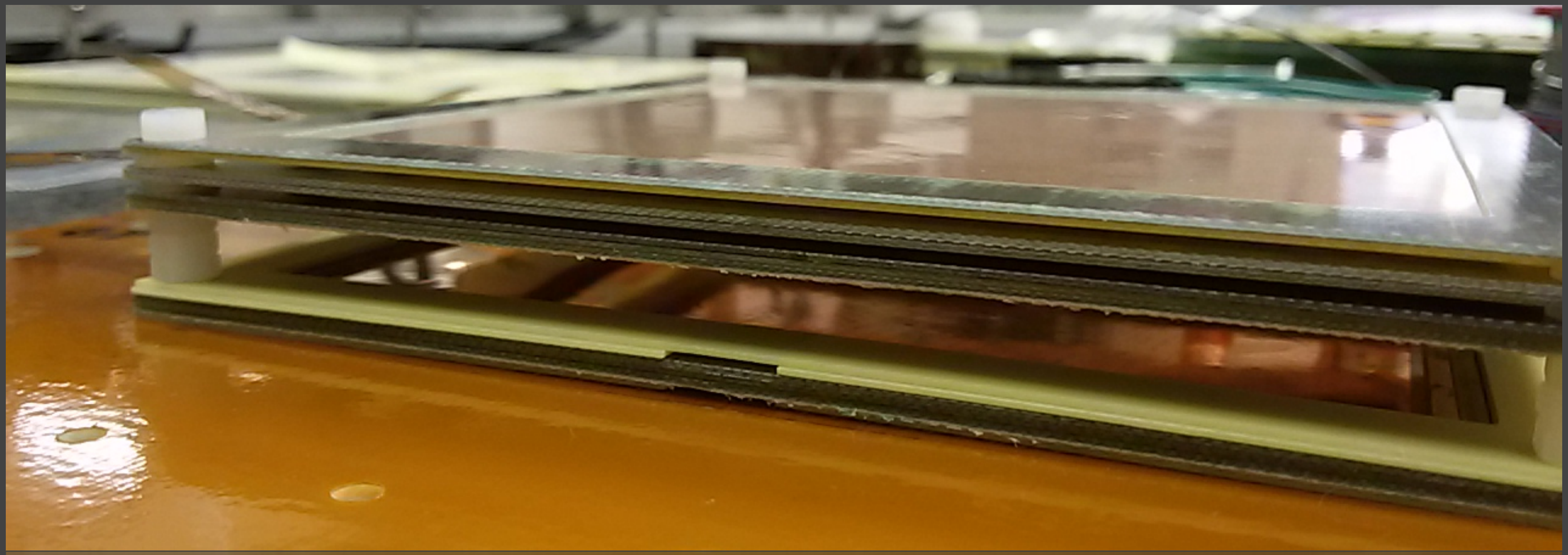
Optical readout of gas detectors offers several advantages:

- 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

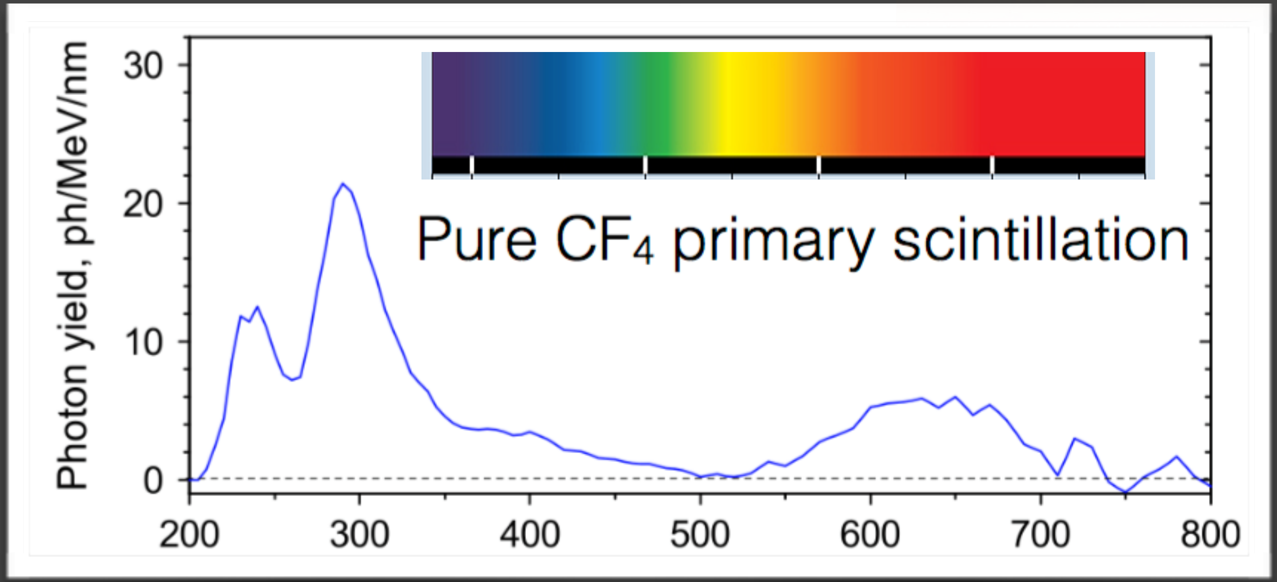
An Optically ReAdout GEM (ORAnGE) device was assembled in 2015;

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



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

Amount and spectrum of emitted light depends on the gas mixture.

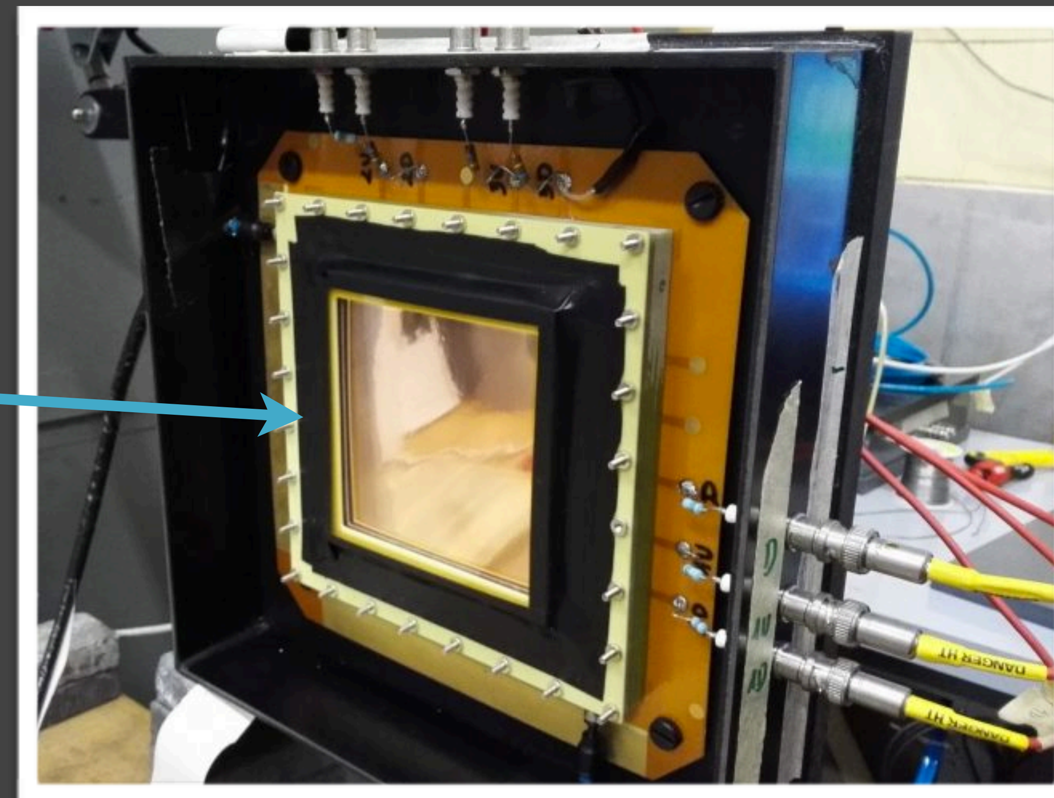


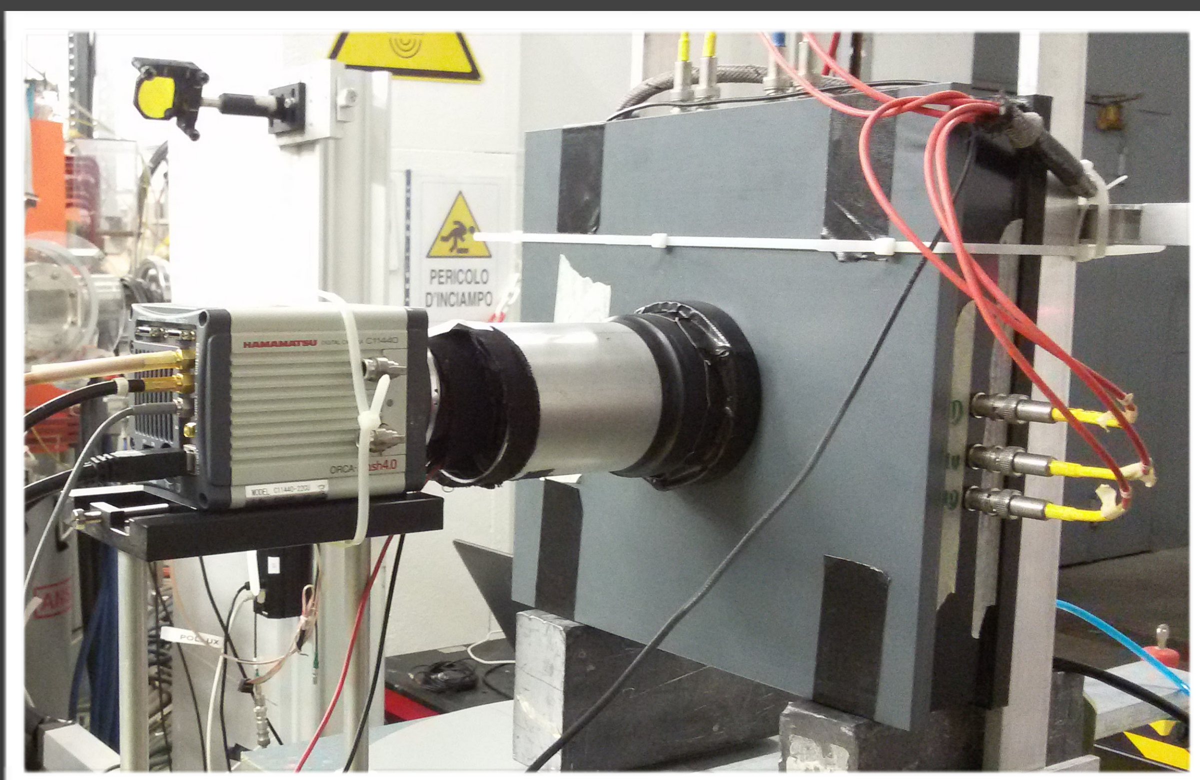
CF_4 represents an ideal candidate:

- often added to the gas mixture as a reliable quencher;
- good light yield and interesting emission spectrum;

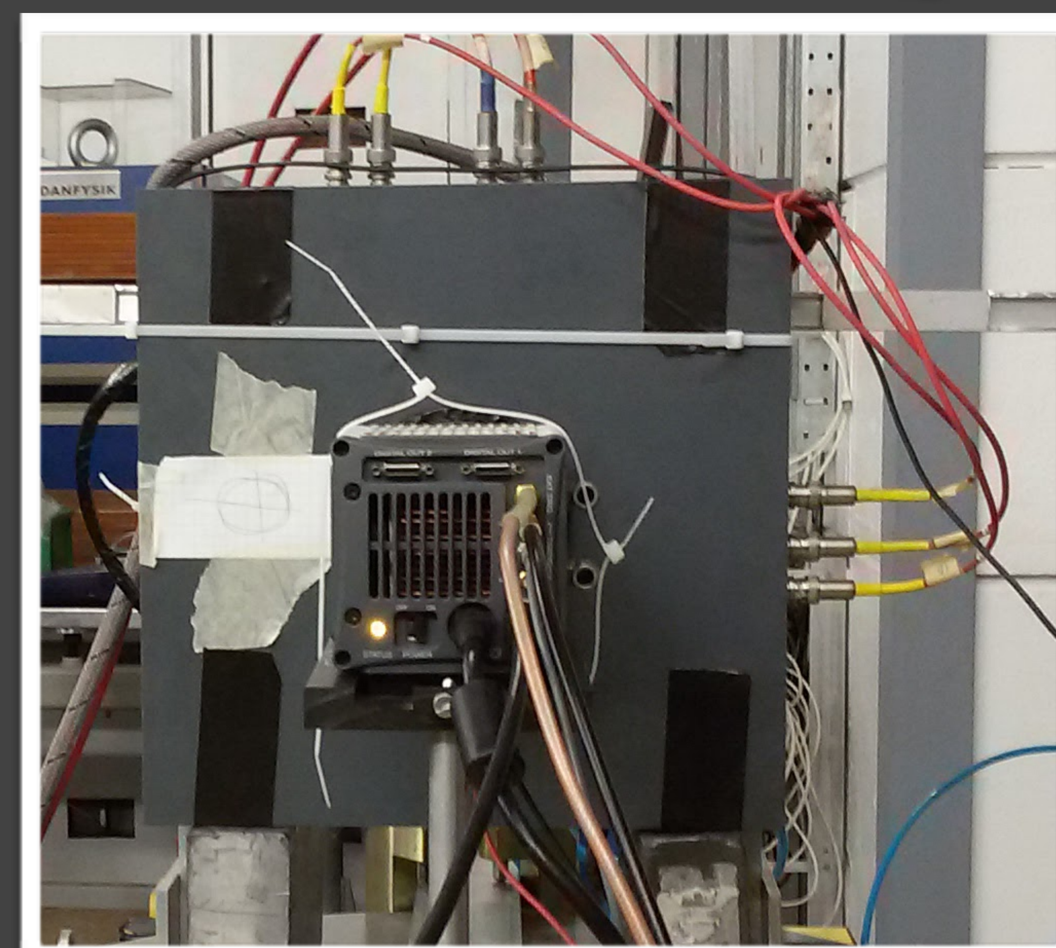
ORANGE

Transparent window is placed below the last GEM to close the gas volume



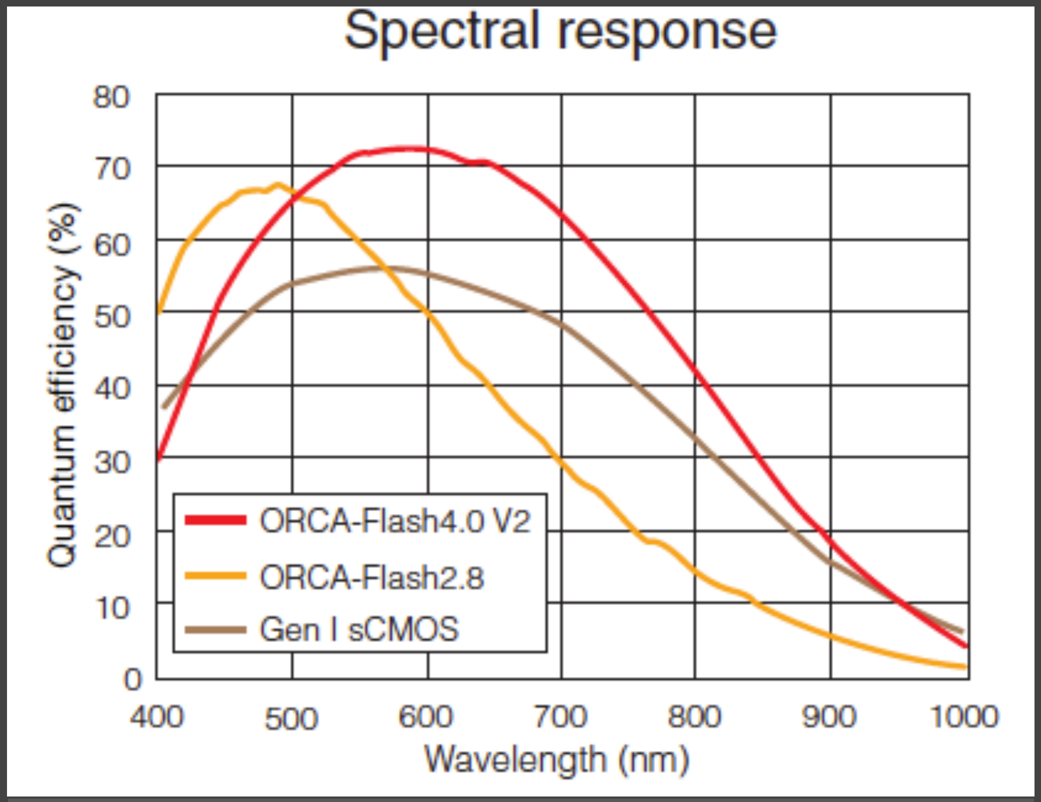


The box is then closed to be "light tight" and the light sensor is then coupled via a cylindric pipe



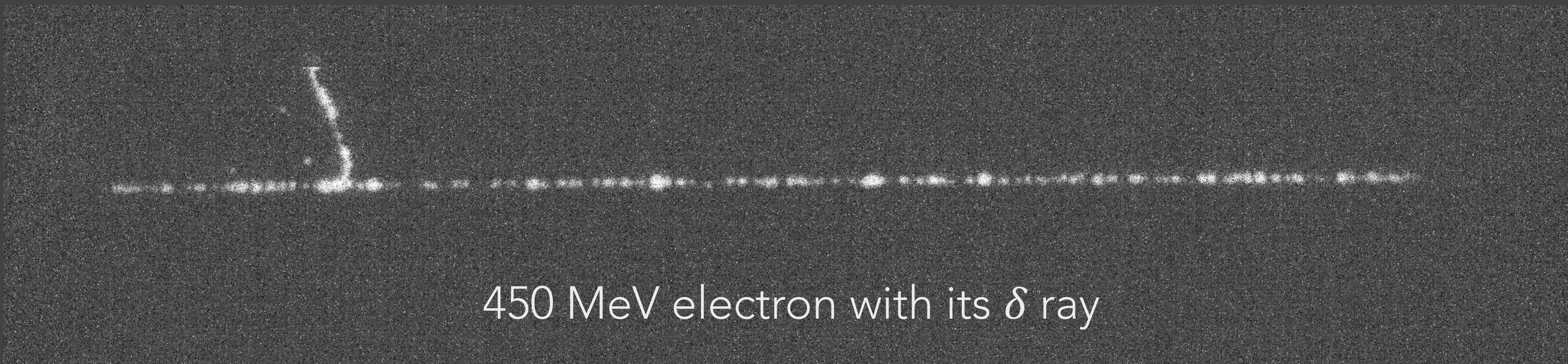
CMOS CAMERA

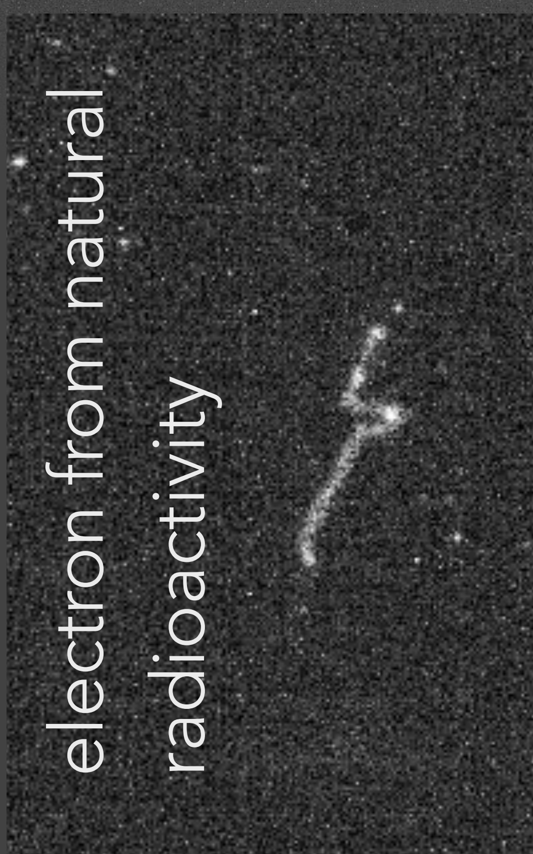
CMOS sensors provide very low noise together with high granularity and sensitivity

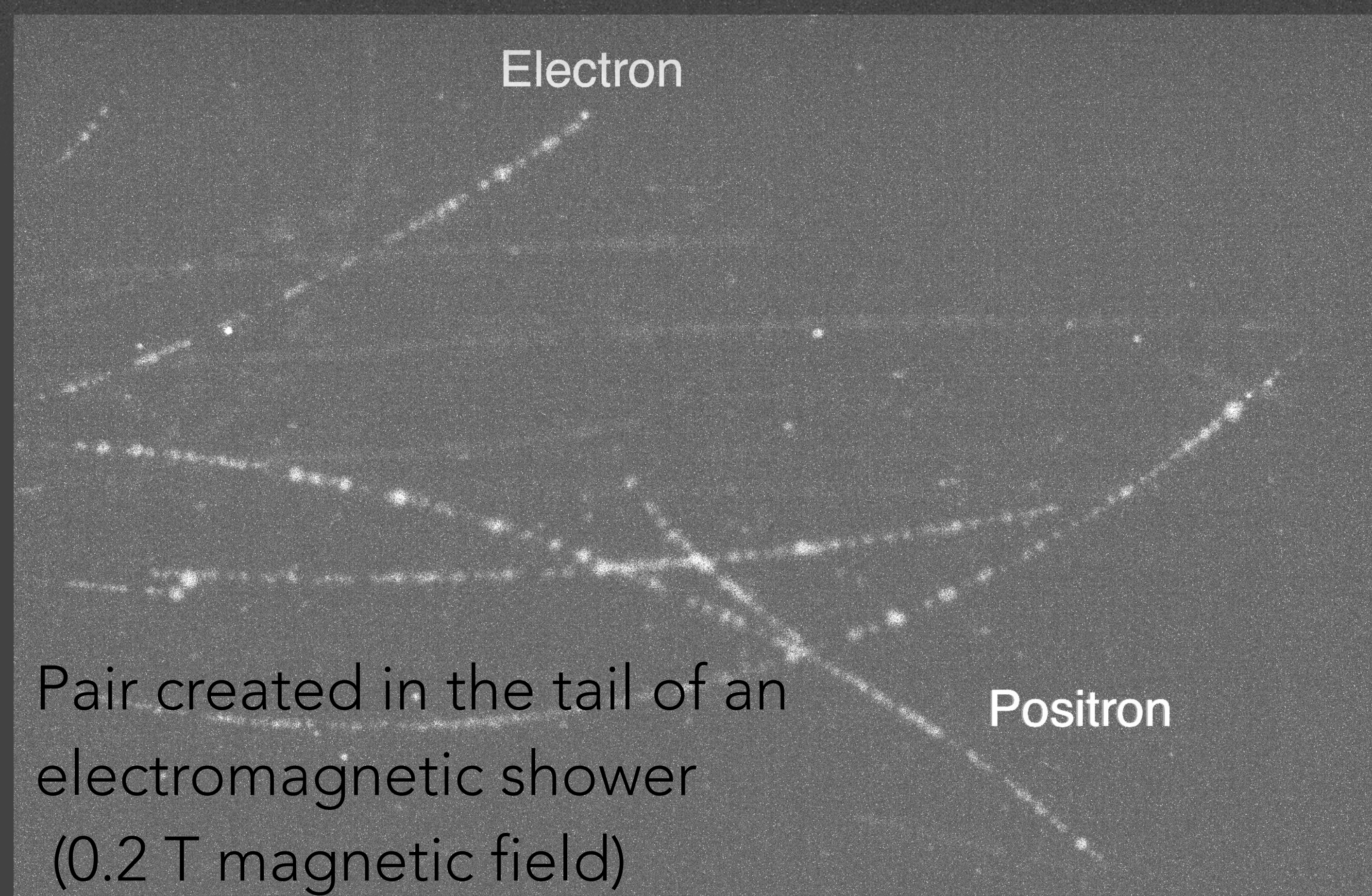


Equipped with a suitable large aperture (f/0.95) and a short focal length (25 mm) lens

PARTICLE TRACKS







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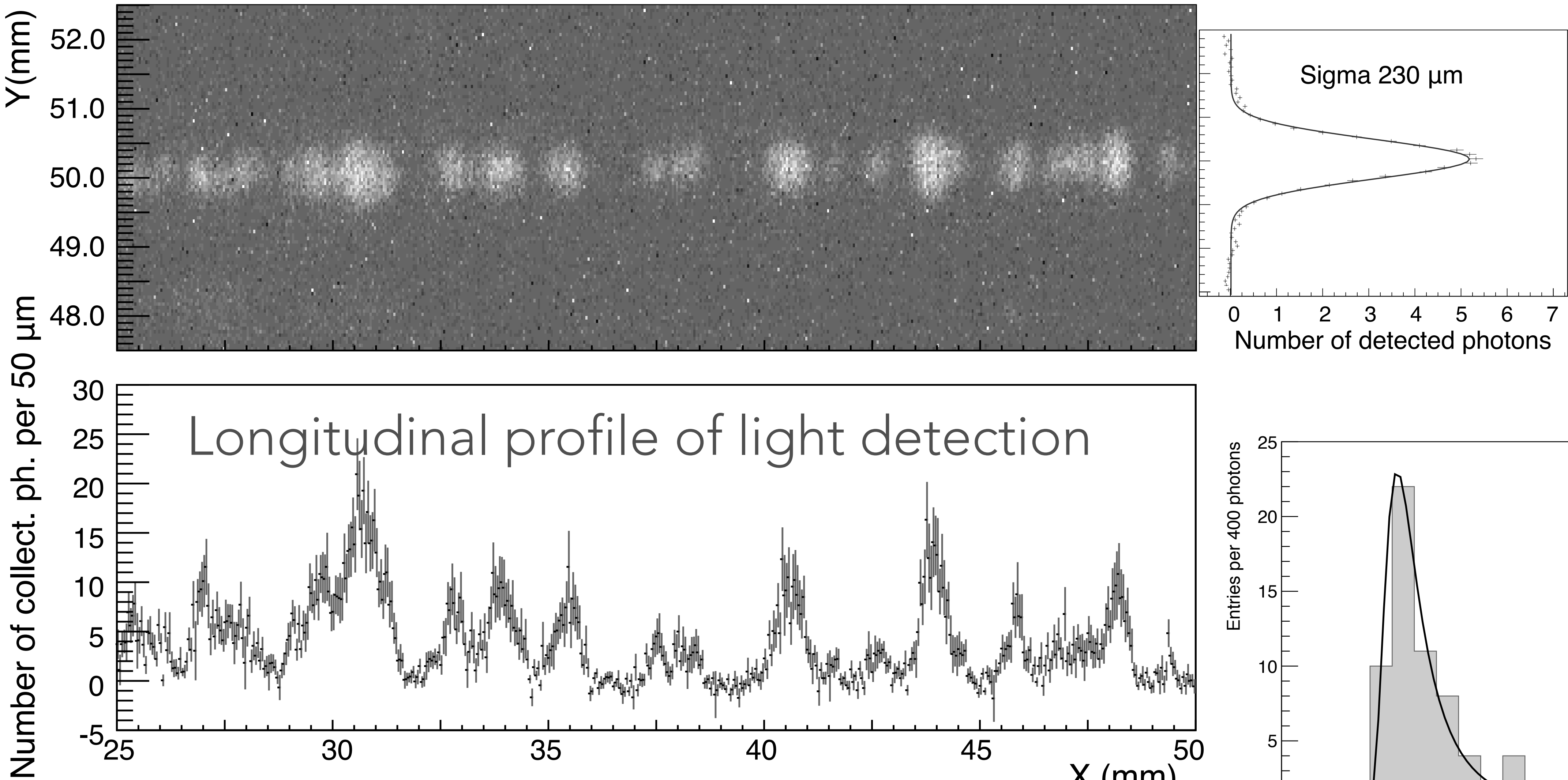
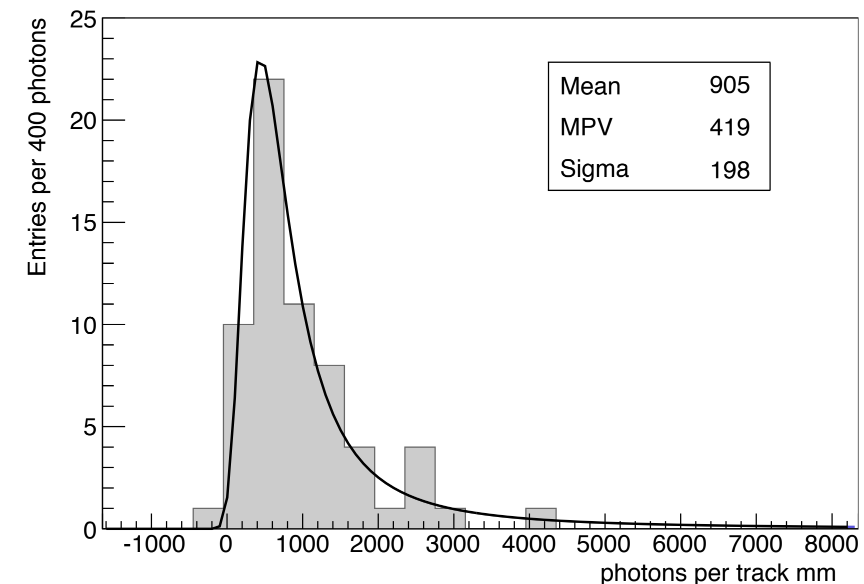
TRACKING PERFORMANCE

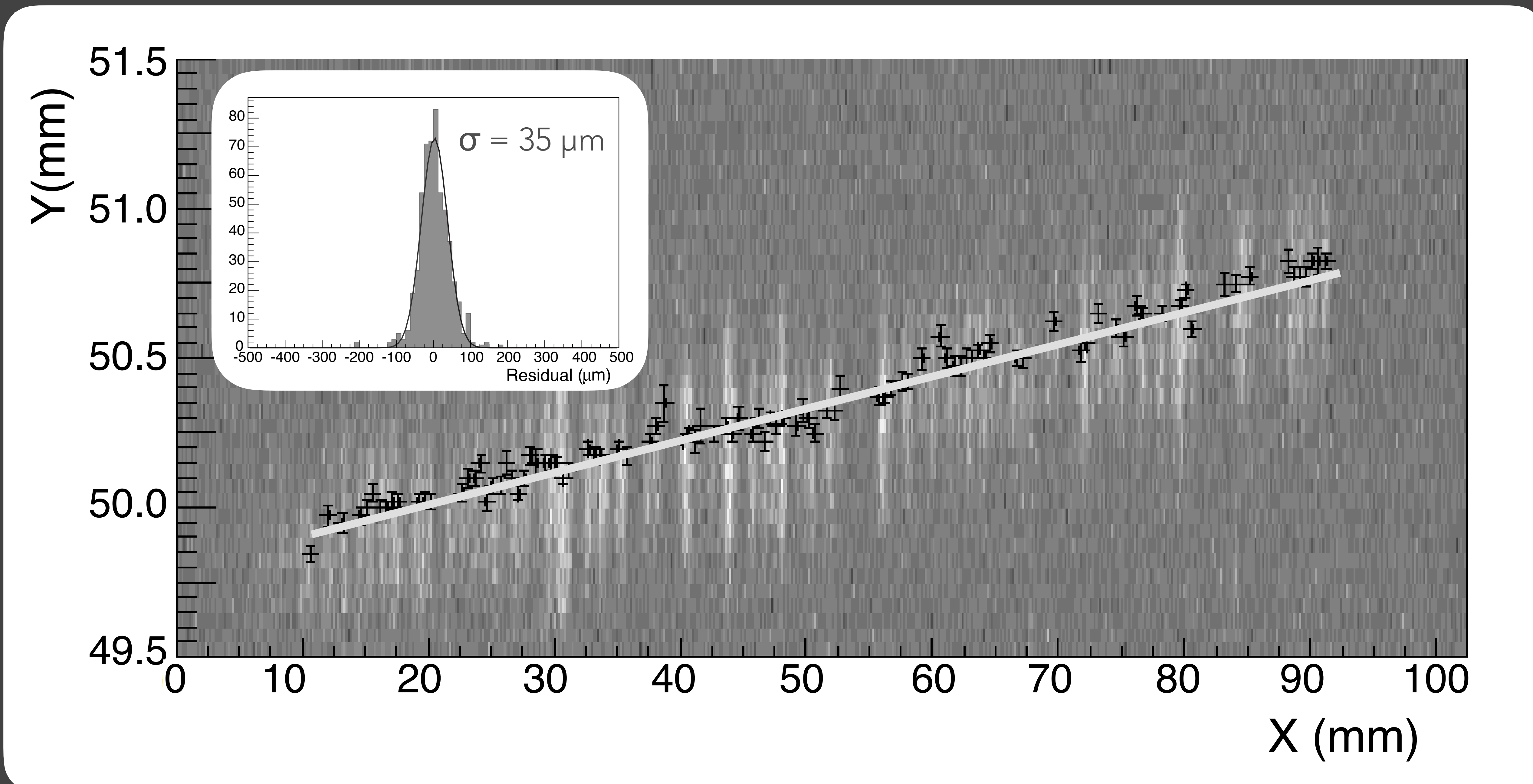


clear cluster structure



About 1000 detected photons per track millimetre, 150 per primary electron (i.e. each 40 eV released in gas).

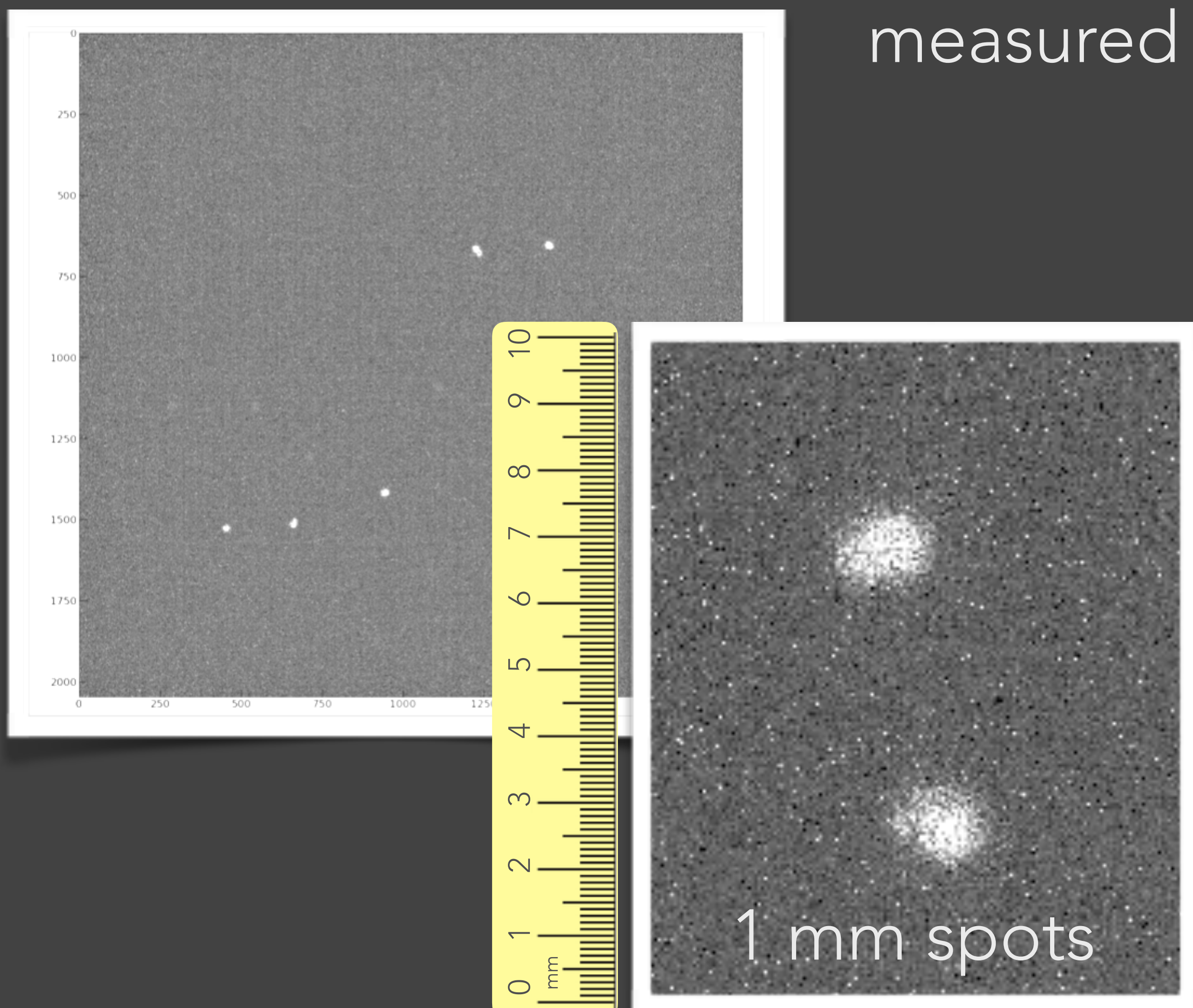
TRACKING PERFORMANCE

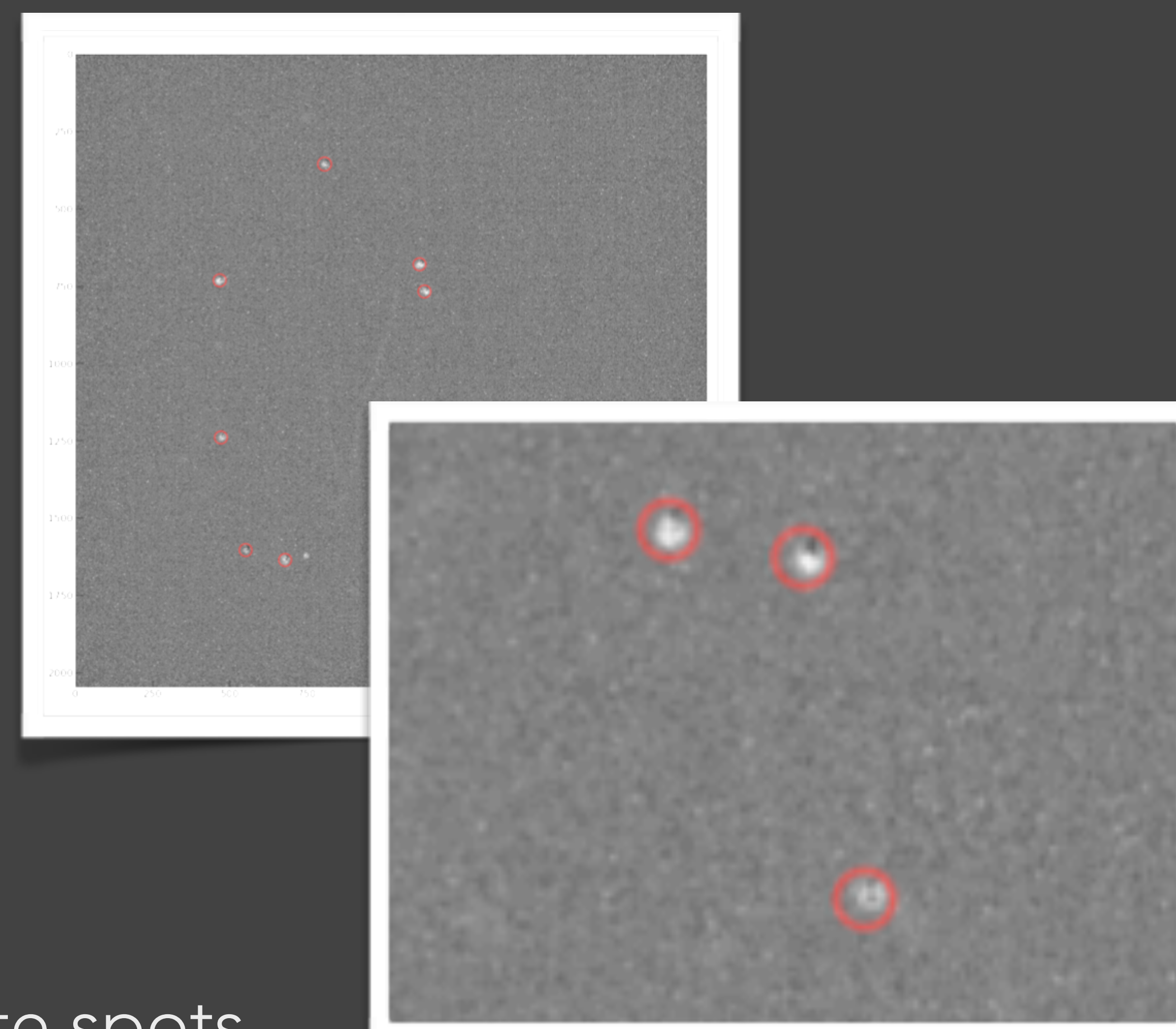


Space resolution of about 35 μm was evaluated from track cluster residuals.

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.

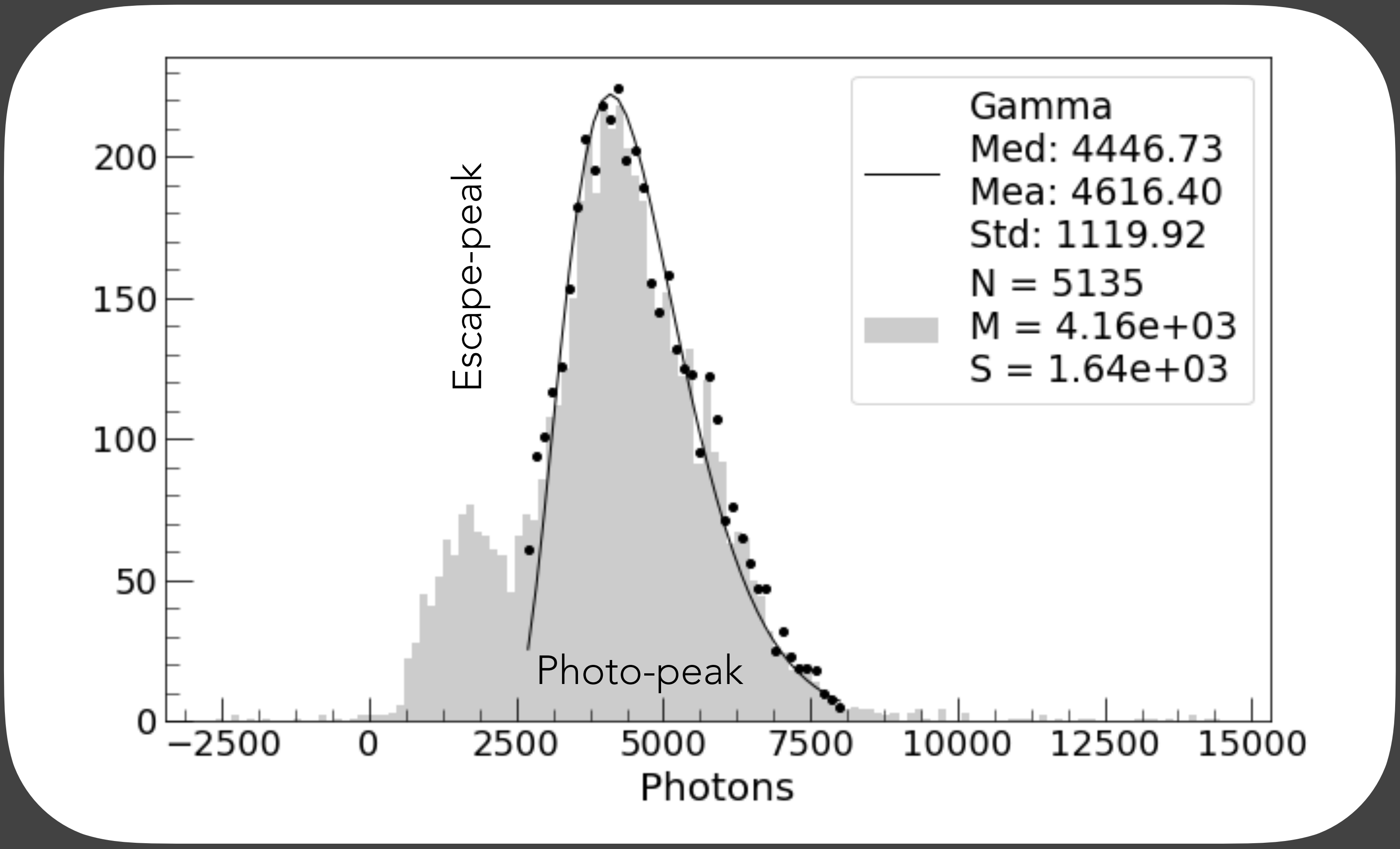




We used a Hough transform to individuate spots and measure their dimension and light yield.

X-RAYS FROM A ^{55}FE SOURCE

Light yield distributions were studied as a function of the mixture and the to the GEM voltages

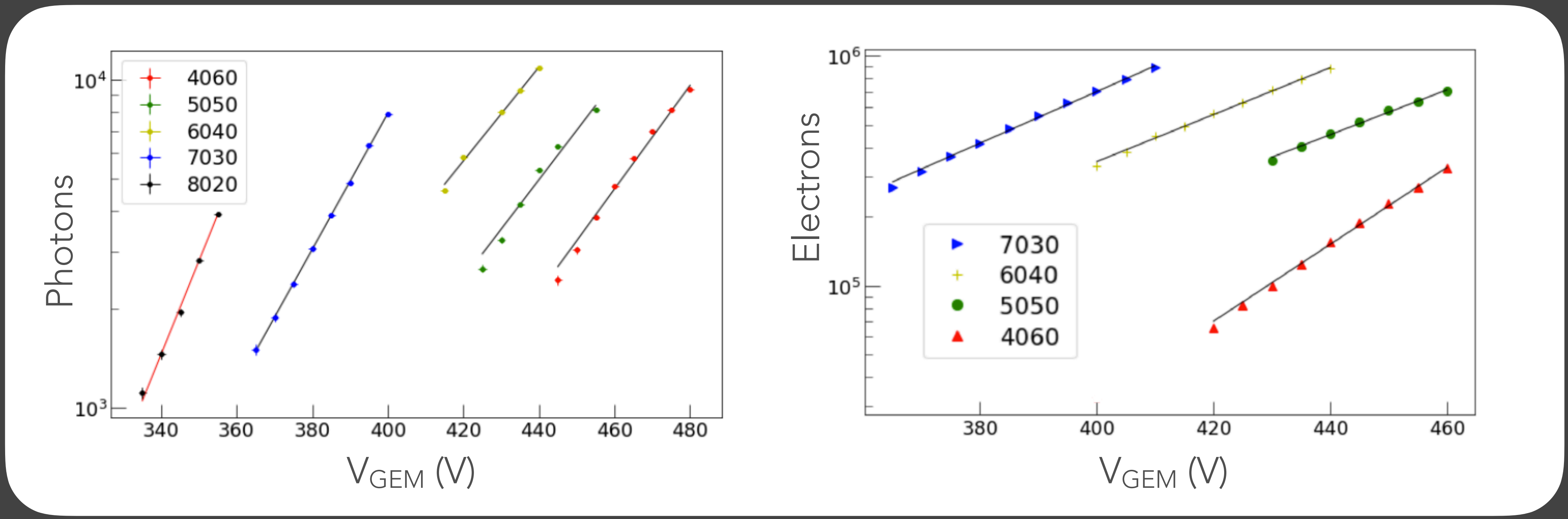


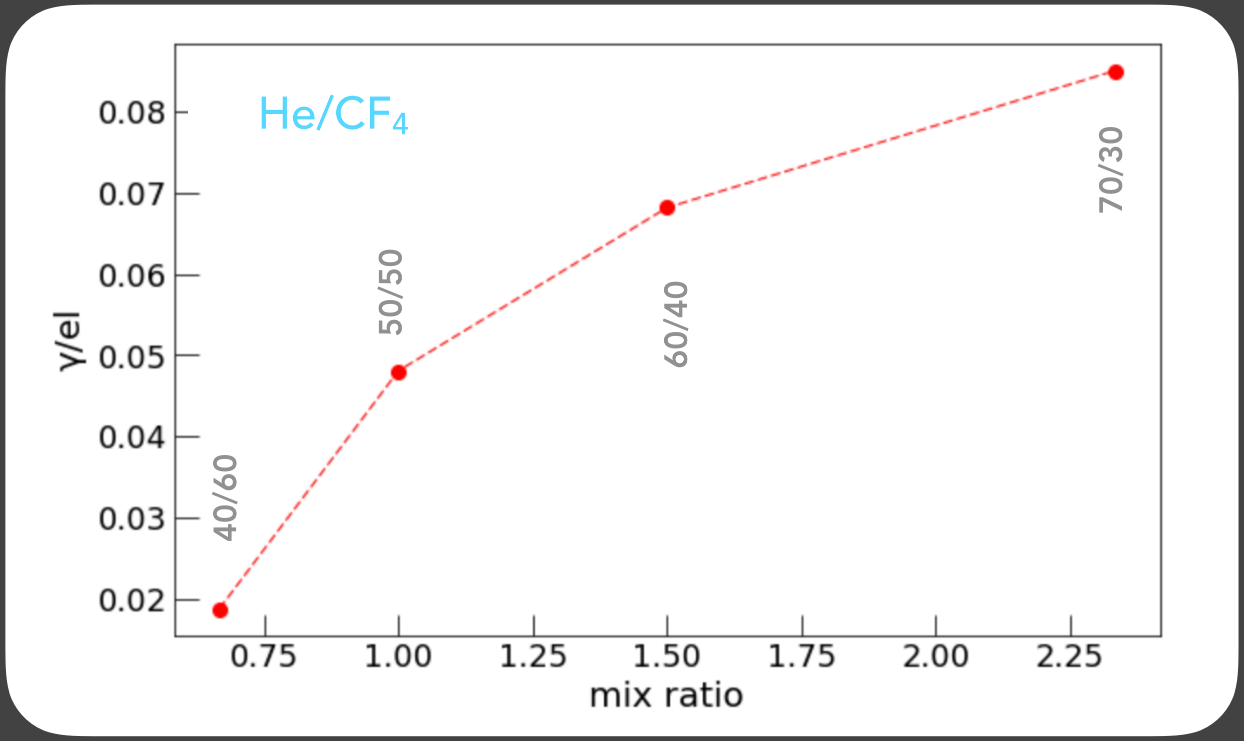
Peak positions and widths were evaluated by a Polya fit

By means of an X-ray tube, electron yield was also studied for different mixtures and different voltages.

X-RAYS FROM A ^{55}FE SOURCE

The two set of measurements were thus compared.

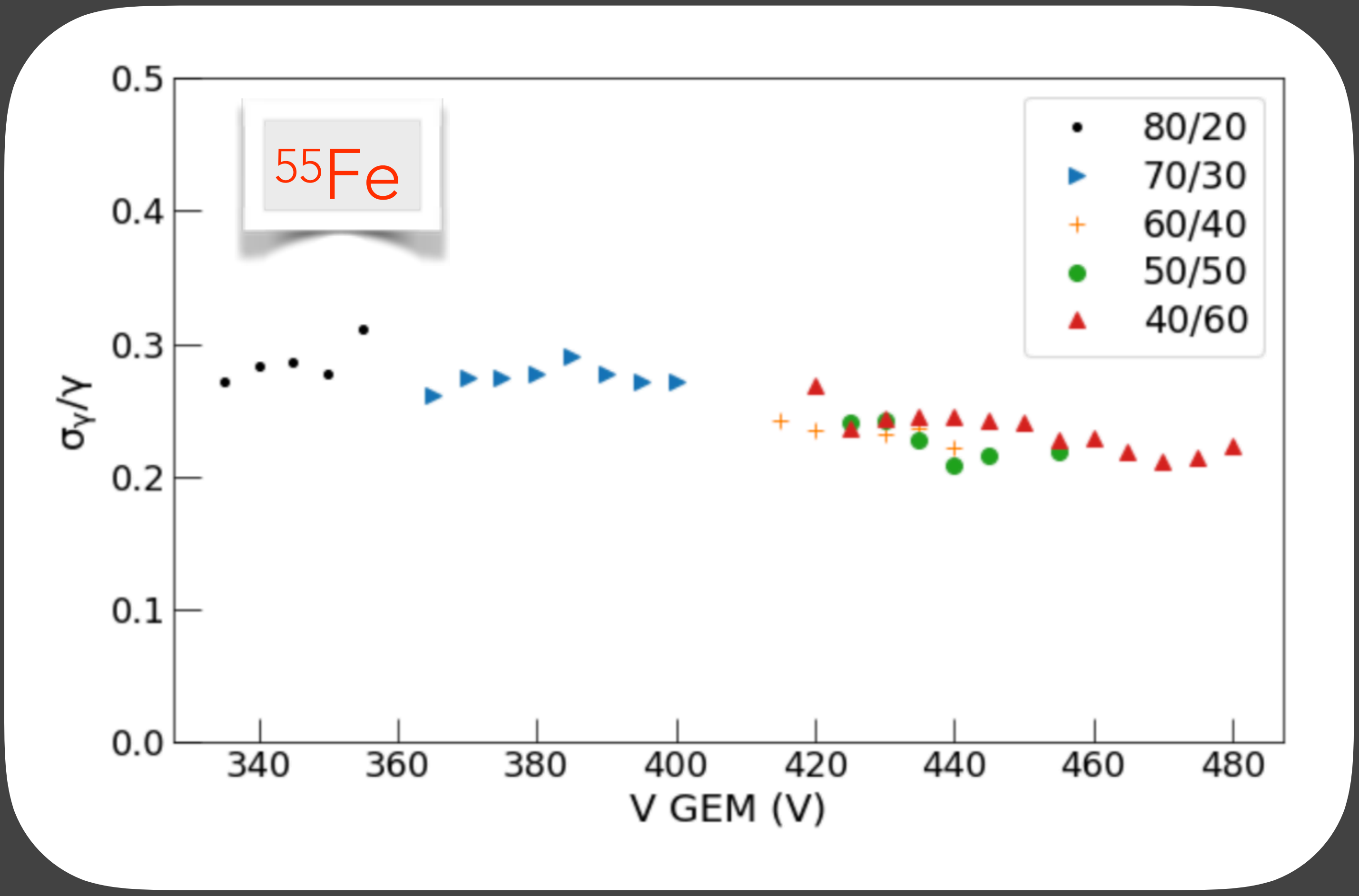


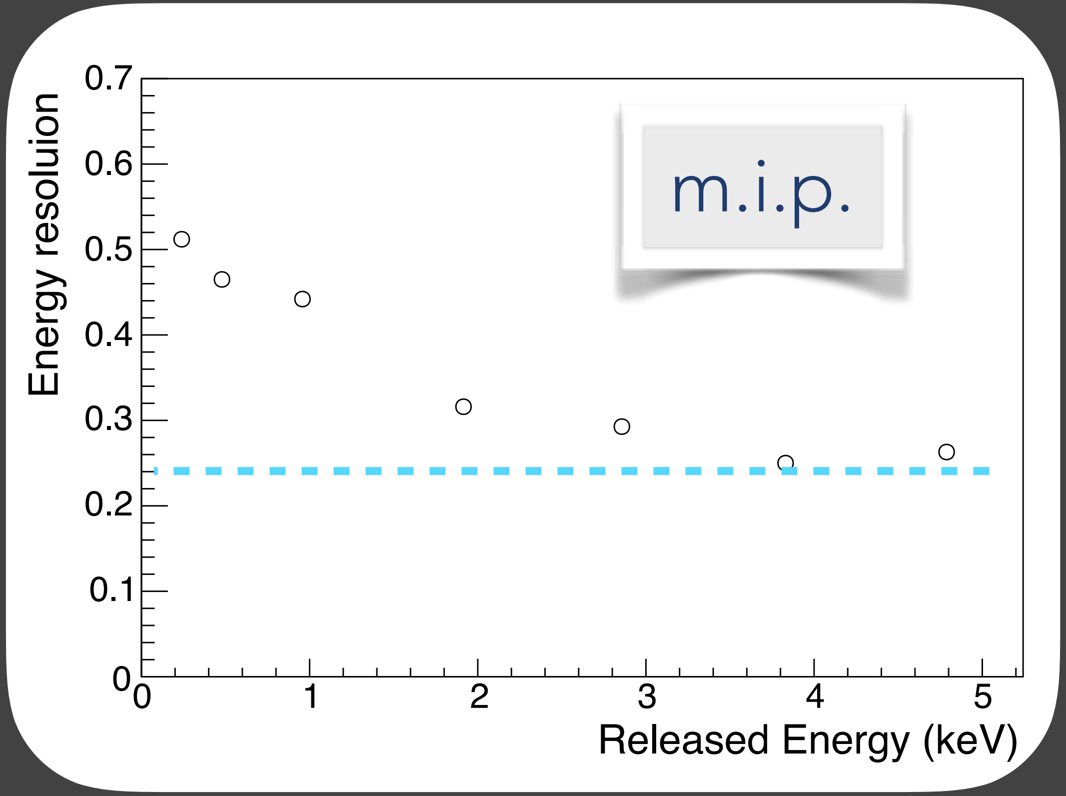


Between 2 and 8 photons are created per 100 electrons in the GEM channels

ENERGY RESOLUTION

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

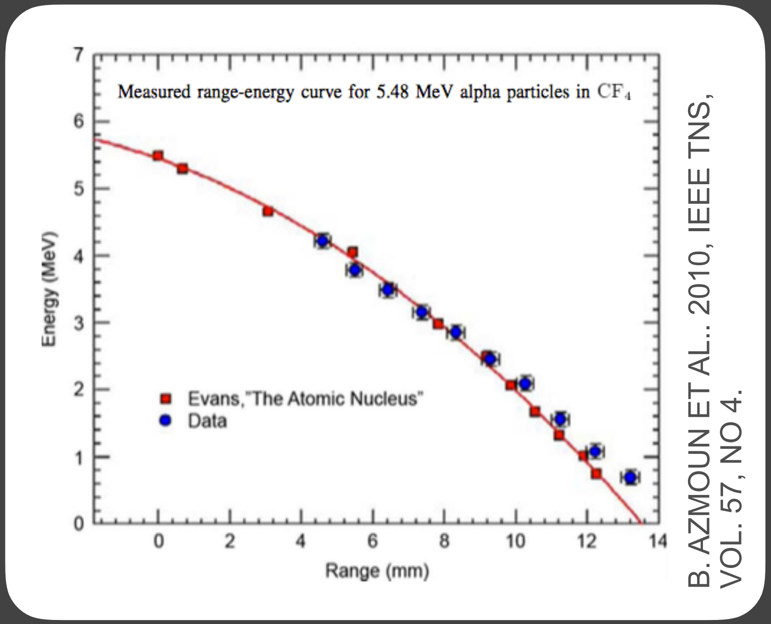


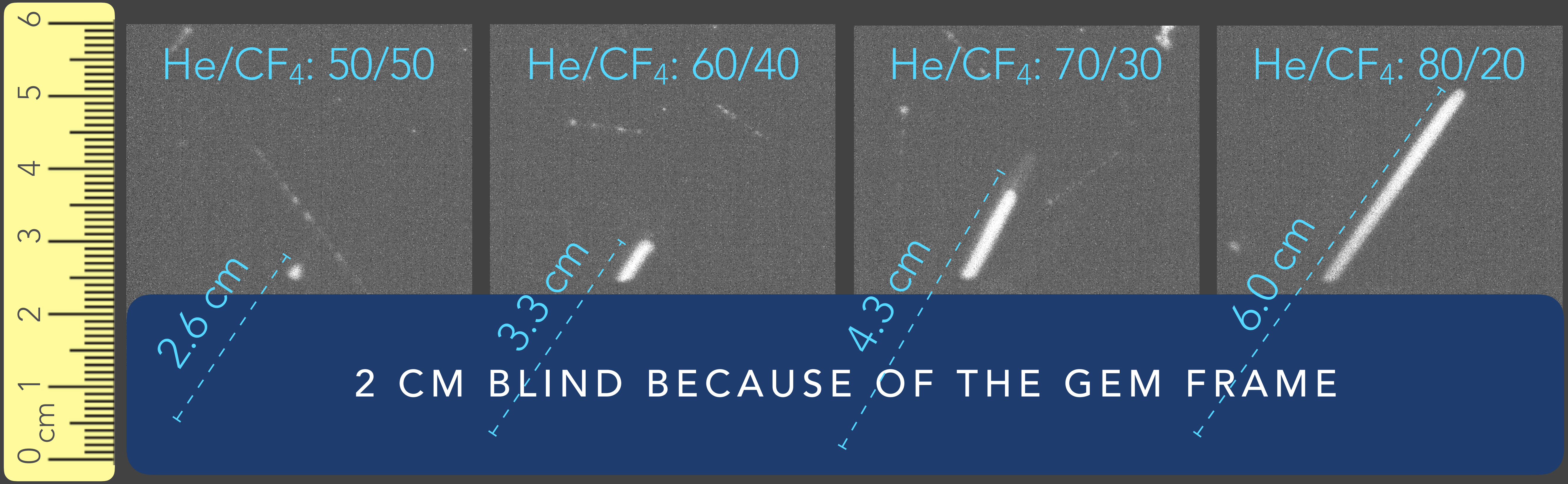


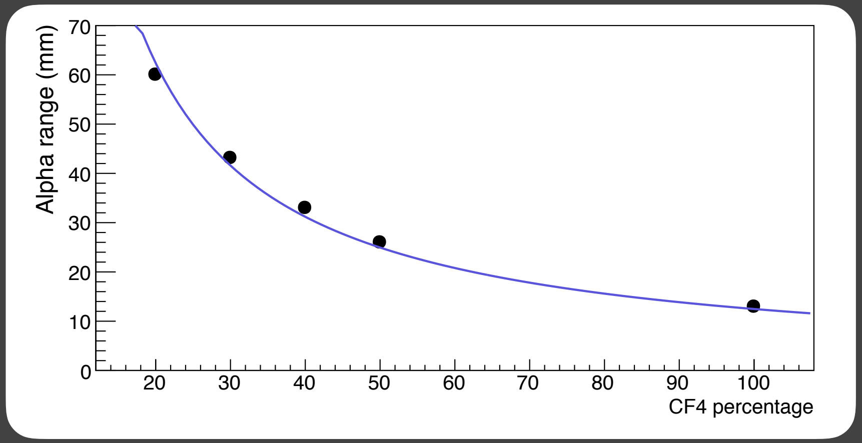
This result is in good agreement with what was evaluated subdividing mip tracks in "slices" of various widths (1 mm - 2 cm) with an released energy simulated by Garfield of 2.4 keV/cm;

ALPHA TRACKS

5.48 MeV alpha particles have a range of 13 mm in pure CF_4;



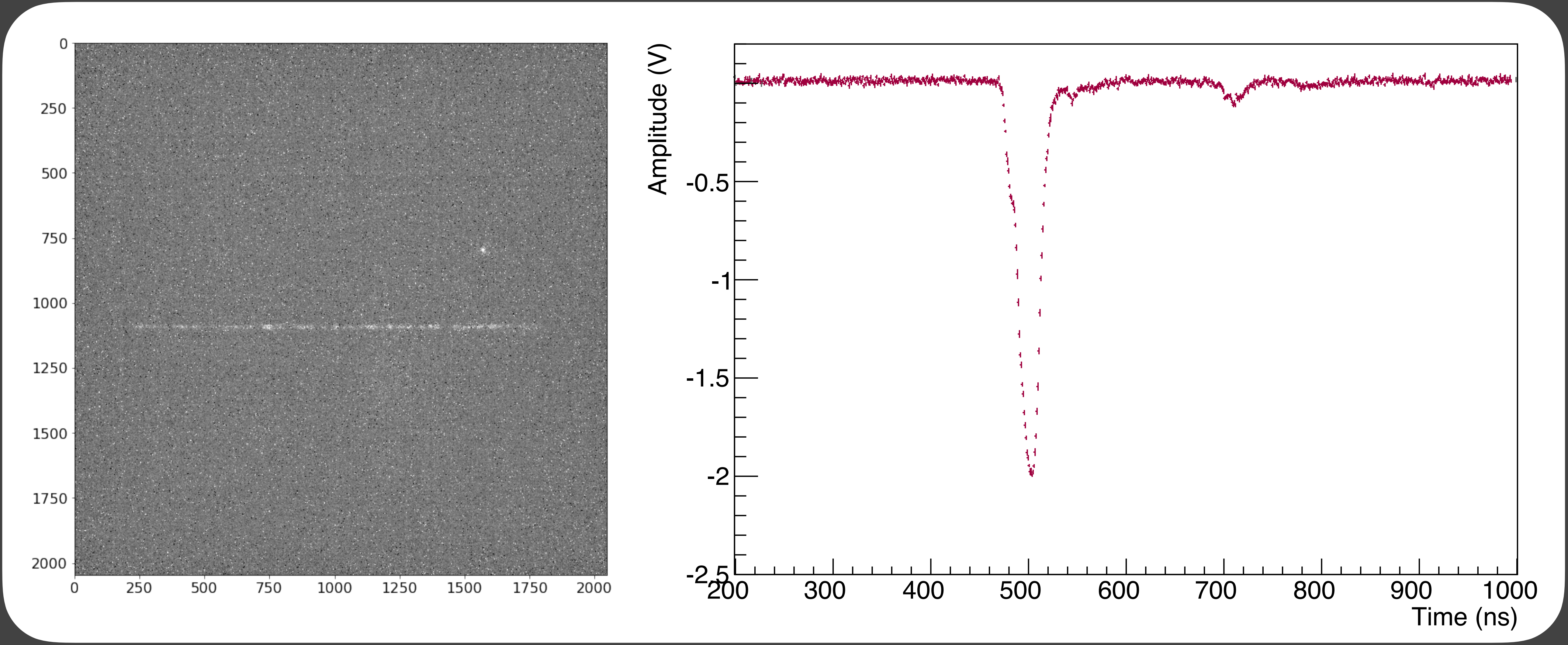




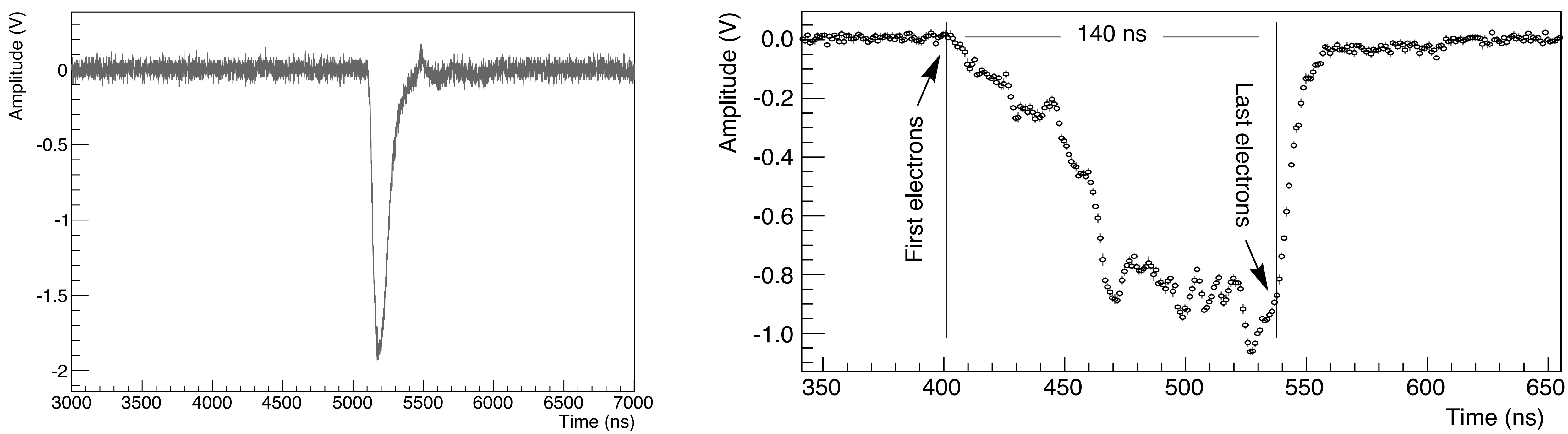
From preliminary measurements, alpha range seems to be "determined" only by CF_4 and to decrease linearly with its amount

COMBINED LIGHT READOUT

CMOS granularity provides useful measurements about X and Y of the track;
The Z coordinate can be extracted from time measurement (TPC mode);
In order to get precise information about the time structure of the signal, light can be concurrently readout with a PMT;



COMBINED LIGHT READOUT

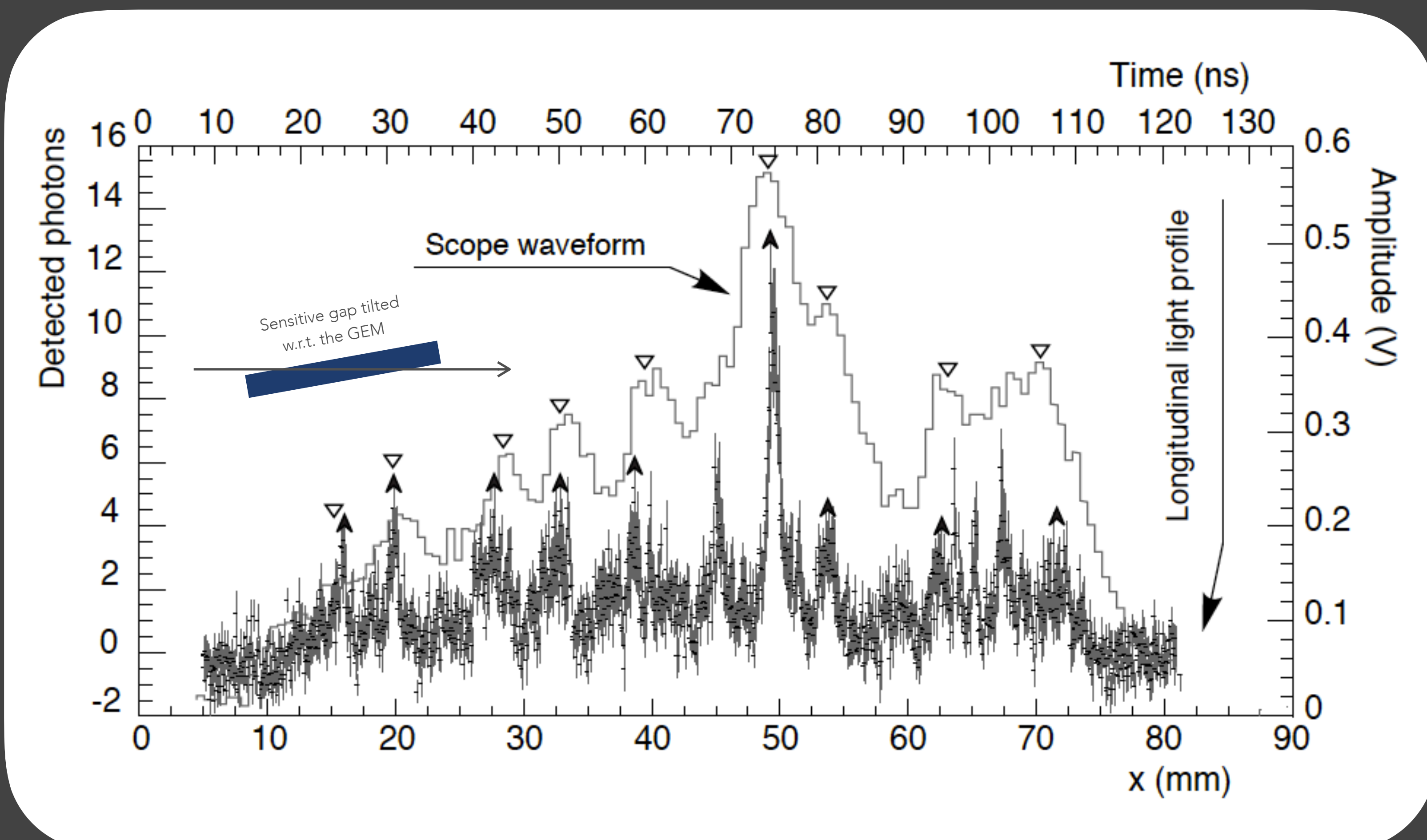


1 cm in 140 ns => drift velocity 7.2 cm/μs in agreement with Garfield expectation of 7.3 cm/μs.

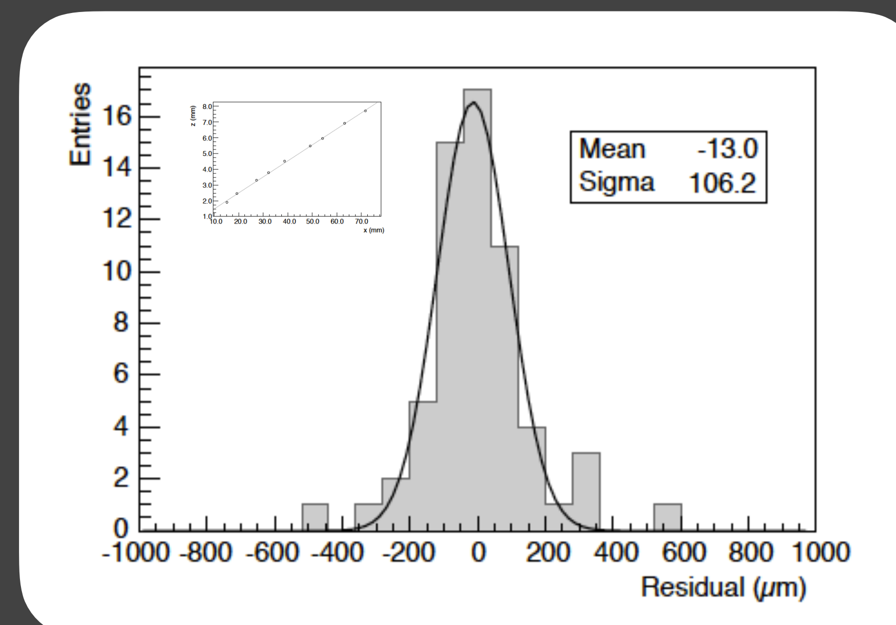
PMT+CMOS COMBINED READOUT

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;



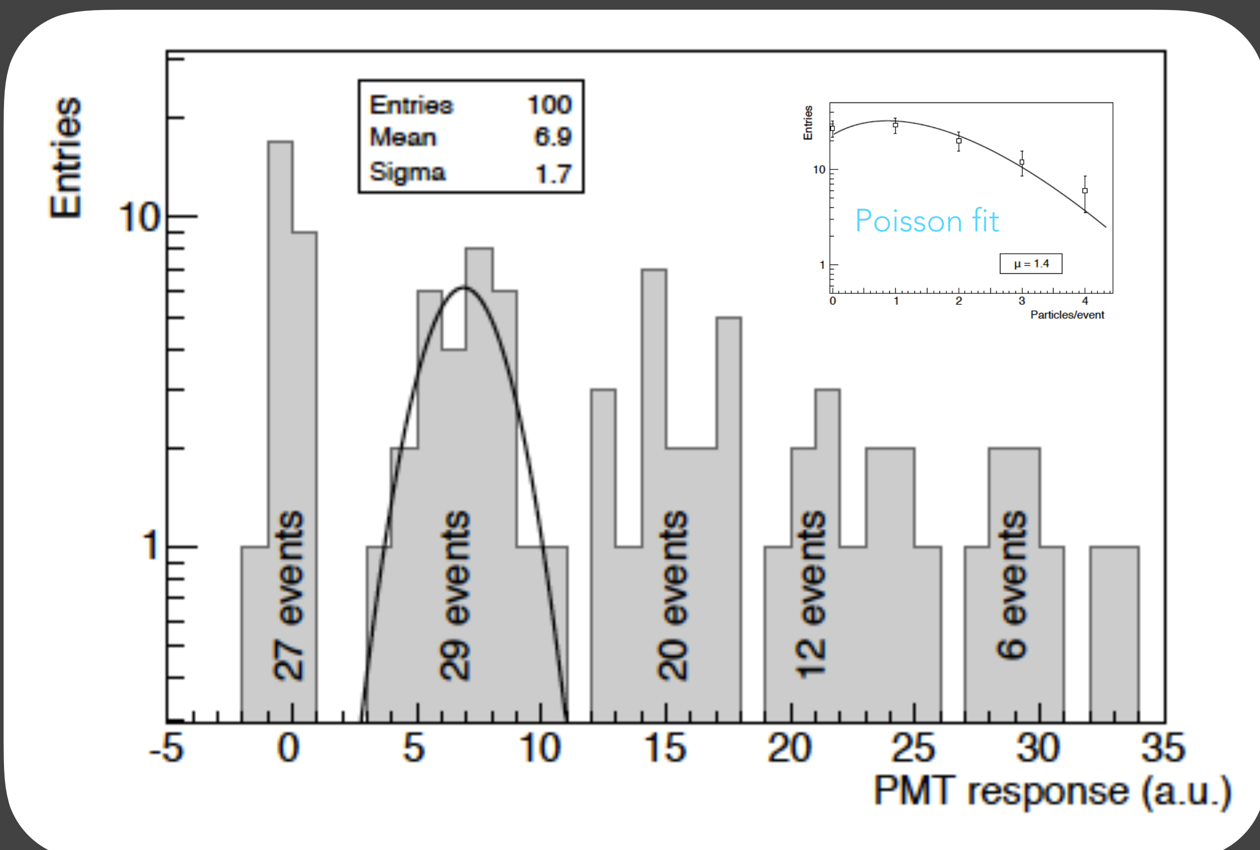
By means of the measured drift velocity, Z coordinate was evaluated;



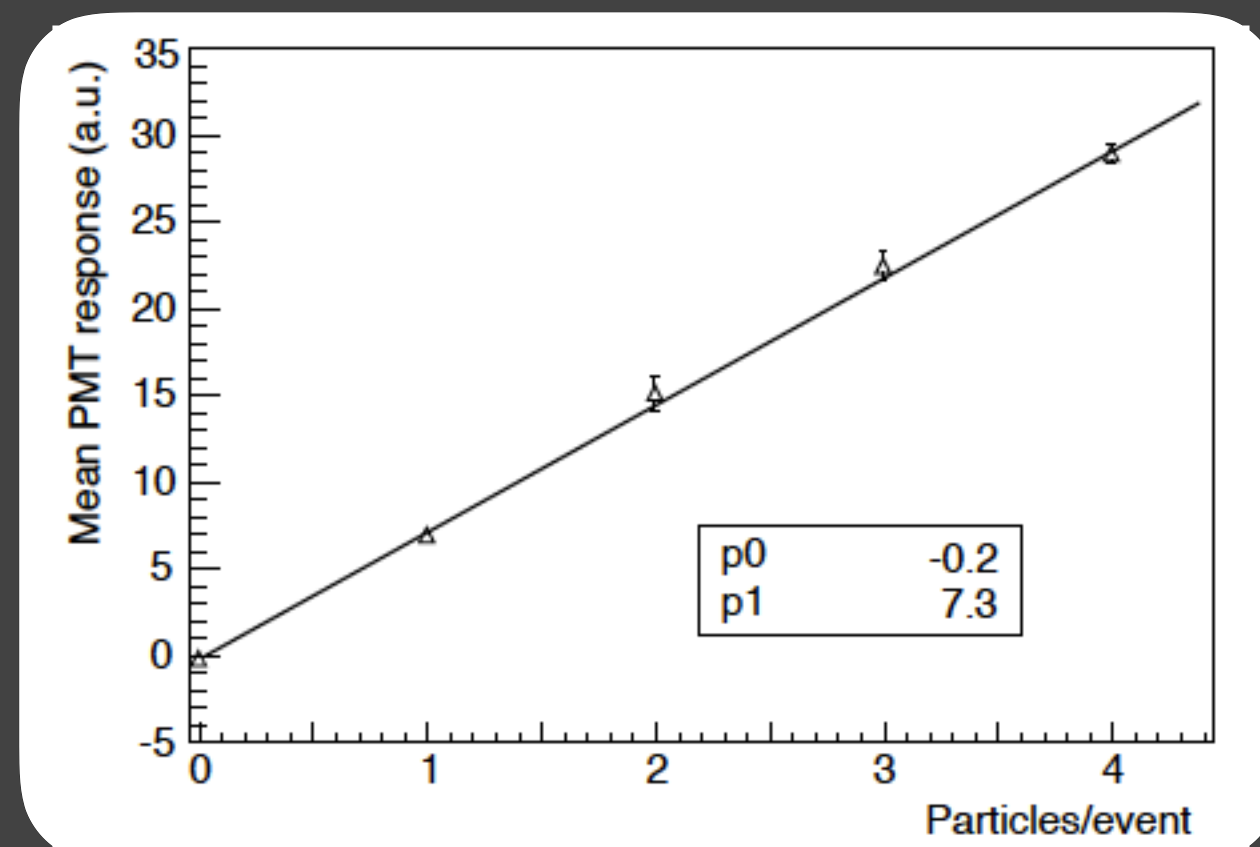
Residual distribution to a 3D fit allows to compute a resolution on Z of 100 μm.

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 %



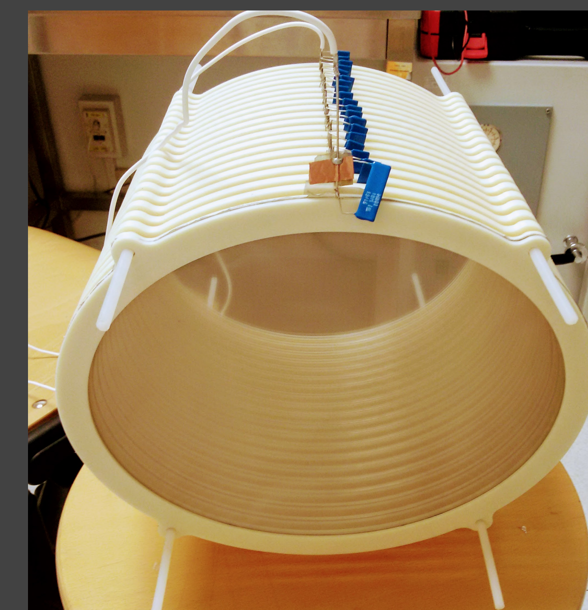
A very good linearity was found.

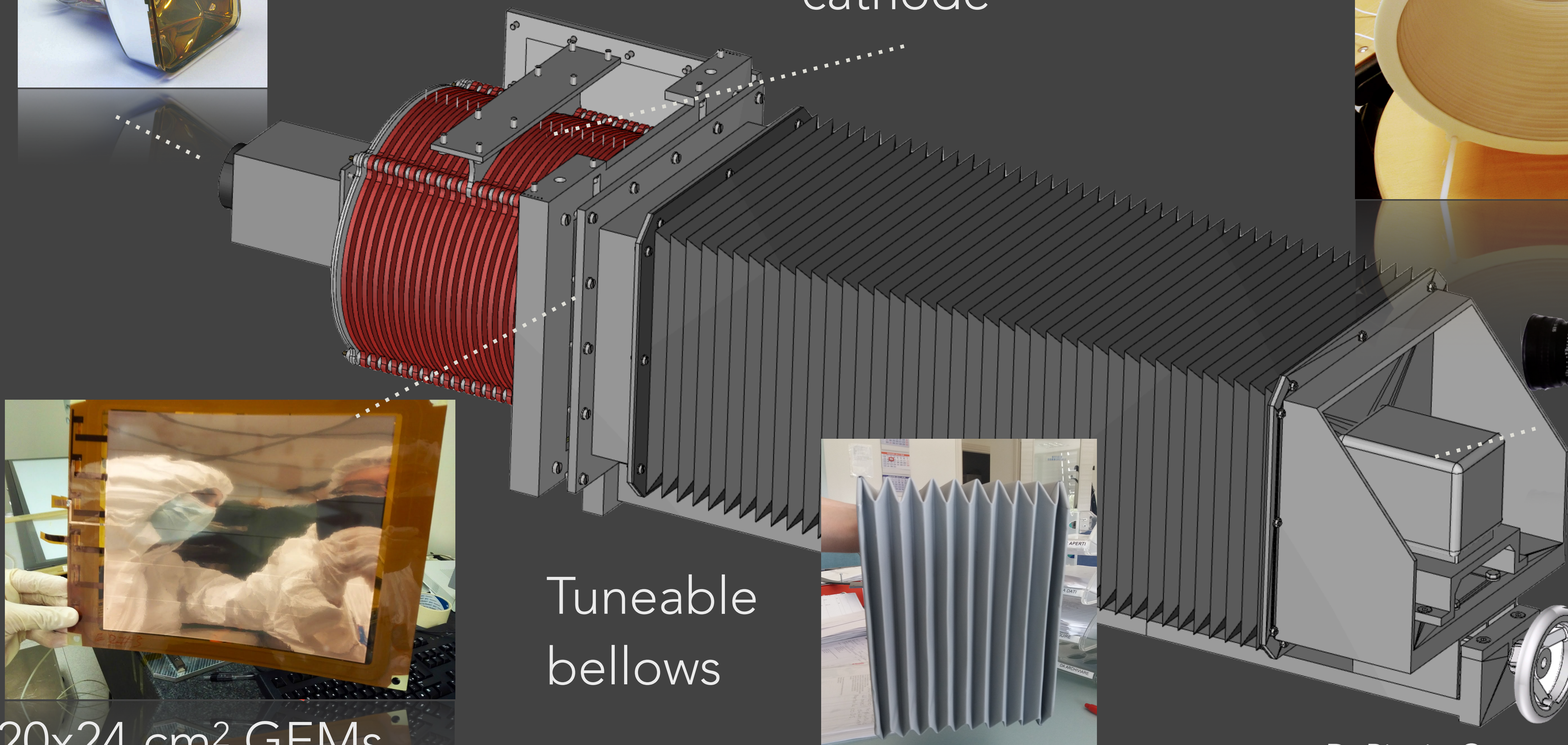
LARGE PROTOTYPE

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





CMOS camera

20x24 cm^2 GEMs

Tuneable bellows

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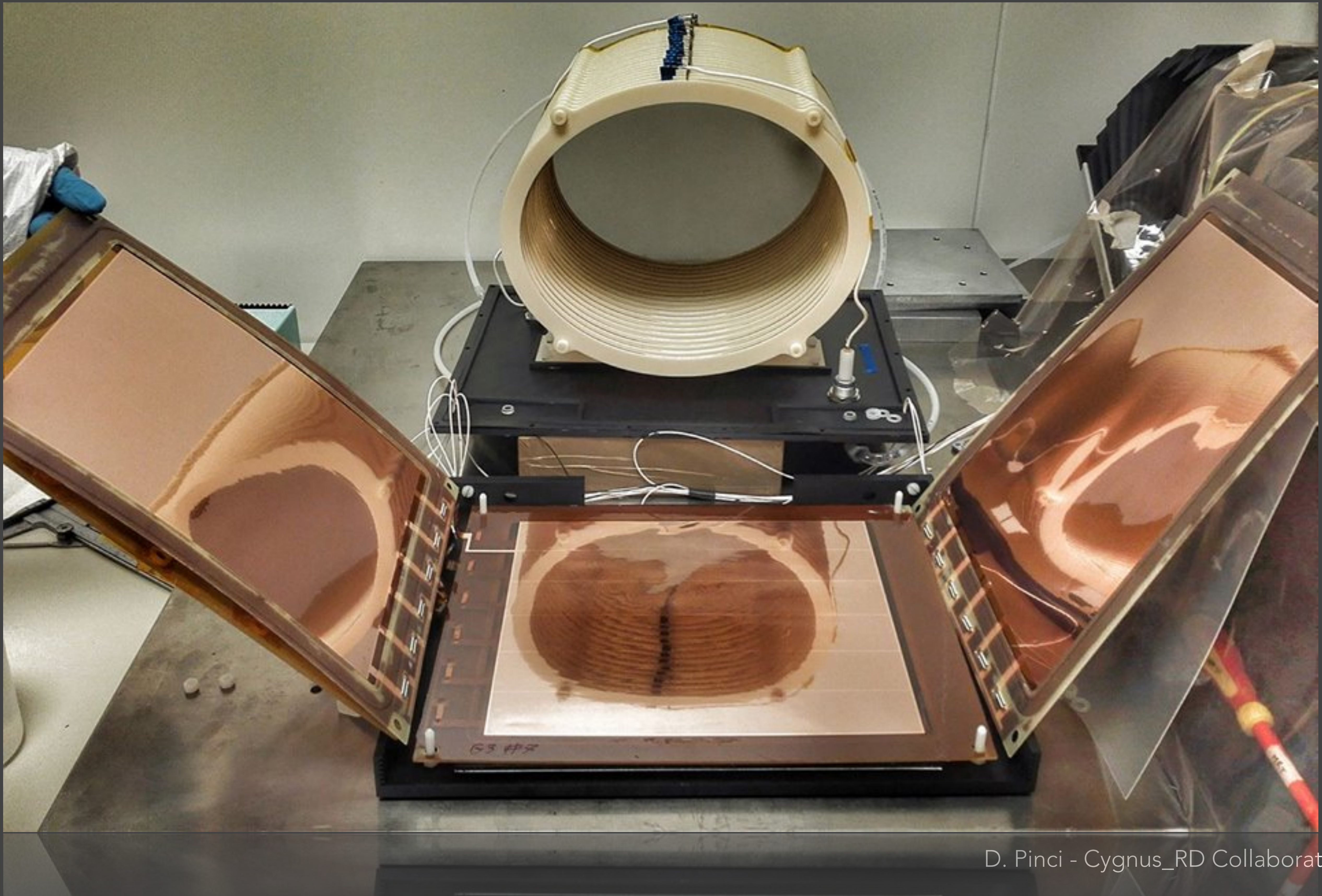
INSIDE THE LEMON PROTOTYPE

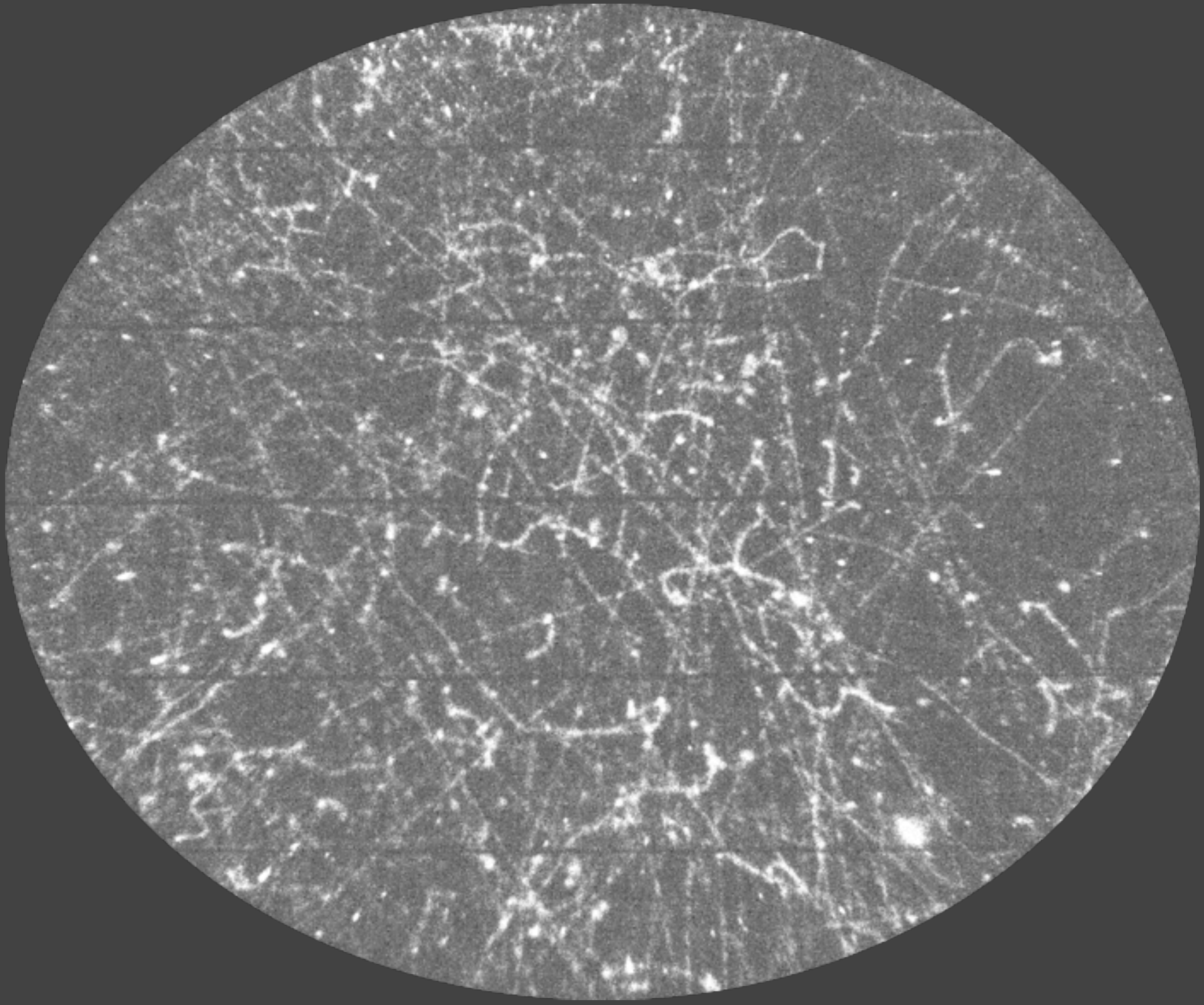


THE LEMON PROTOTYPE

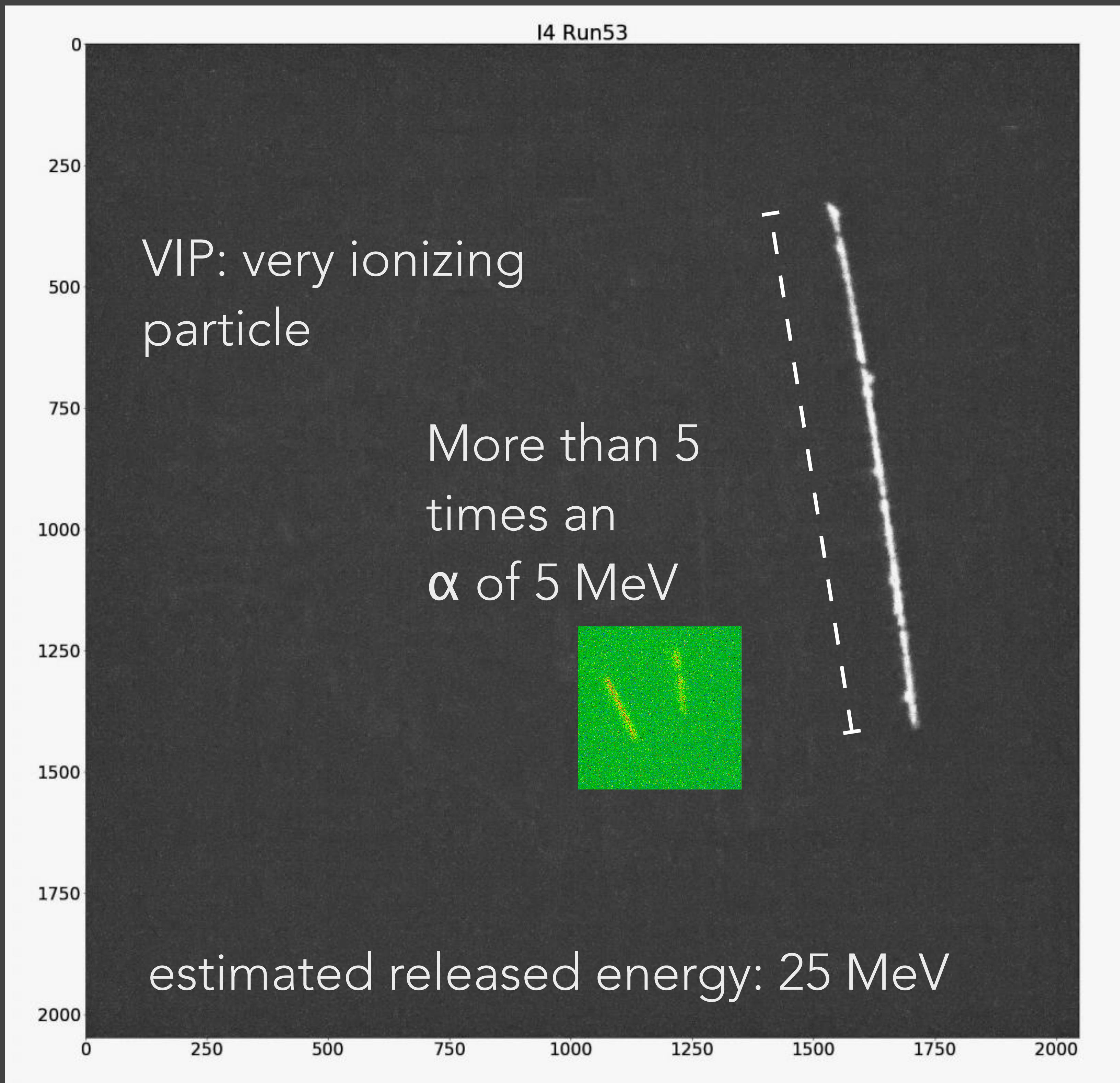
laboration

LEMON: FIRST RESULT

5 sec of natural background



LEMON: V.I.P.



VIP: very ionizing particle

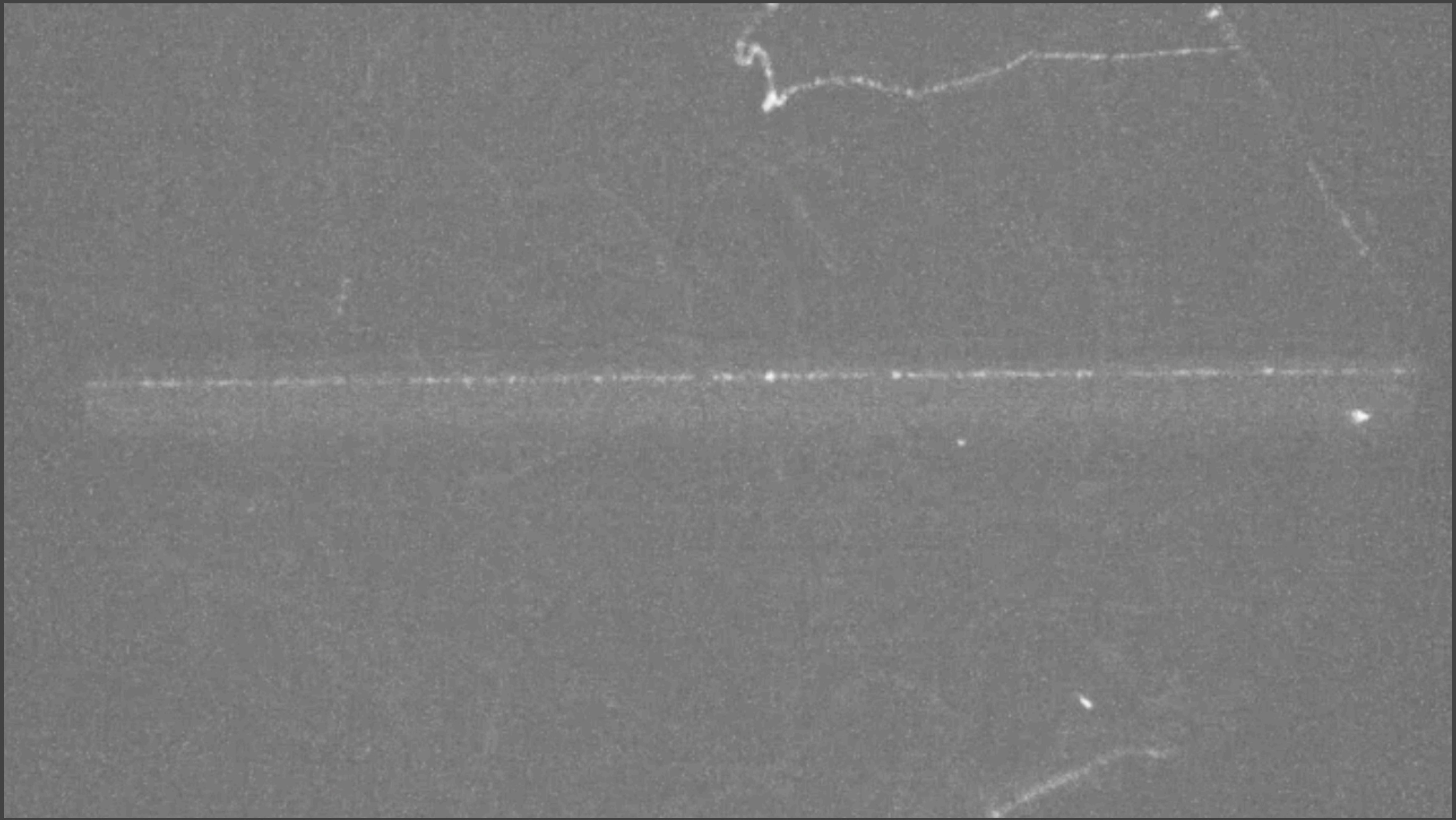
More than 5 times an α of 5 MeV

estimated released energy: 25 MeV

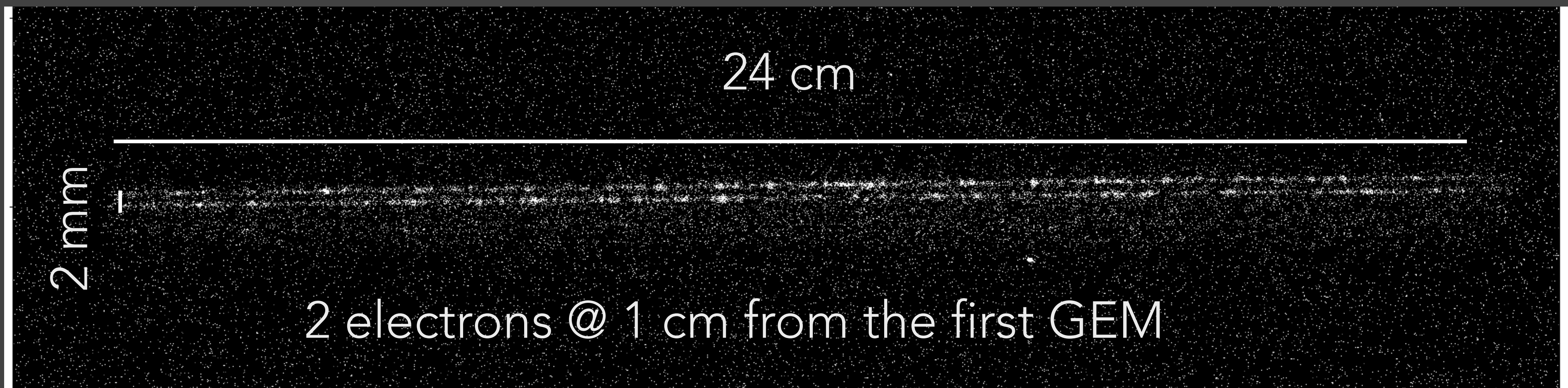
α particles light collected by 2 GEM

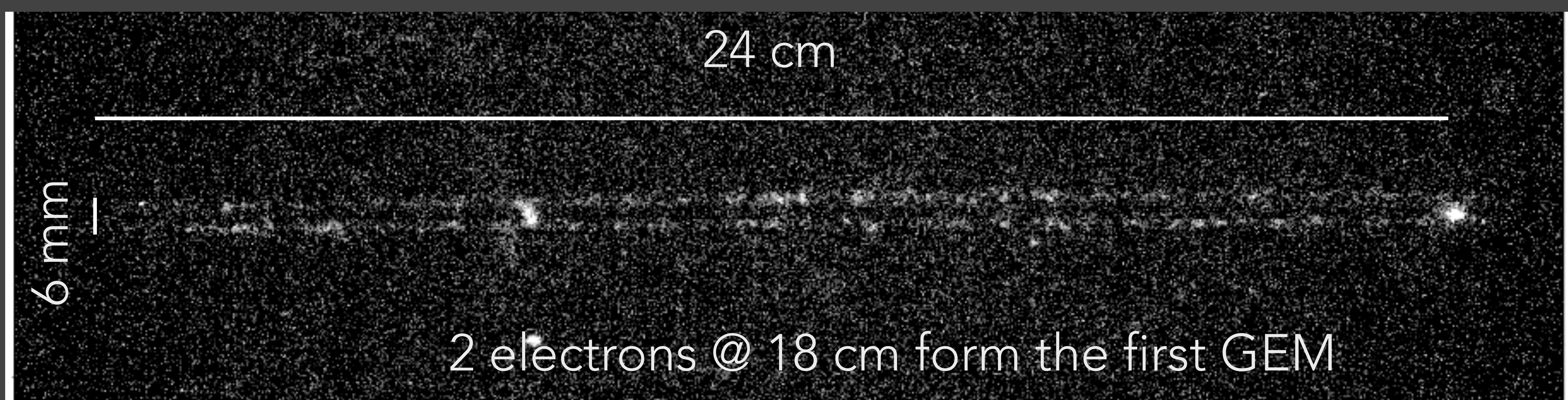
6.25 cm window

LEMON: ELECTRONS AT BTF



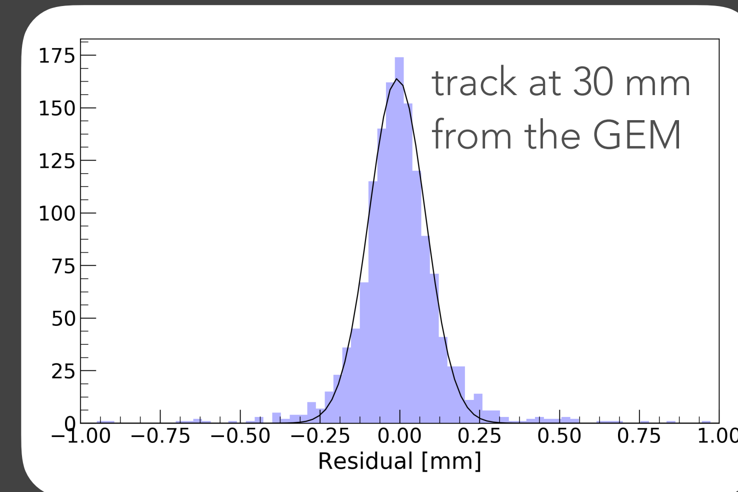
LEMON: TRACK SEPARATION

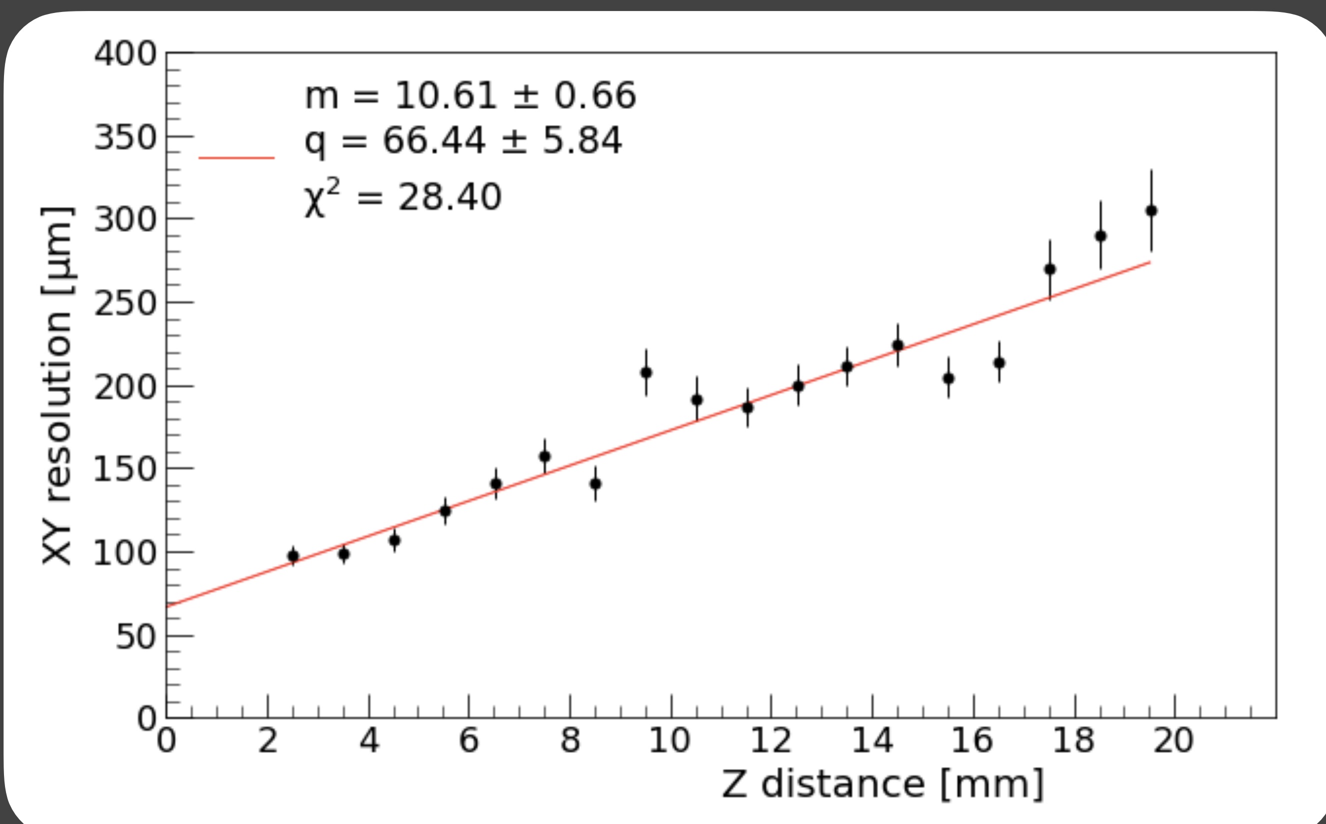




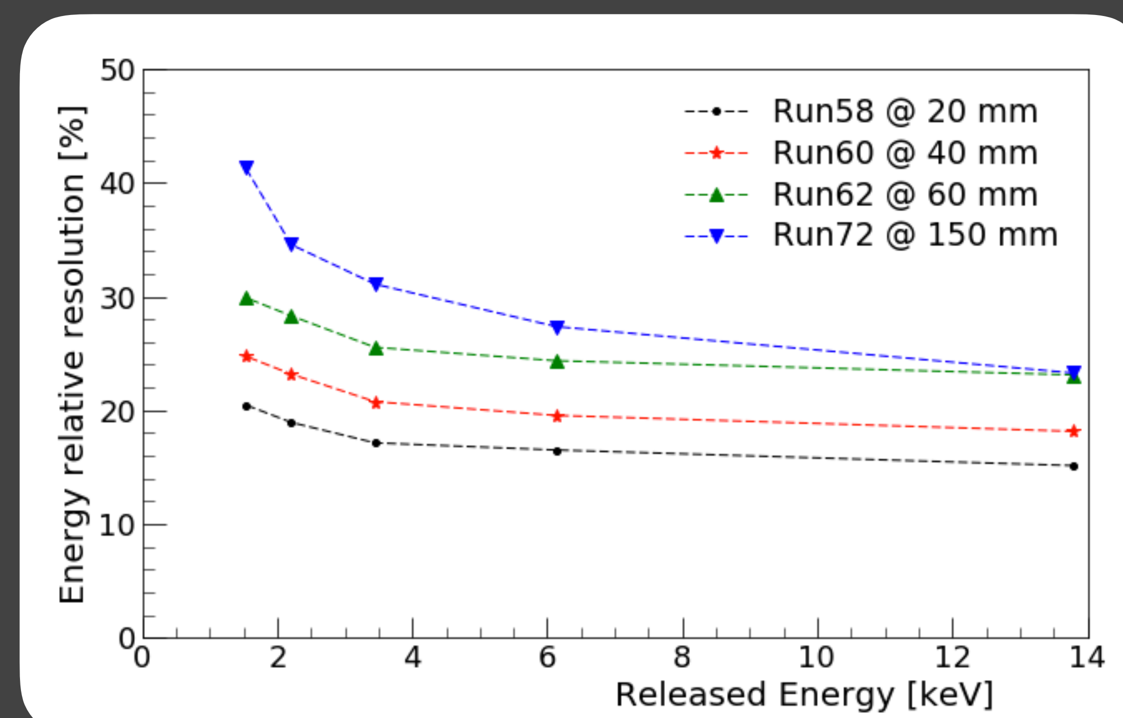
SPACE AND ENERGY RESOLUTION (X,Y)

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;





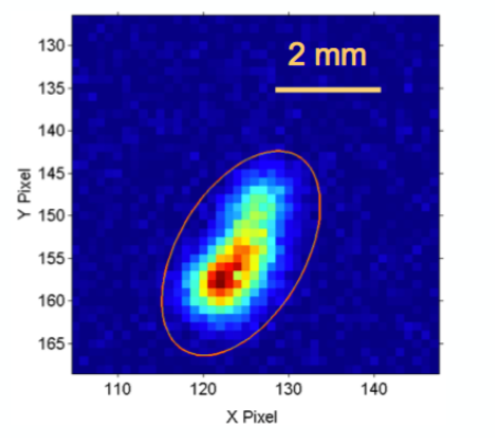
Energy resolution was studied at different depths (Z).



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

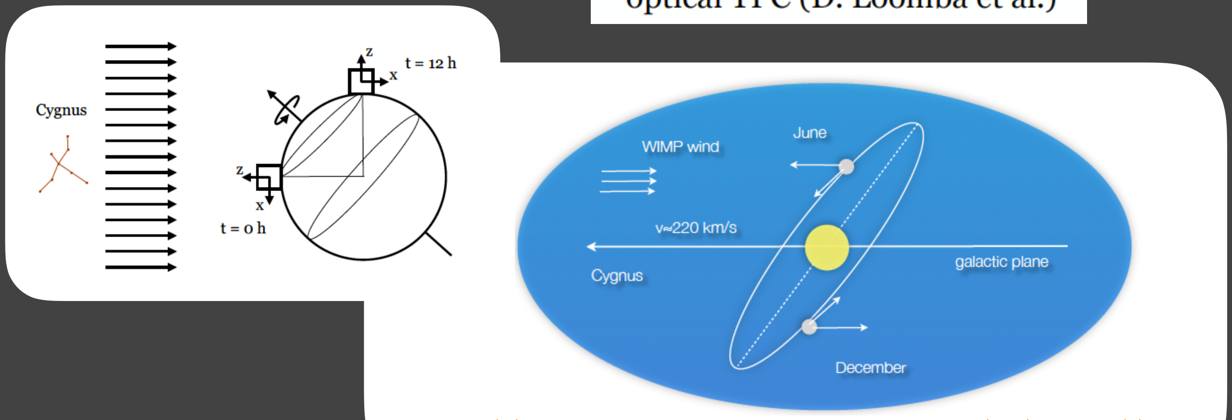
APPLICATIONS

This device is being developed for DM search: nuclear recoil tracks in gas can be long enough to be acquired and reconstructed



example high energy F recoil in optical TPC (D. Loomba et al.)

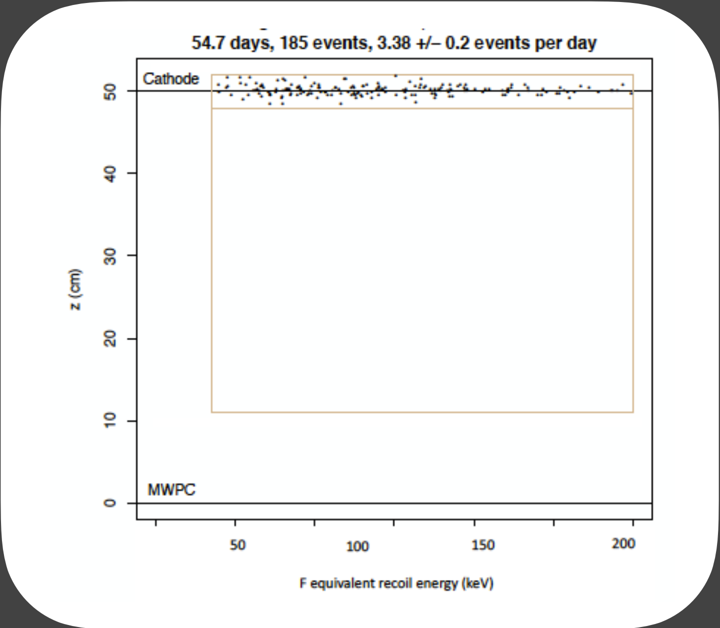
Directionality: to exploit asymmetries and modulation of the Dark Matter signals for background discrimination;



$$v(t)_{DM} = v_{sun} + v_{orb}\ cos\gamma\ cos(\omega(t - t_0))$$

Energy Measurement: total energy and dE/dx (pid, head-tail);

Sensitive Volume Fiducialization: to reject events close the detector walls, due to decays of radioactive materials

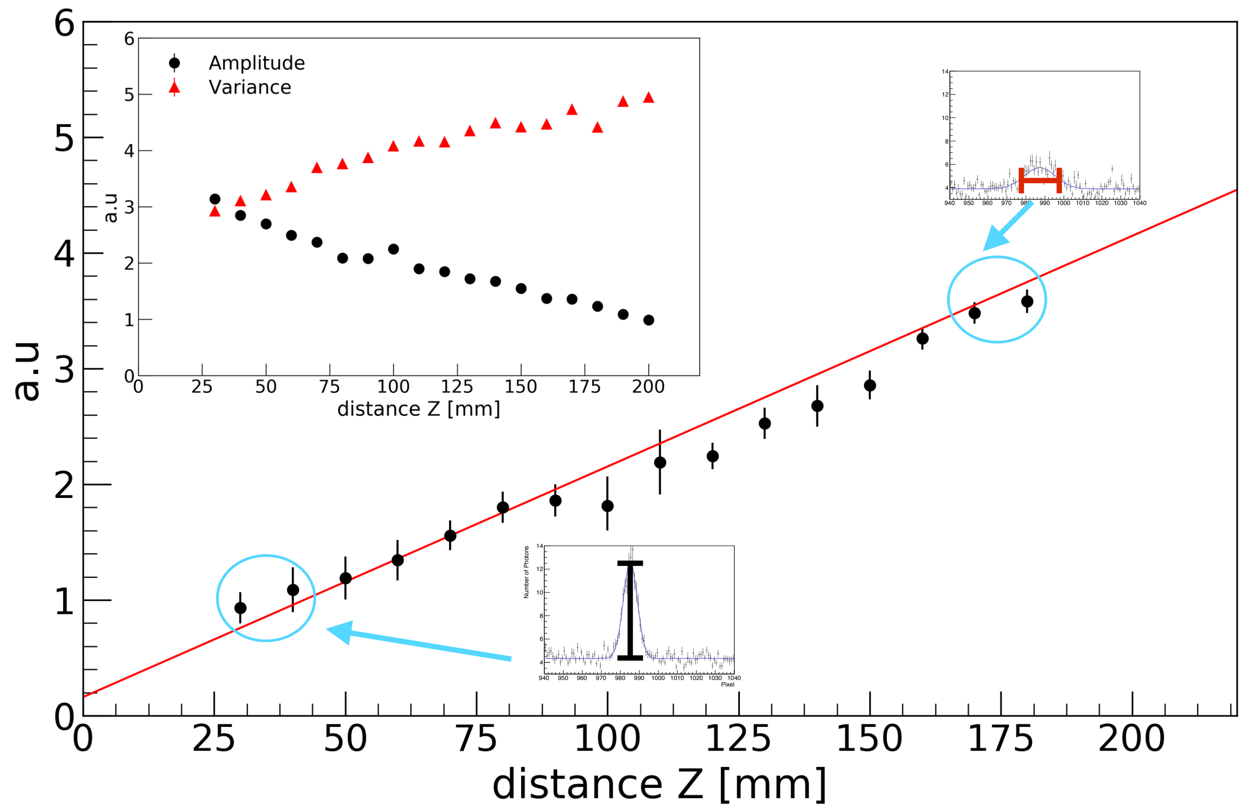


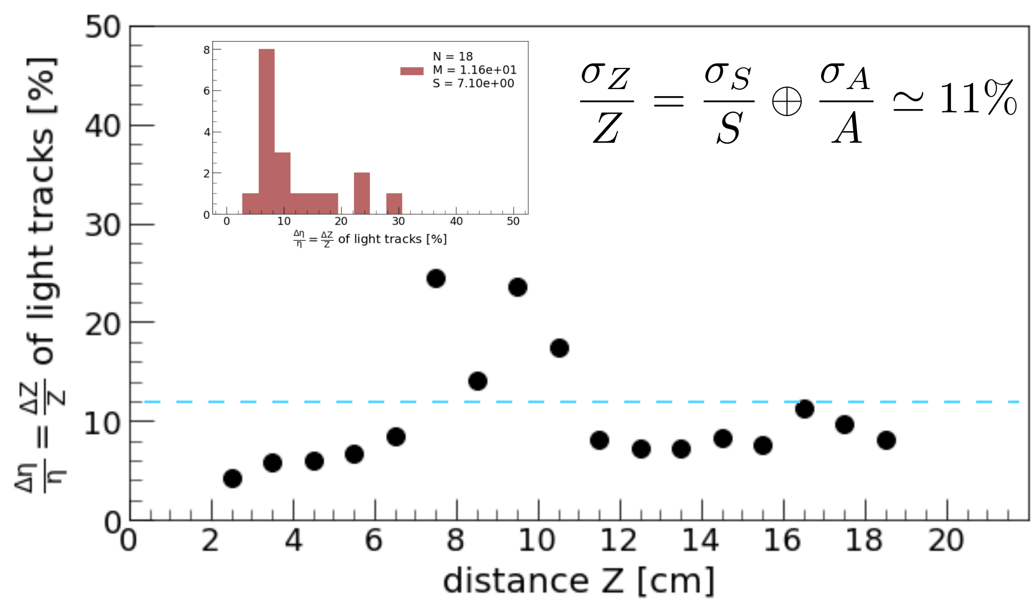
Z RESOLUTION

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);

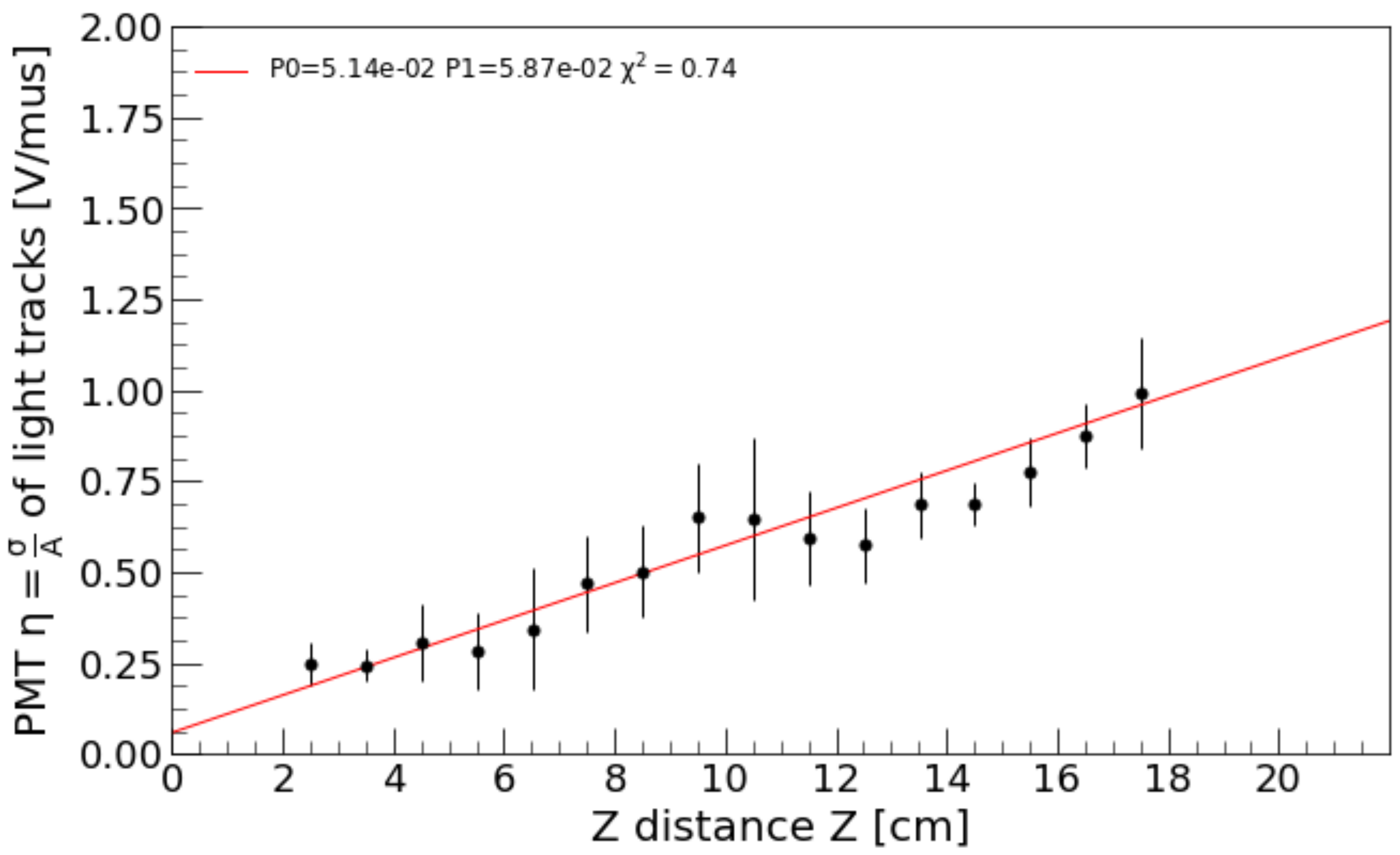


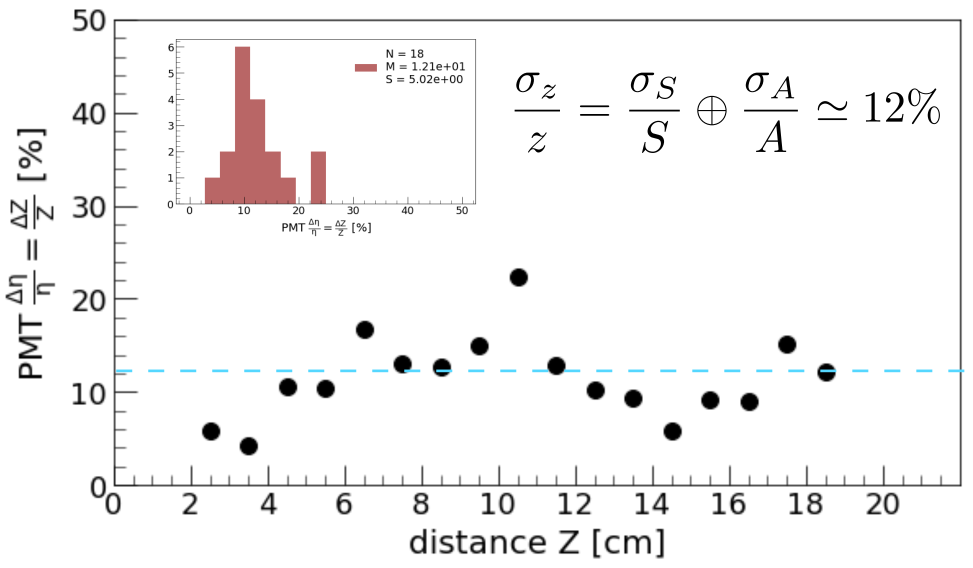


σz~ 2-3 cm @ 20 cm

Z RESOLUTION

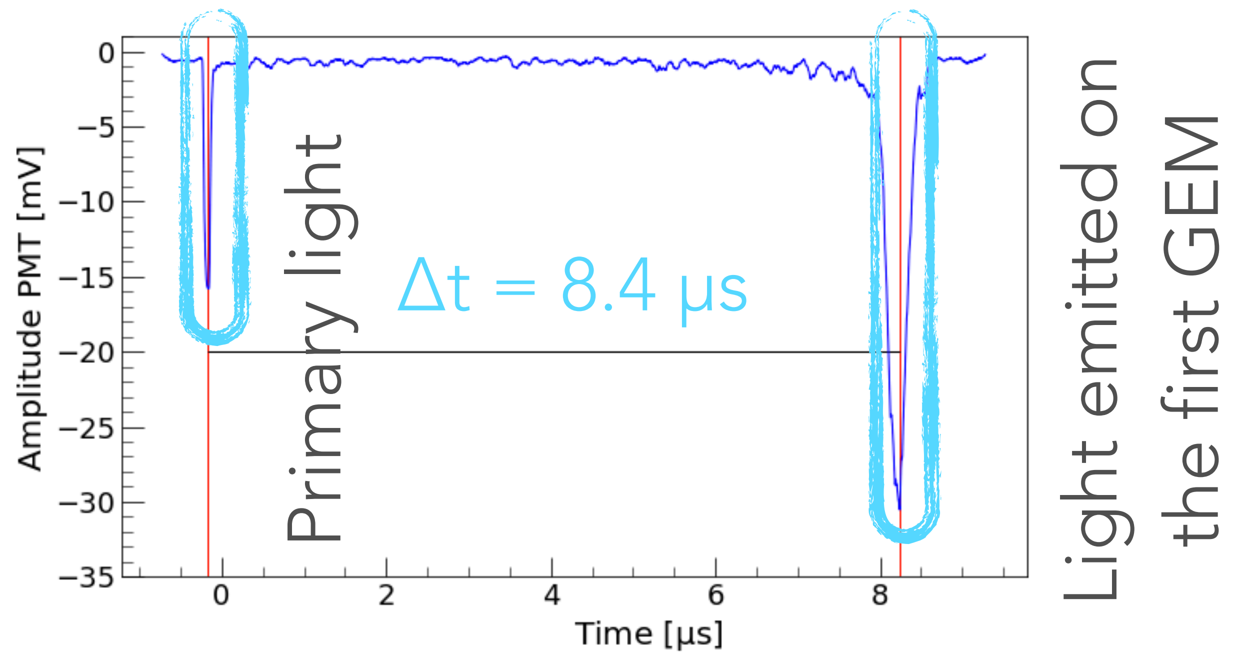
The longitudinal electron diffusion modifies the structure of the PMT signal; Also in this case, the signal amplitude (A) and width (S) are expected to depend on the track Z and their ratio η_{PMT}=A/S is expected to increase with Z





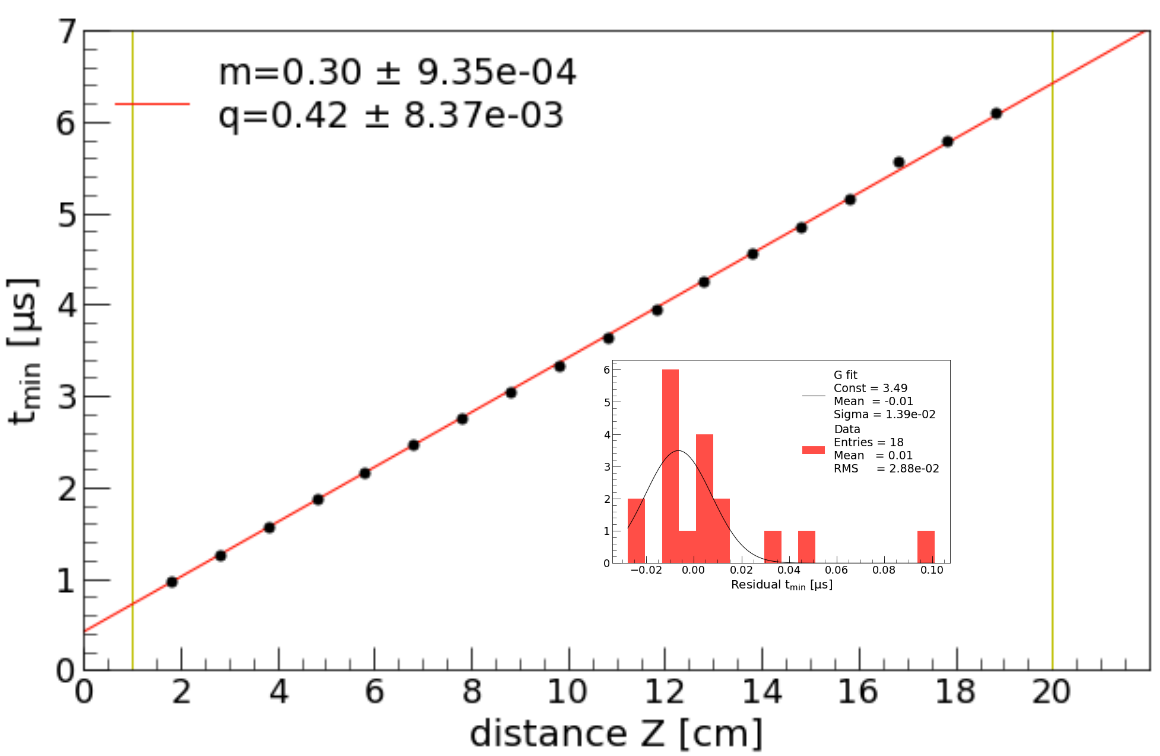
σ_z~ 2-3 cm @ 20 cm

PRIMARY LIGHT



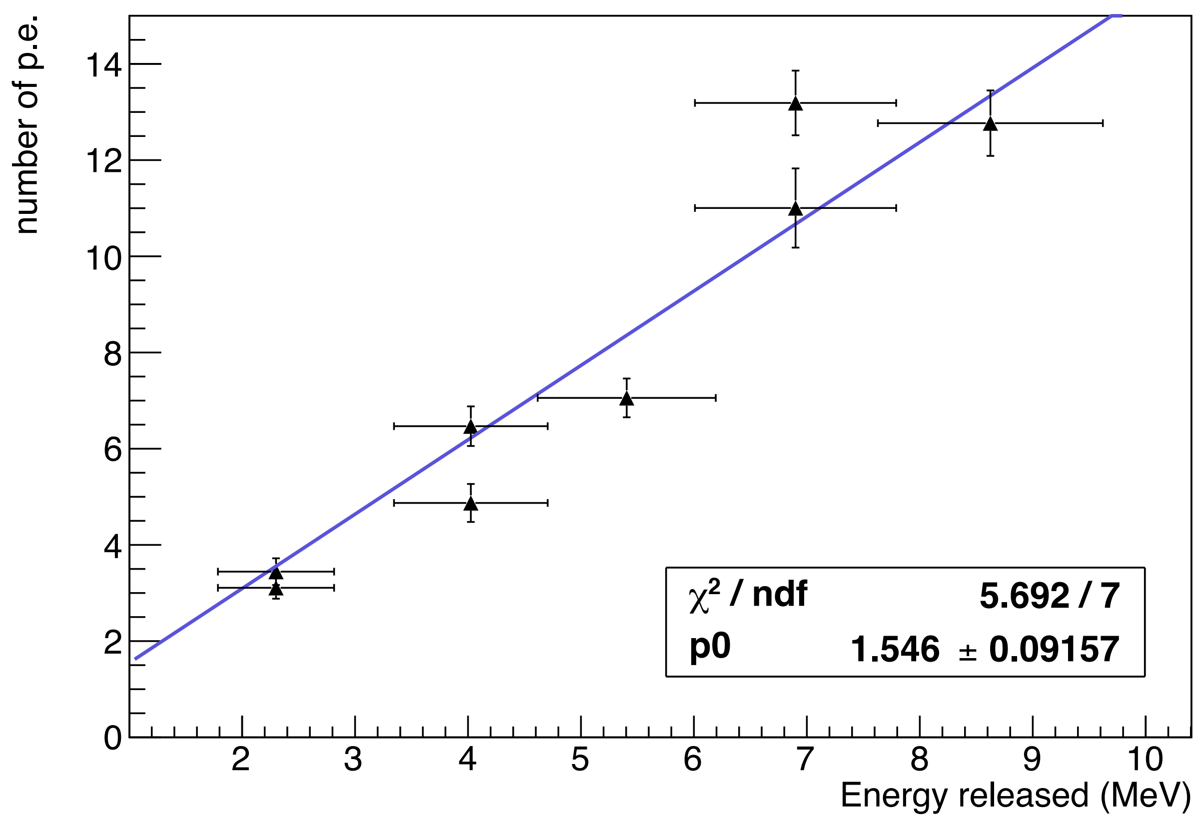
Another possibility of evaluating the event depth is provided by the prompt detection of the light emitted by the gas during the crossing of the ionising particle.

By sending bunches of 50 electrons primary light was easily detected;
Very good linearity in Δt is found;
From residual distribution, a resolution on Z of 50 μm is evaluated.



SENSITIVITY TO PRIMARY LIGHT

Measurements of primary light were performed by using a large window PMT (7x7 cm^2) offering a QE of ~1% @ 600nm;



By modulating the beam intensity (number of 450 MeV impinging the detector per bunch) we evaluated the number of photoelectron collected per released energy:

1.5 p.e./MeV

Optimising the PMT response for the expected emission range a sensitivity of 1 p.e./10 keV, can be reached.

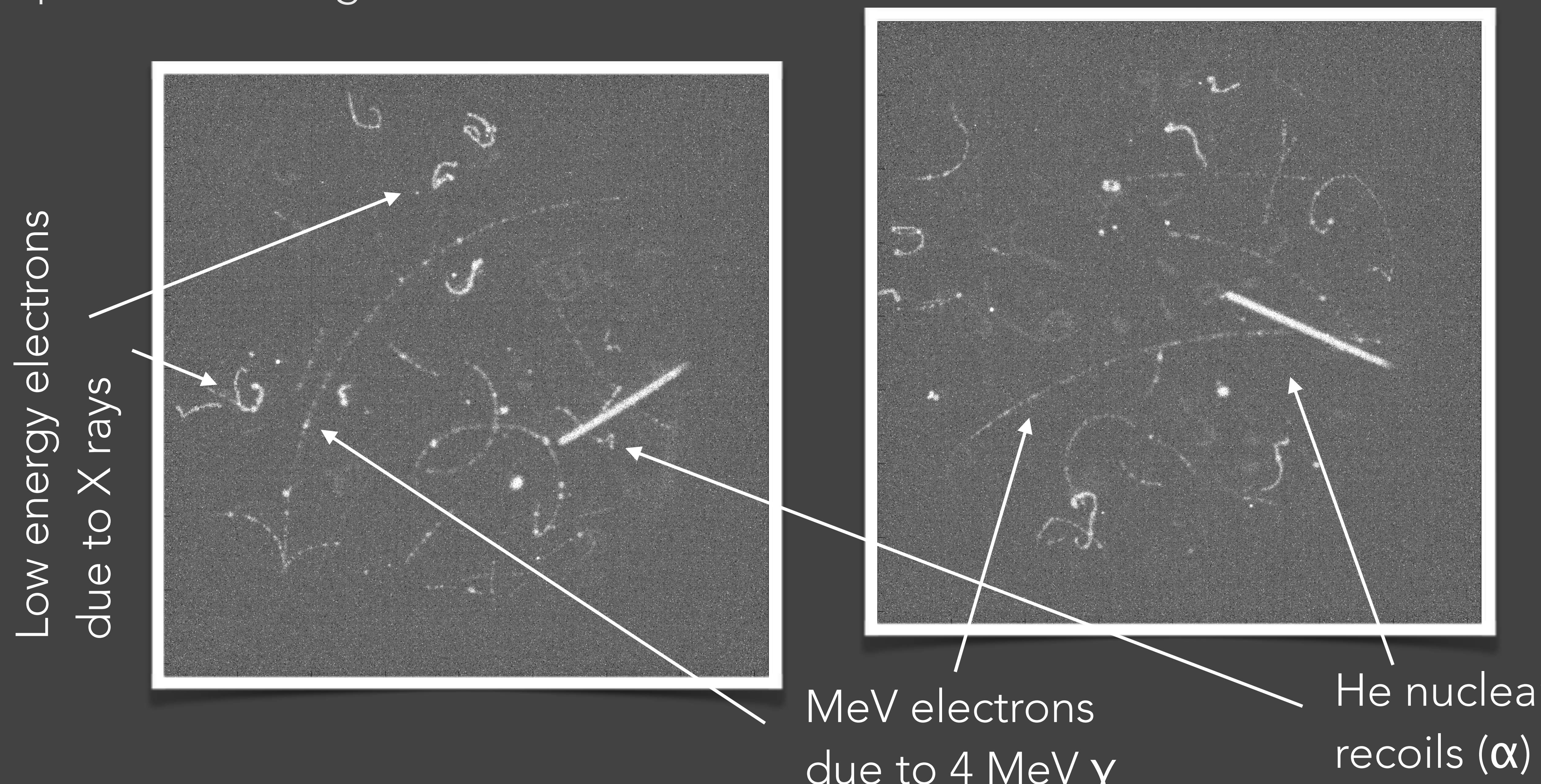
NEUTRONS

Neutrons represent an useful tool to study the behaviour of nuclear recoils in gas and to evaluate the response of the detector;
For this reason, an intermediate step for CYGNUS_RD collaboration toward the realisation of a DM detector is a medium prototype (100-1000 litres) used to characterise the neutron flux in underground laboratories (“UNDER” project);

Under the careful control of radio-protection service, preliminary measurements were taken with neutrons two weeks ago at LNF.

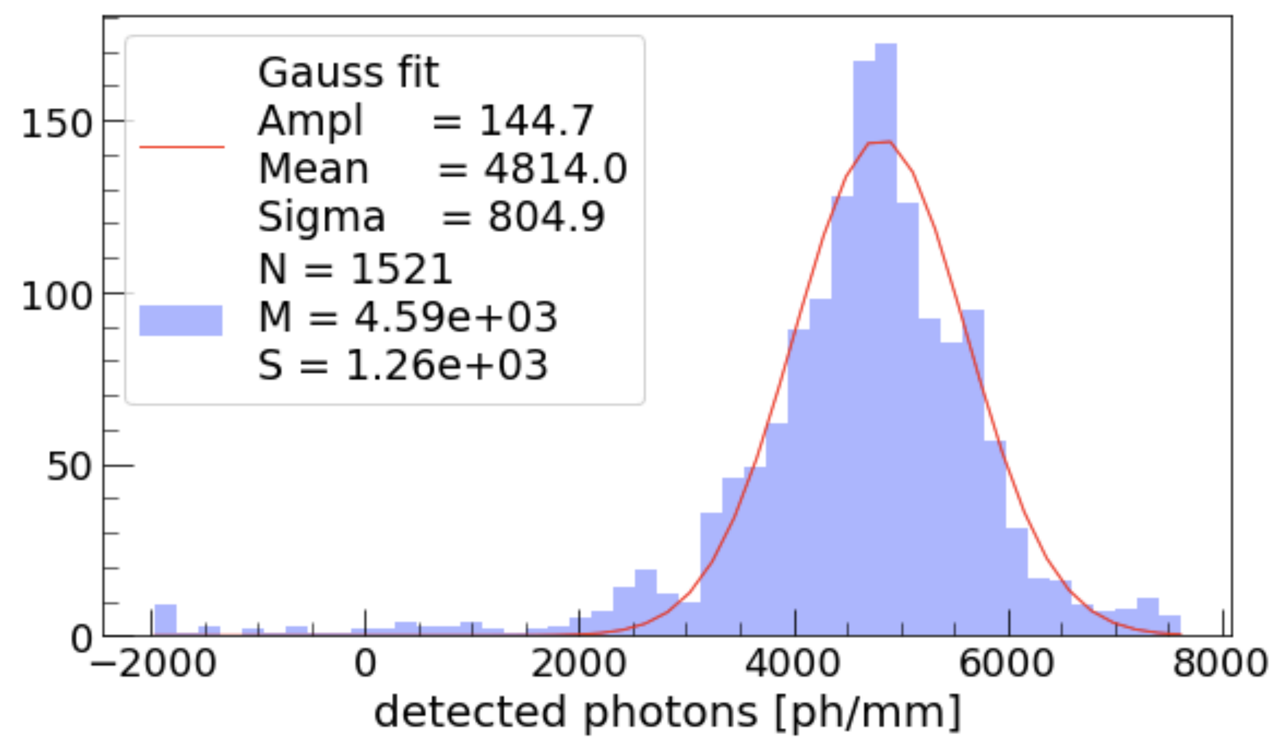
MEASUREMENTS WITH NEUTRONS

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.

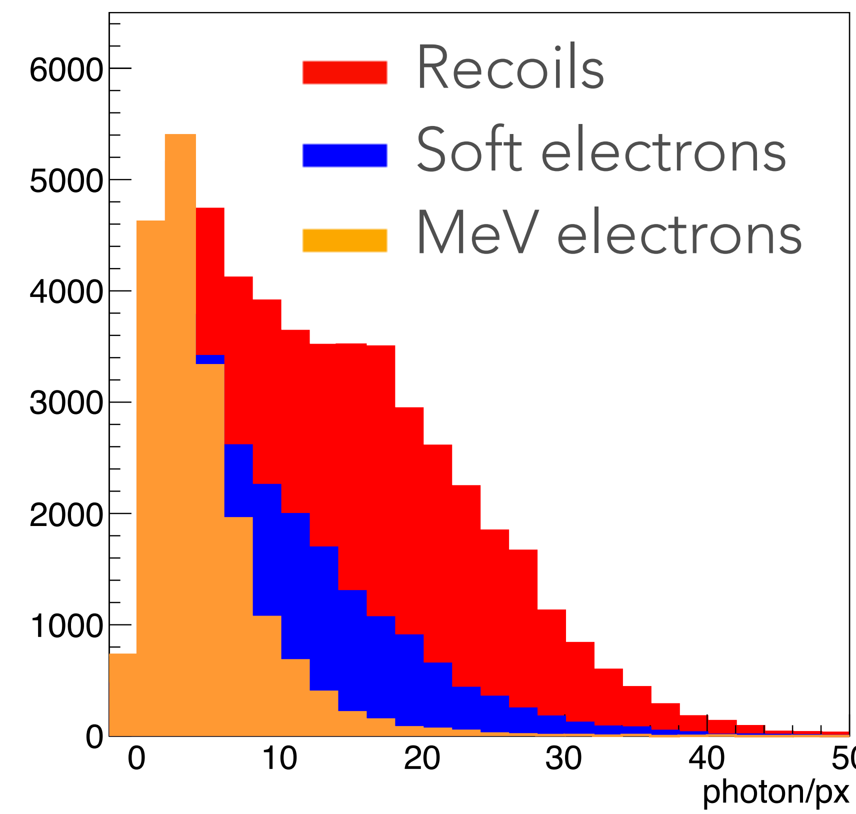


NEUTRON LIGHT YIELD

Nuclear recoil tracks are quite brighter than others;



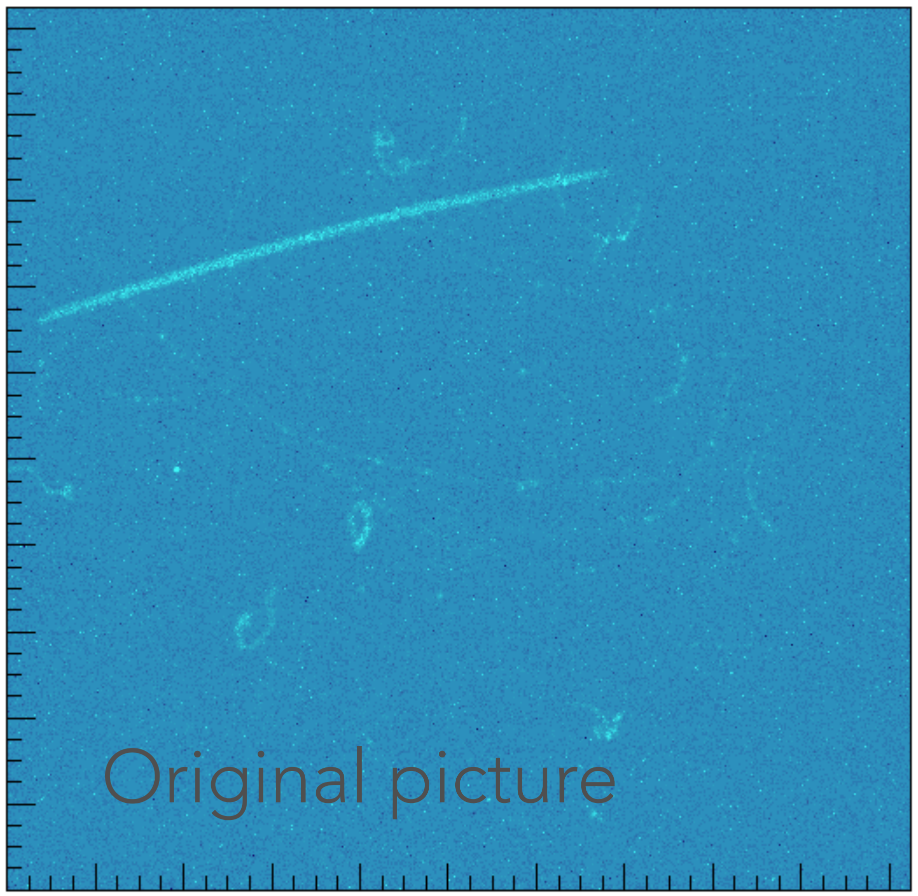
4000 photons are detected per track millimetre; (4 times more than mips)

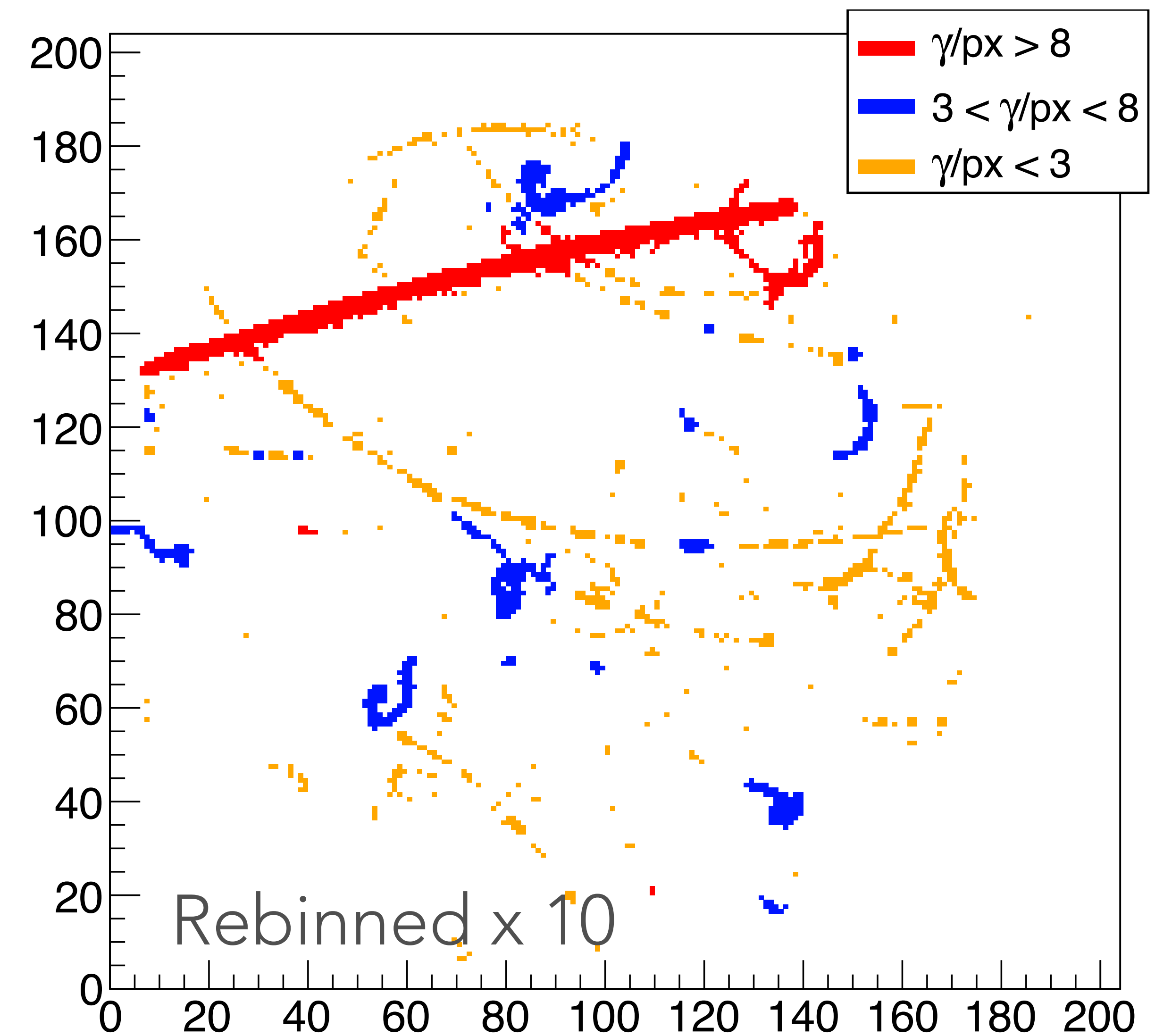


Also the distributions of light density (photons per pixel) are quite different.

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.

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.

Next step will be exposing LEMON to FNG neutrons and trying a 4D track reconstruction (x, y, z, E) to evaluate the sensitivity of this technique to low energy nuclear recoils.

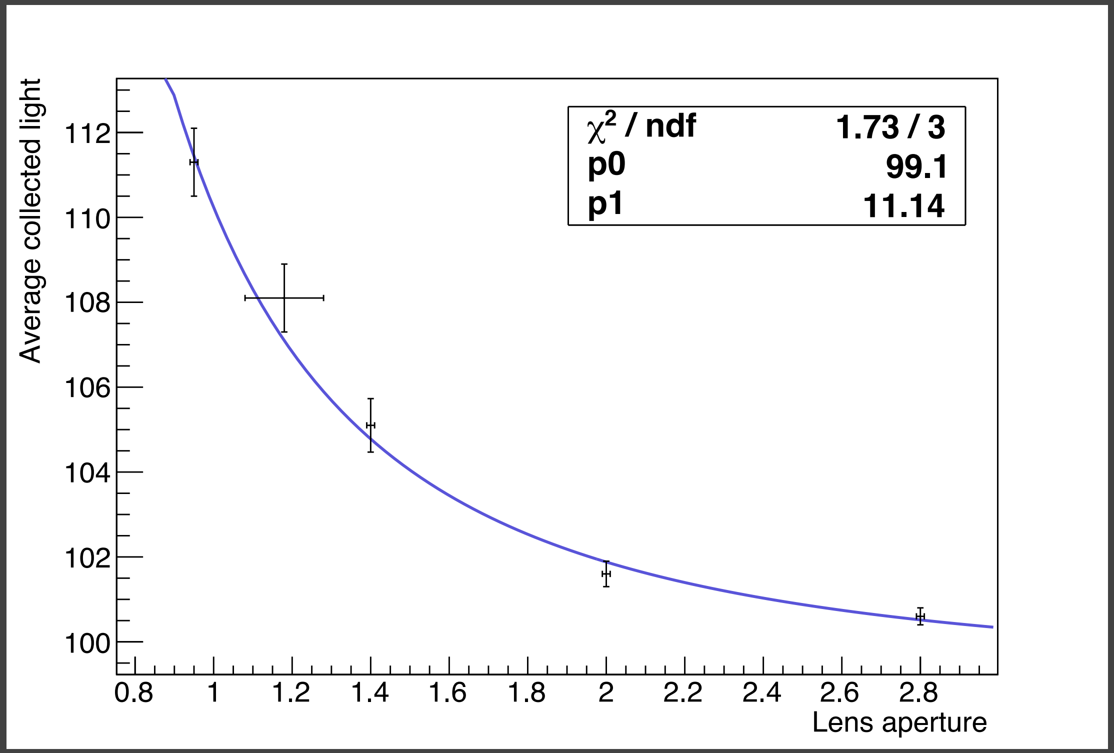
Join us!

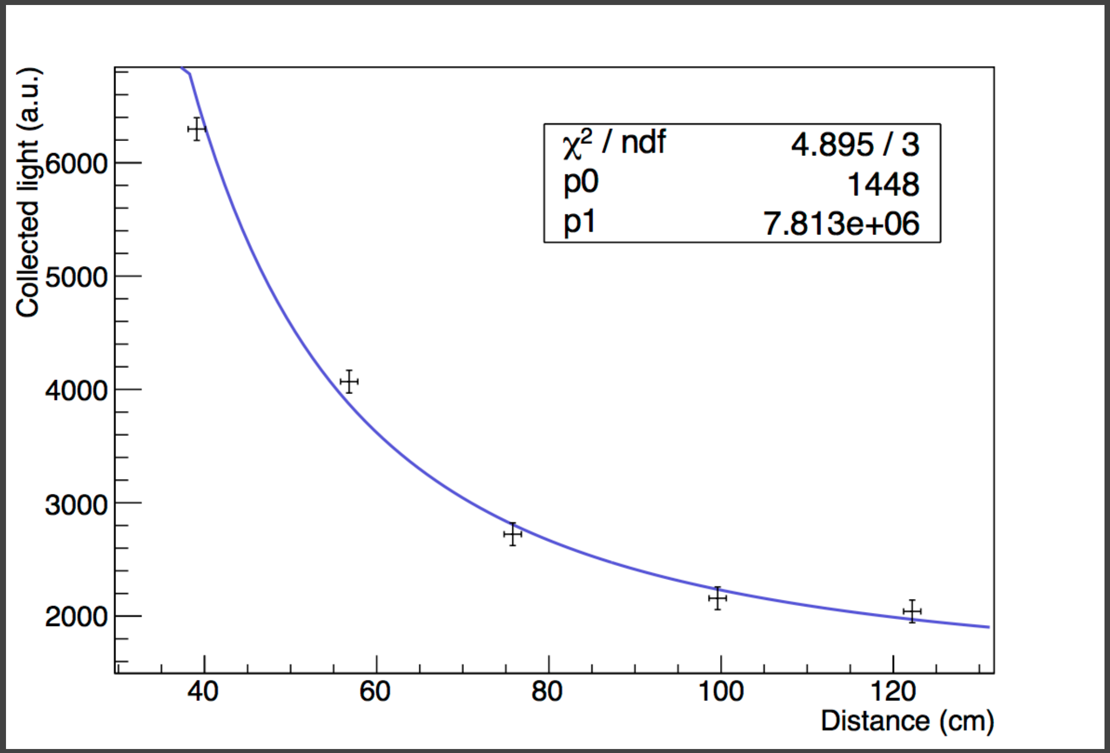

Thank you
We really want to thank LNF people and services for the enduring and excellent support. GRAZIE!
CYGNUS-RD Italian collaboration - https://web.infn.it/cygnus/

BACKUP

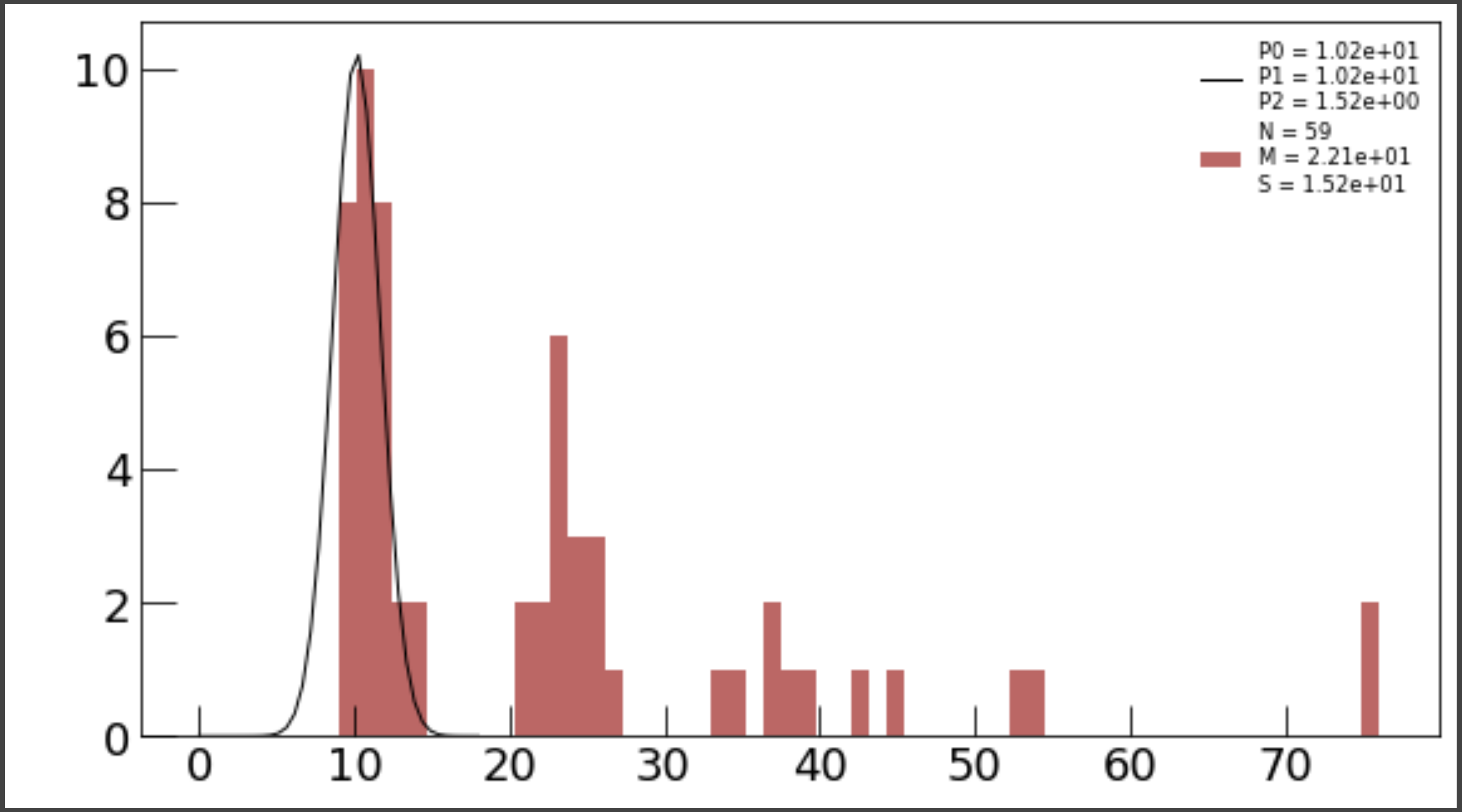
LIGHT EMISSION ISOTROPY

aperture and distance light emission demonstrating that the emission is isotropic

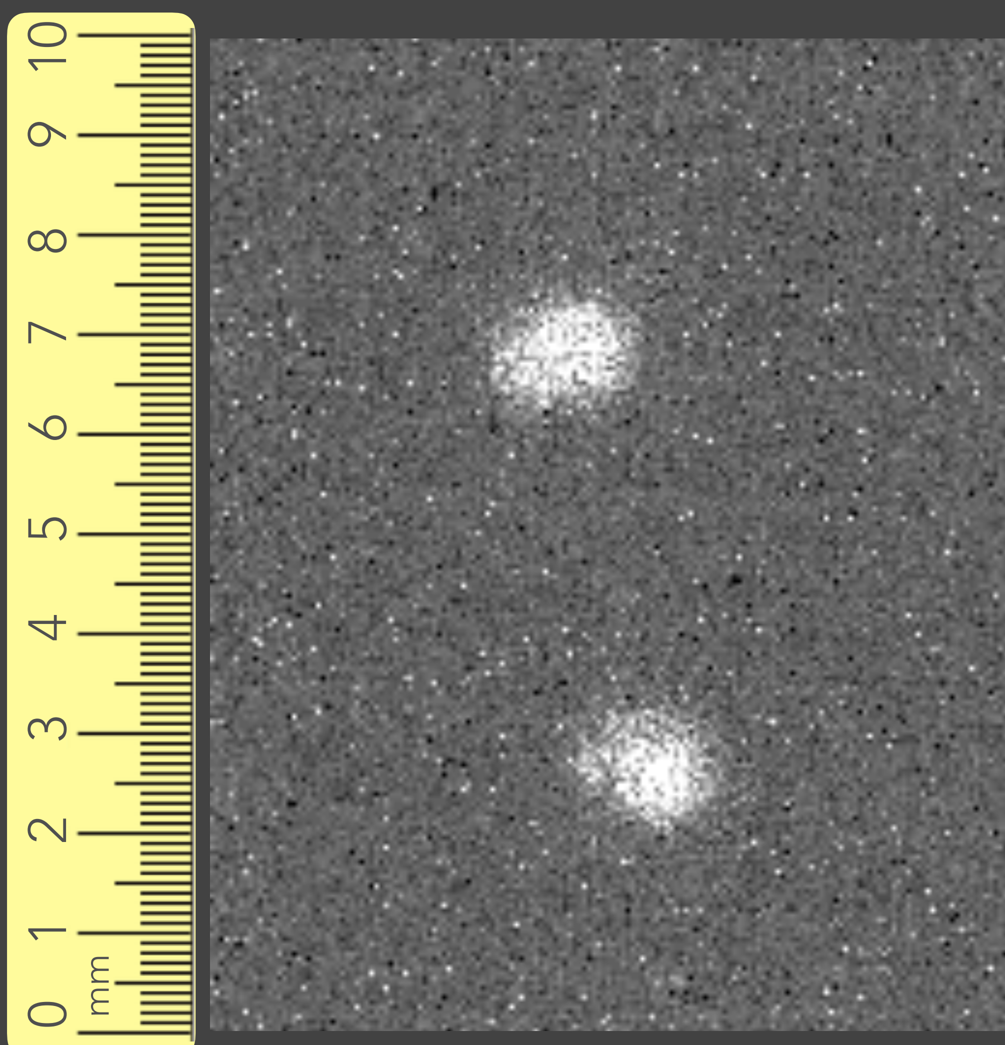




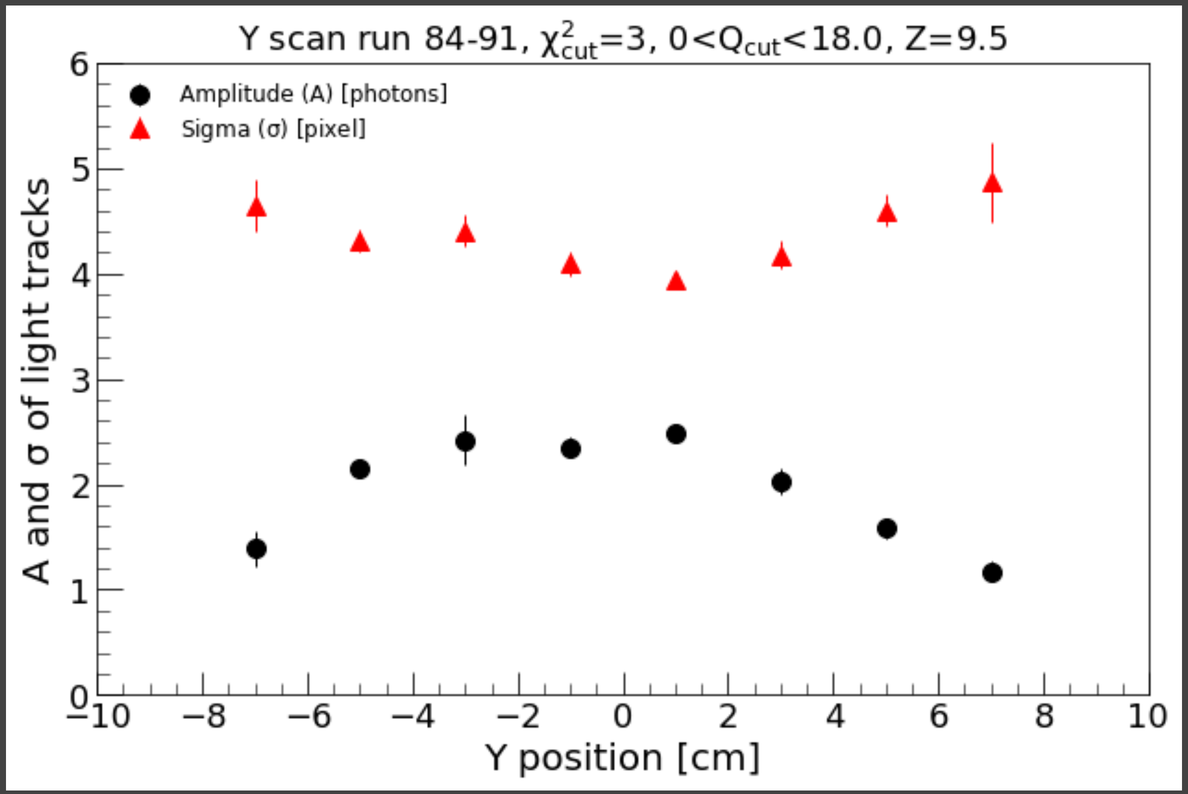
PARTICLE COUNTING

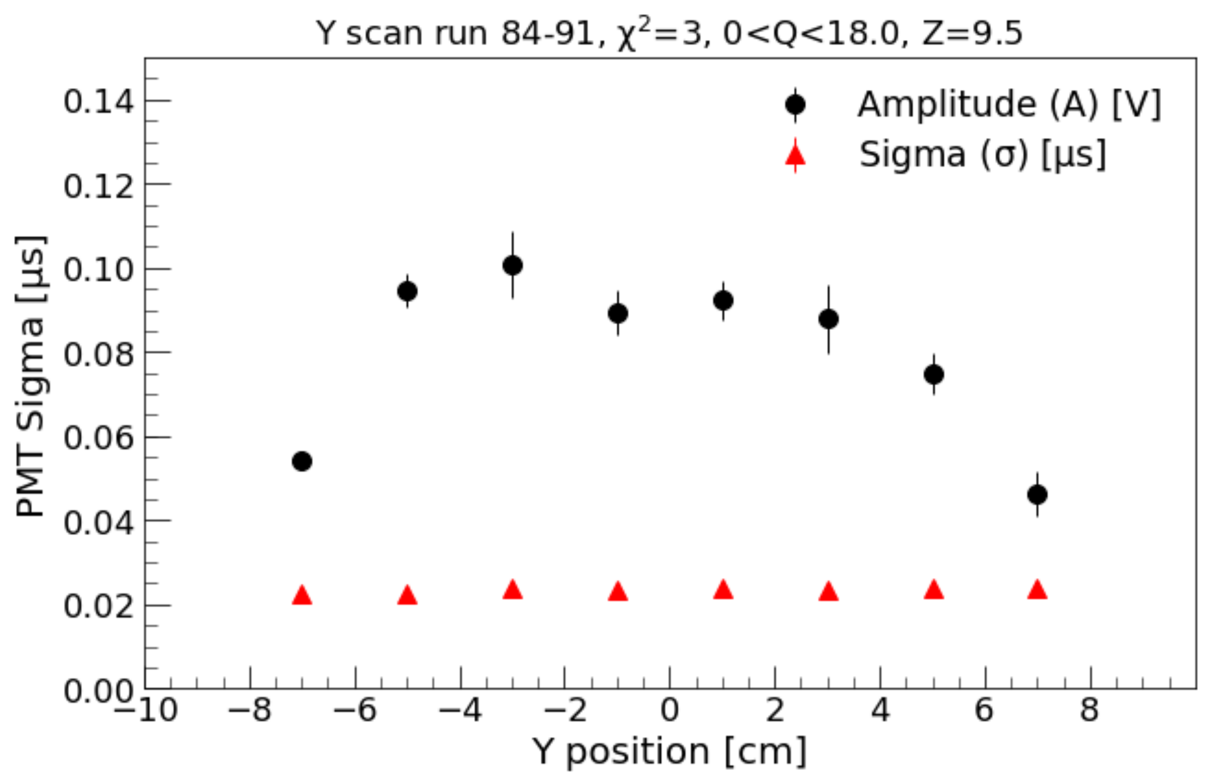


X-RAY FROM A ^{55}FE SOURCE



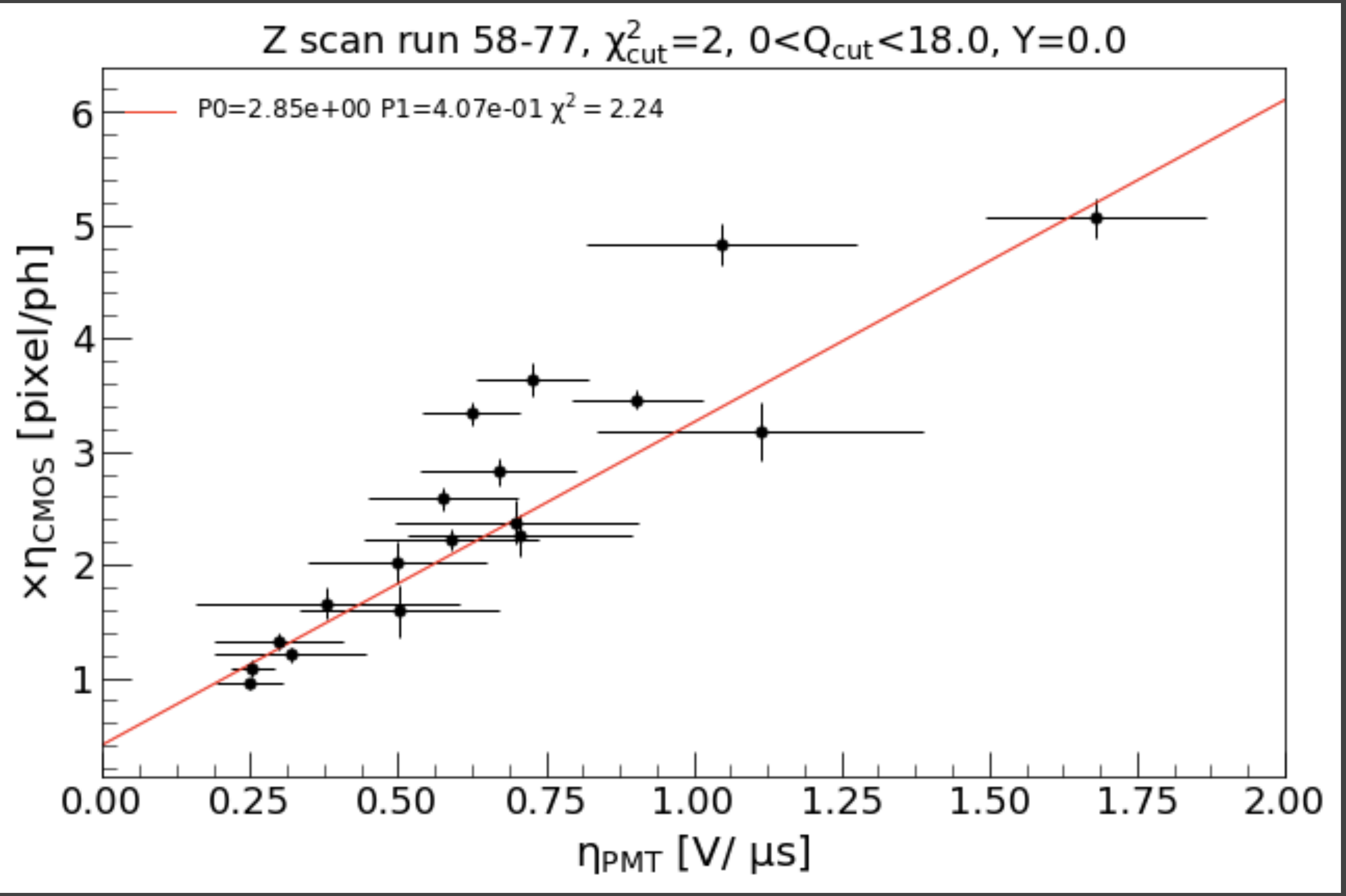
Y SCAN


Y scan run 84-91, χ^2_{cut}=3, 0<Q_{cut}<18.0, Z=9.5
Amplitude (A) [photons]
Sigma (σ) [pixel]
A and σ of light tracks
Y position [cm]

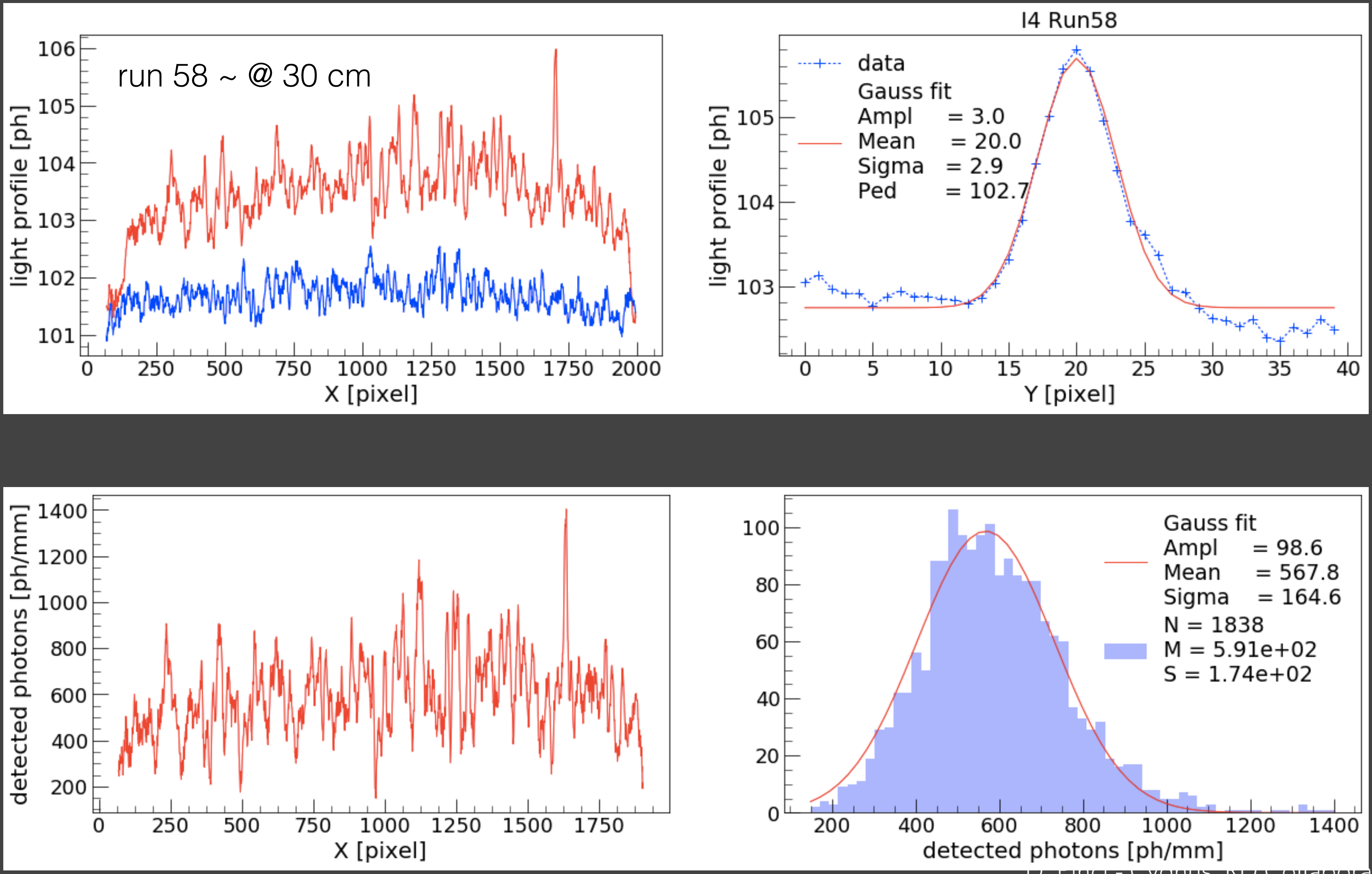

Y scan run 84-91, χ^2=3, 0<Q<18.0, Z=9.5
Amplitude (A) [V]
Sigma (σ) [μs]
PMT Sigma [μs]
Y position [cm]

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 eta (A/S) is expected to increase with Z



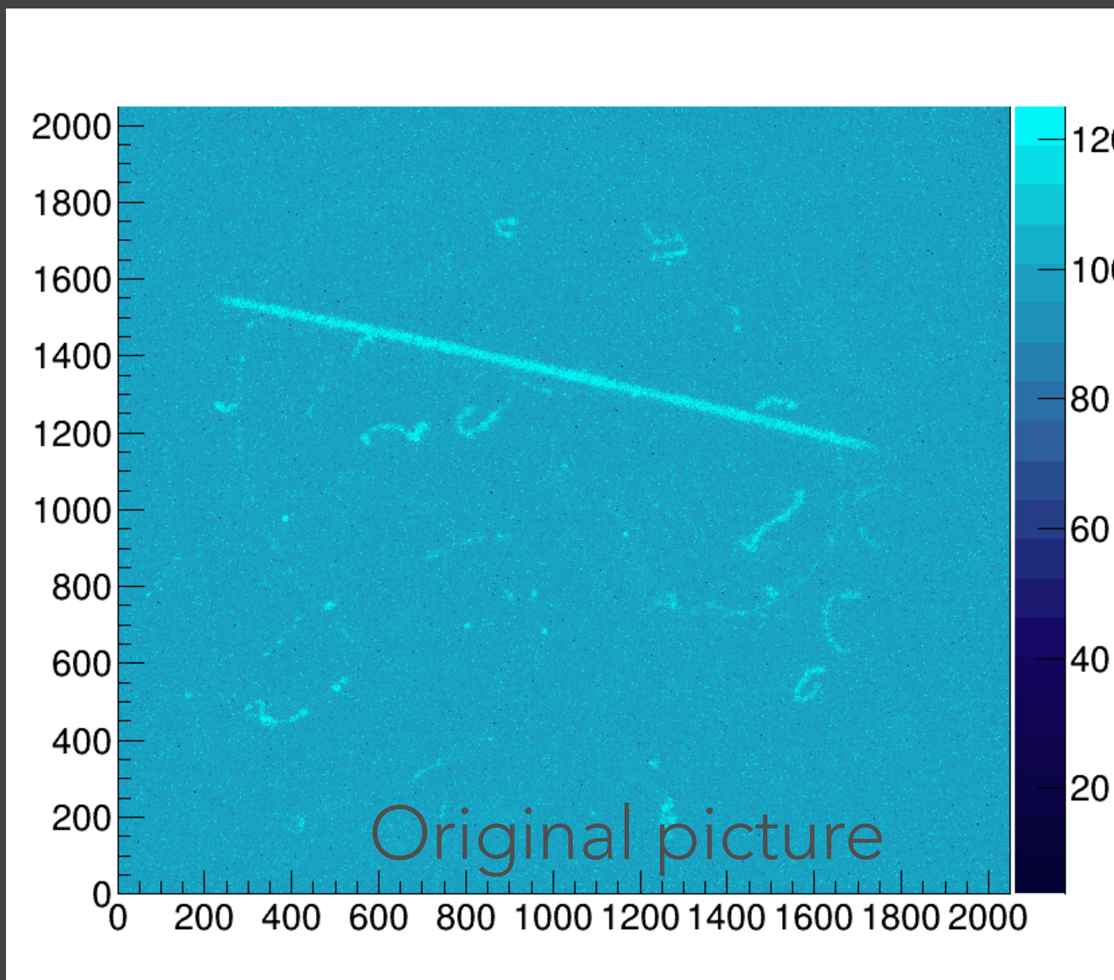
PHOTONS DETECTED

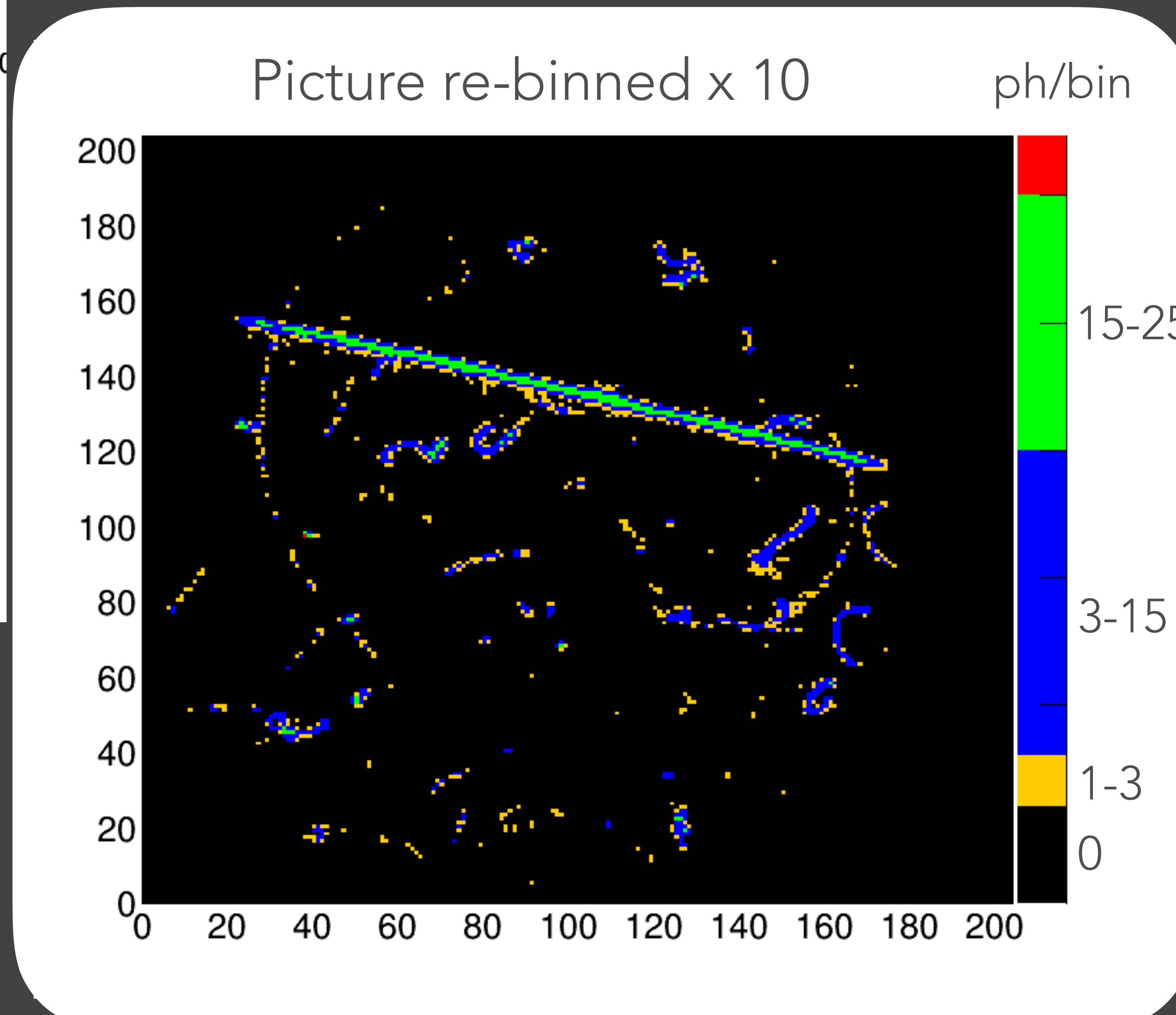


MEASUREMENTS WITH NEUTRONS

Specific ionisation allows a fast particle identification

Very Preliminary





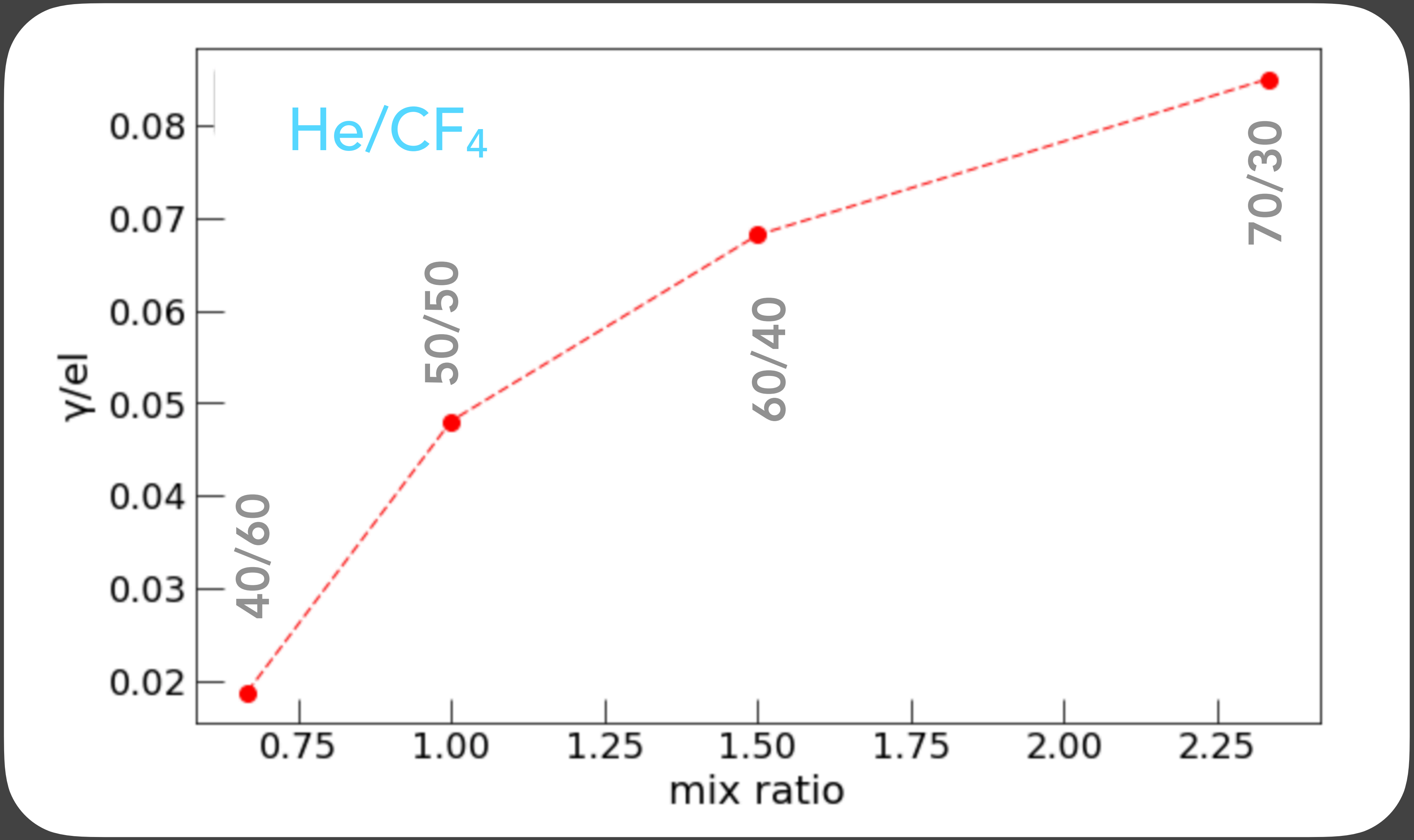
MeV electrons: 1-3 ph/px

keV electrons : 3-15 ph/px

Nuclear recoils: 15-25 ph/px

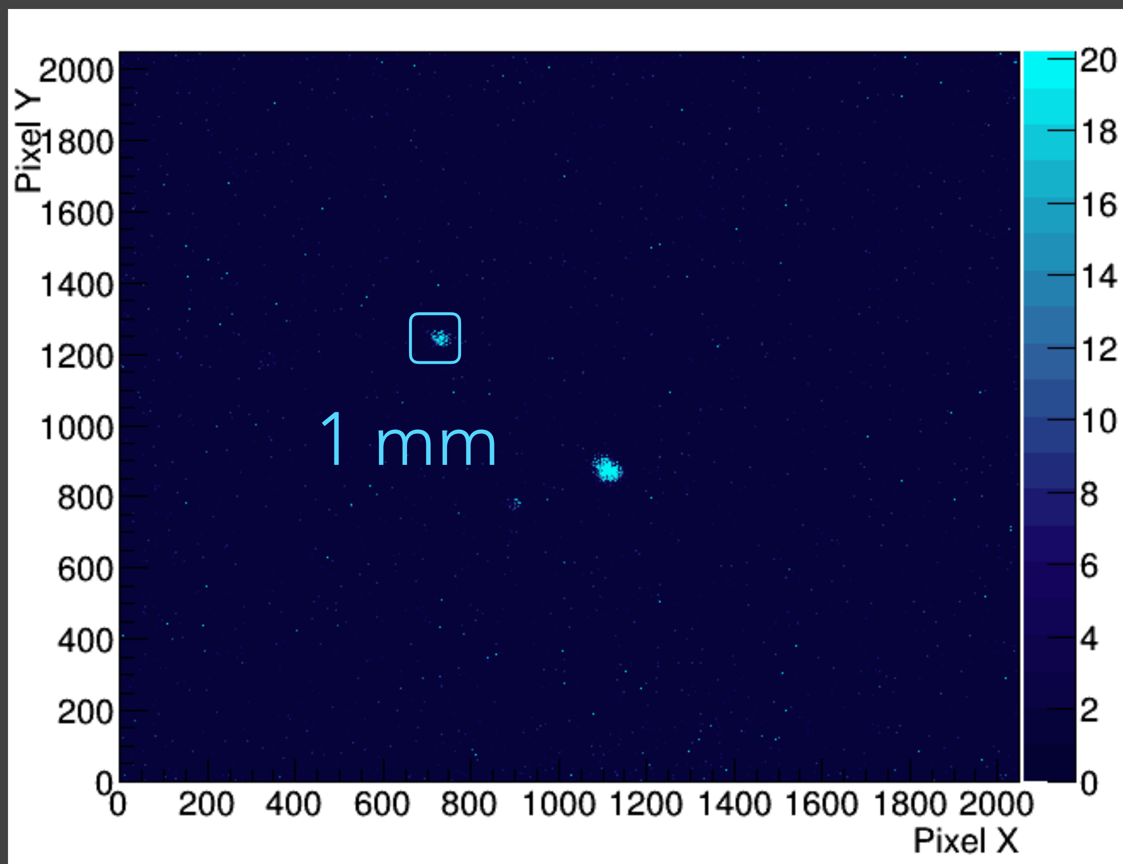
X-RAY FROM A ^{55}FE SOURCE

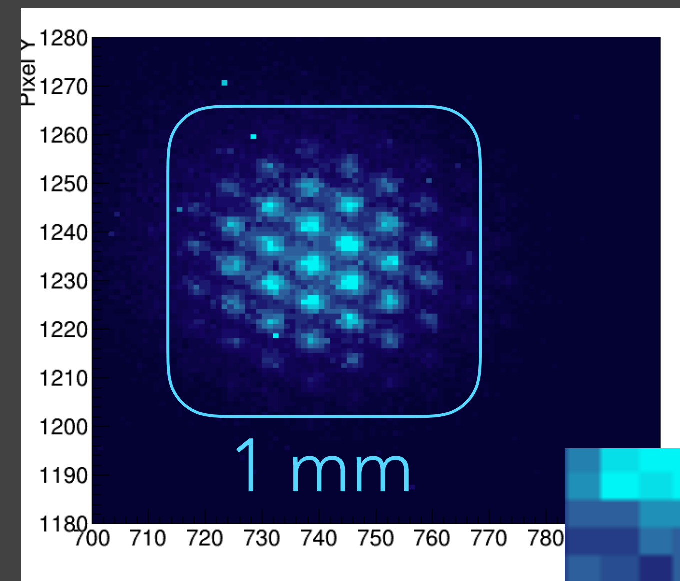
From their ratio, it was possible to evaluate the average ratios of photons produced over electrons produced.

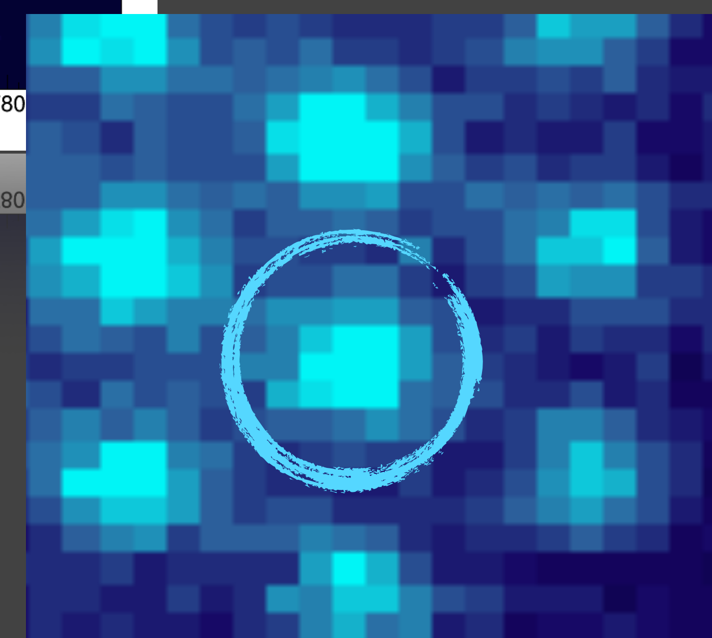


Between 2 and 8 photons are created per 100 electrons in the GEM channels

FIRST MEASUREMENTS





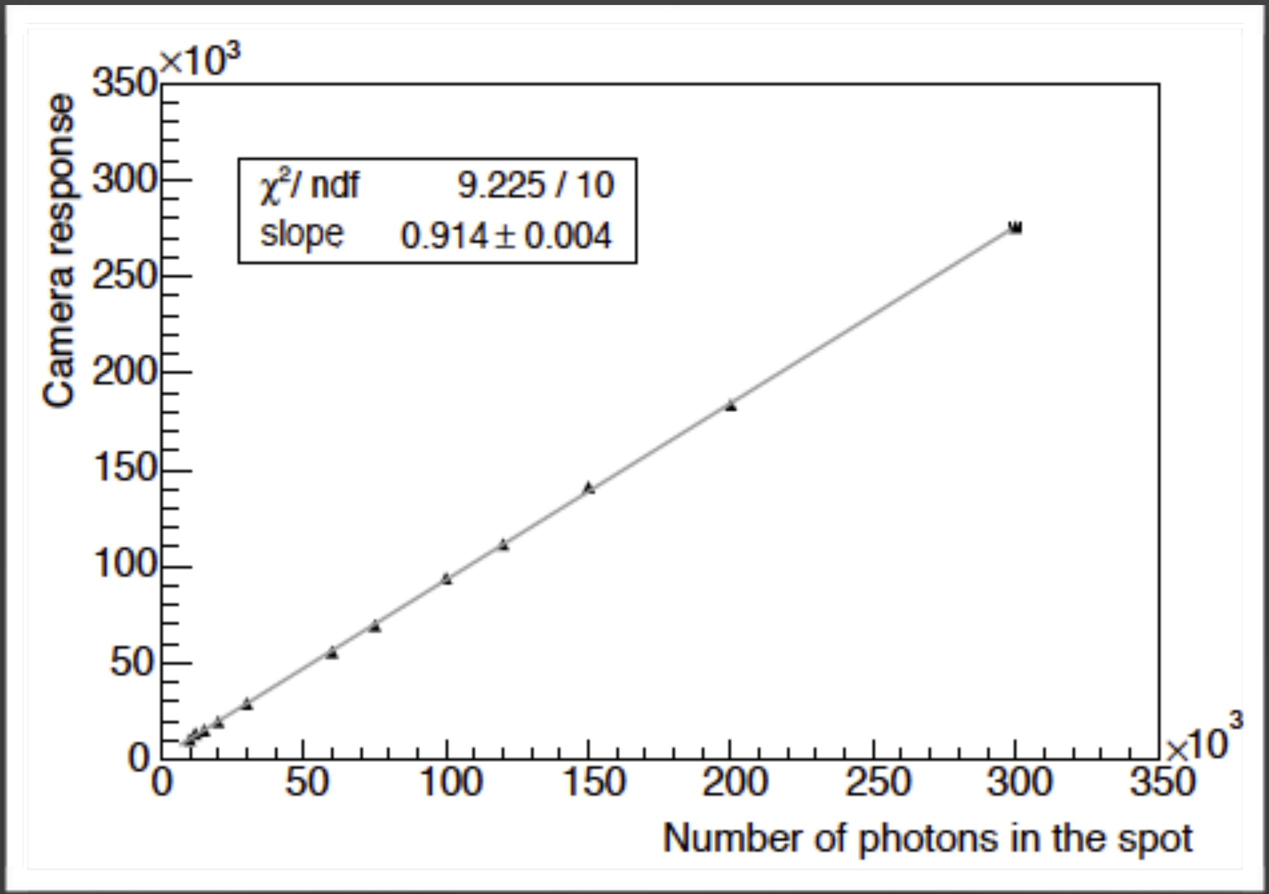


Once the high voltage to the GEM structure is turned ON, several hot spots due to micro discharges within the channels appeared (even without a sizeable current being drawn);

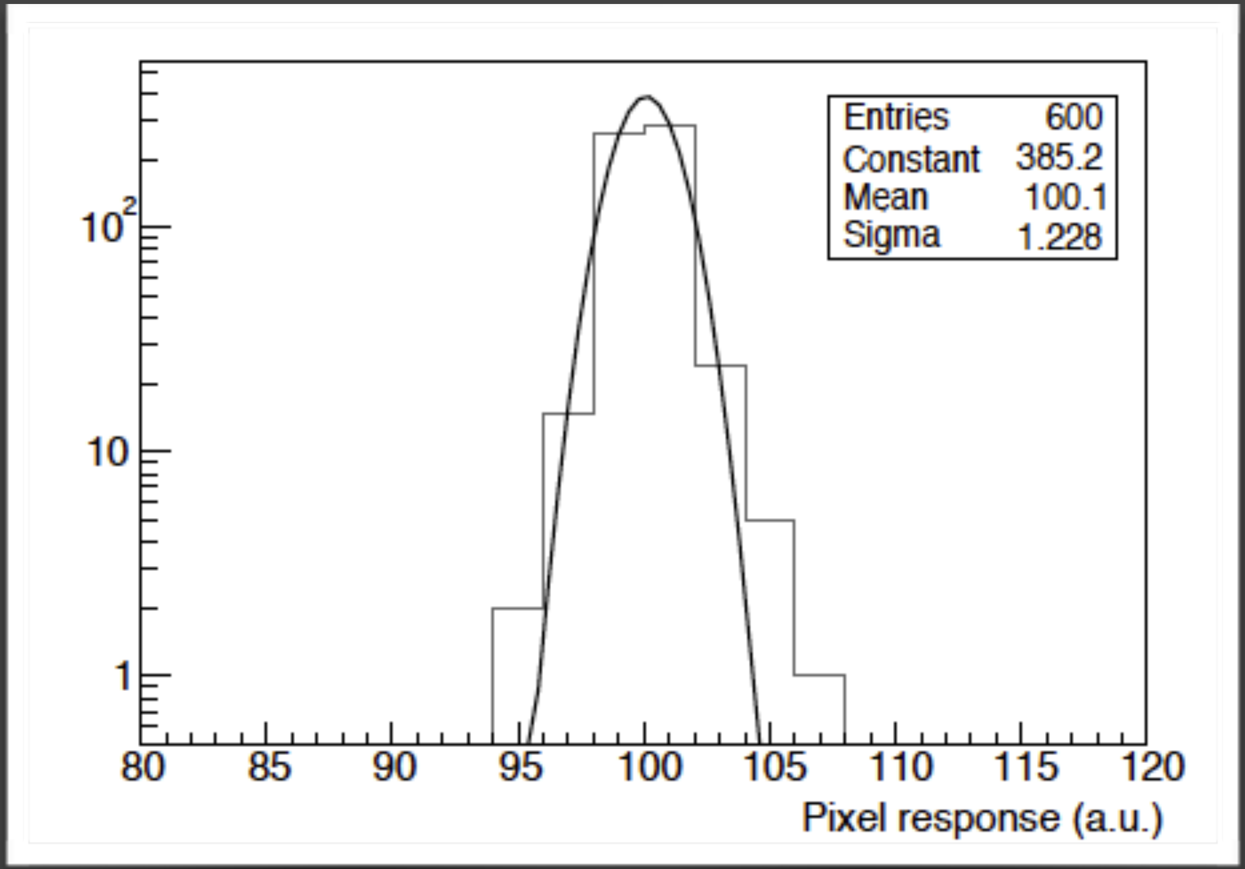
The hole texture is clearly visible.

CAMERA PERFOMANCE

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

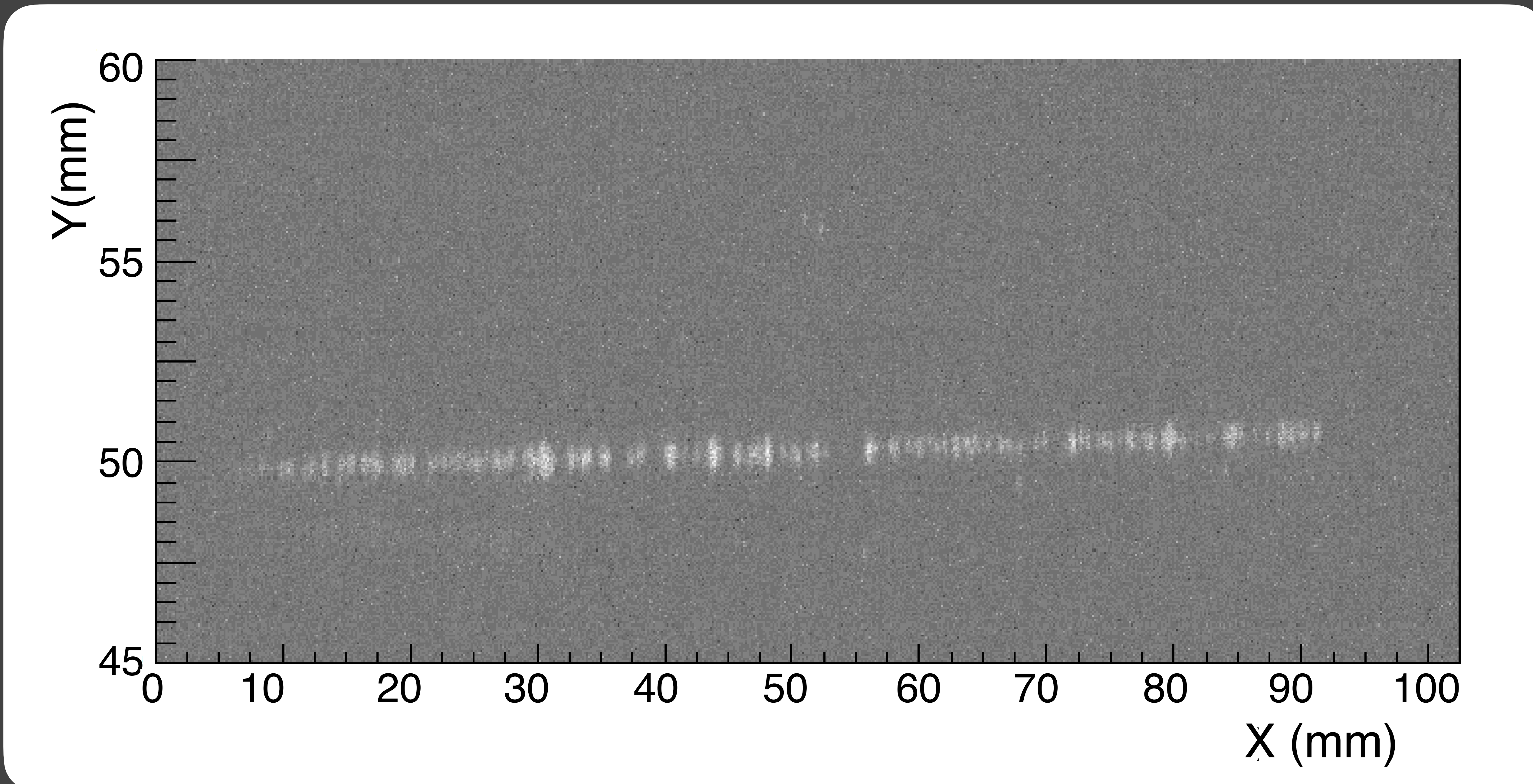


The camera behaviour is well linear in the whole studied range with a response of 0.91±0.01 counts per photon

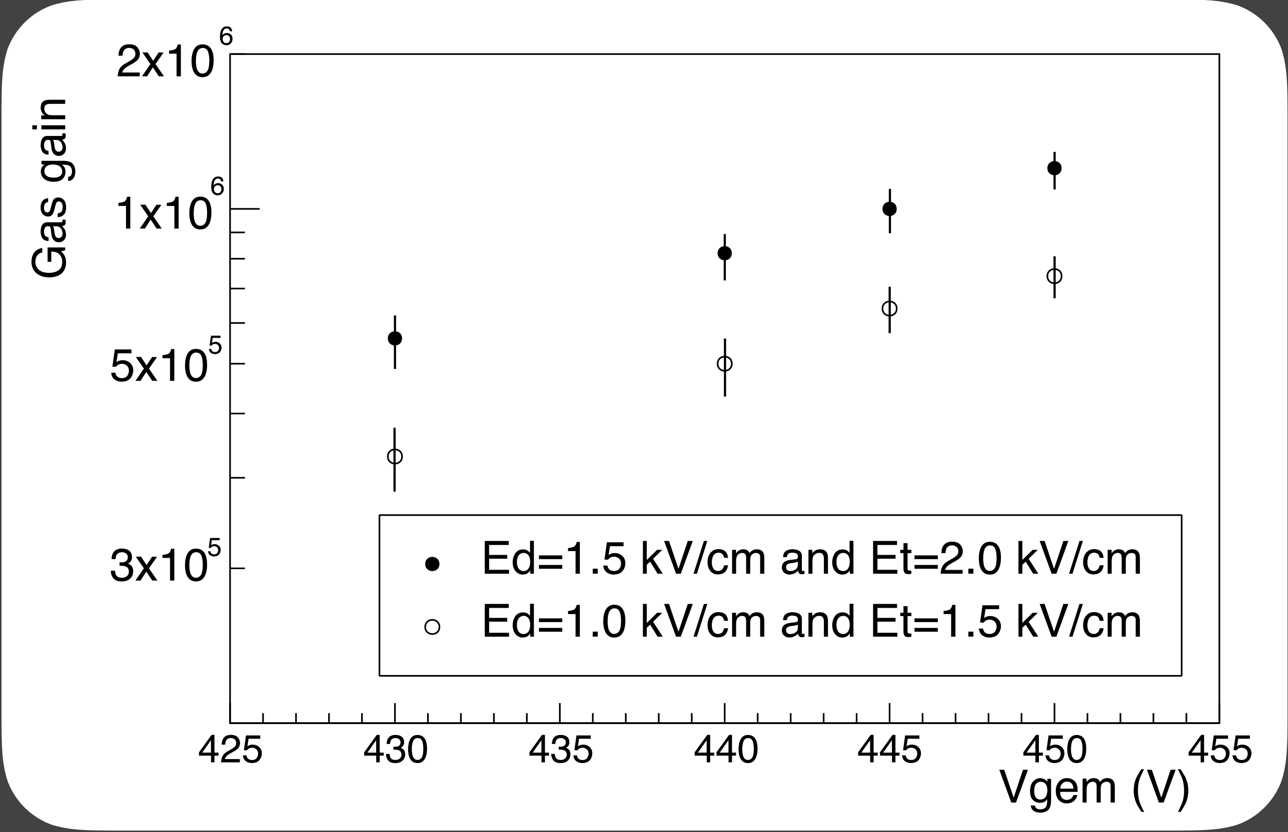


Fluctuations of the pedestal are lower than 2 counts, i.e. lower than two photons per pixel in good agreement with the expectations

TRACKING PERFORMANCE



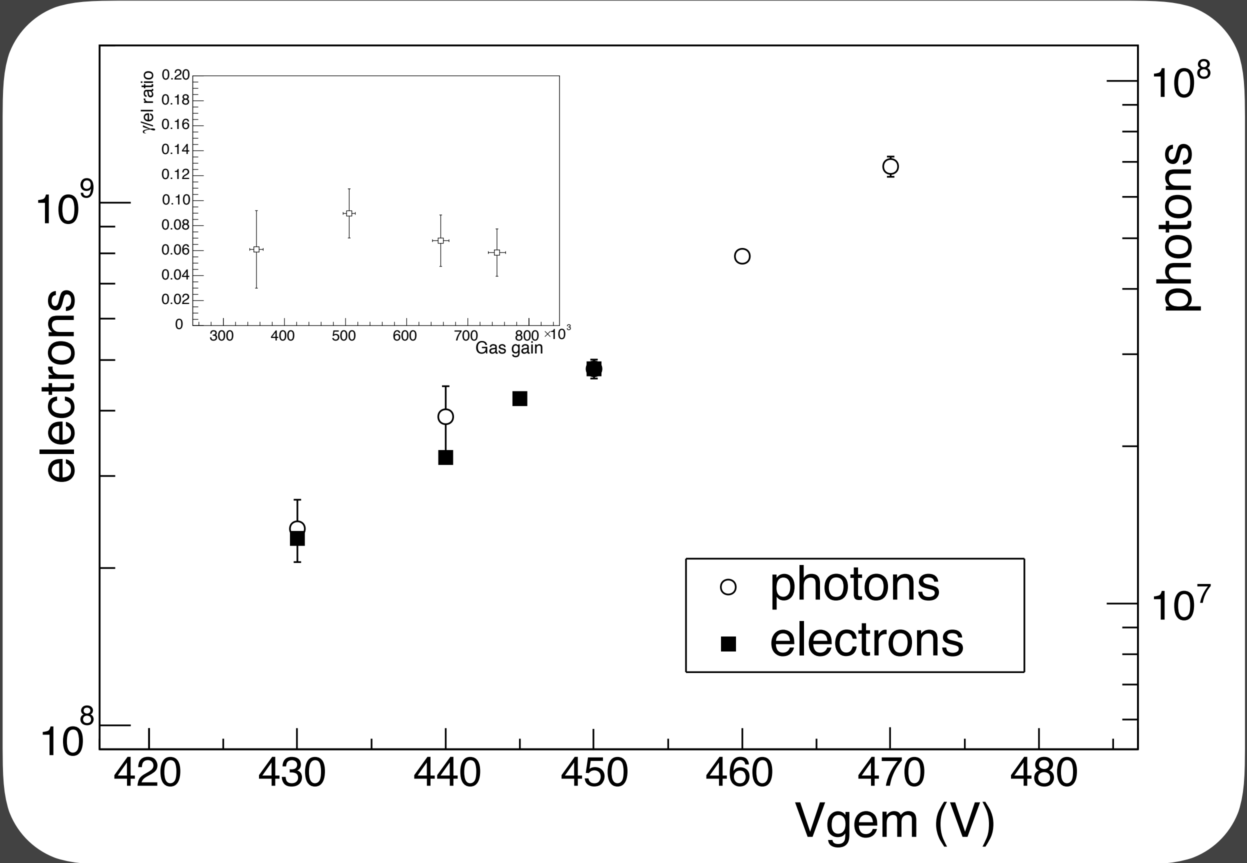
ELECTRON AND LIGHT YIELD



Total number of secondary electrons produced per primary (gas gain) was studied as a function of the GEM voltage (in two different configuration of the other fields).

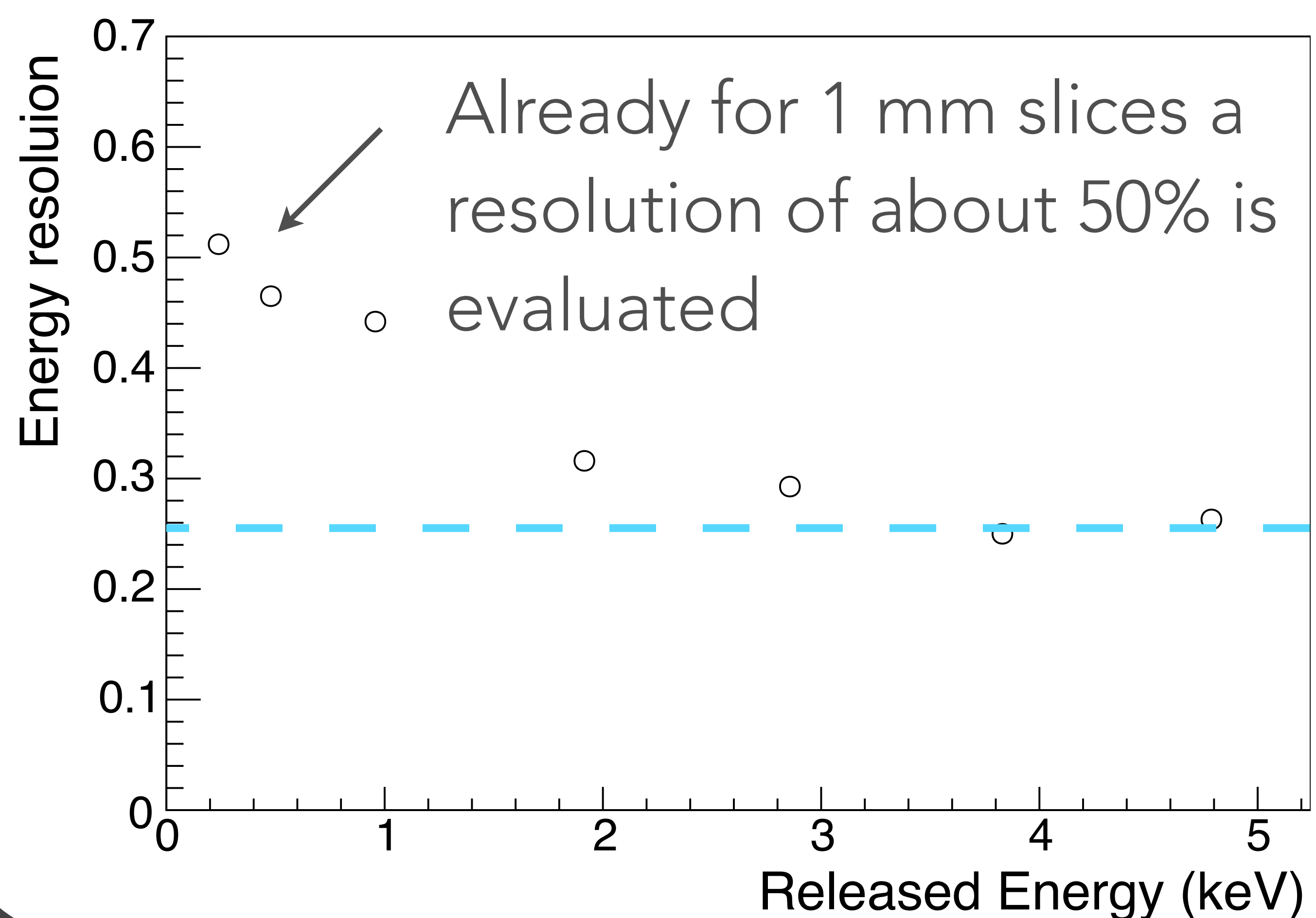
Gains of around 10^6 are achieved (!)

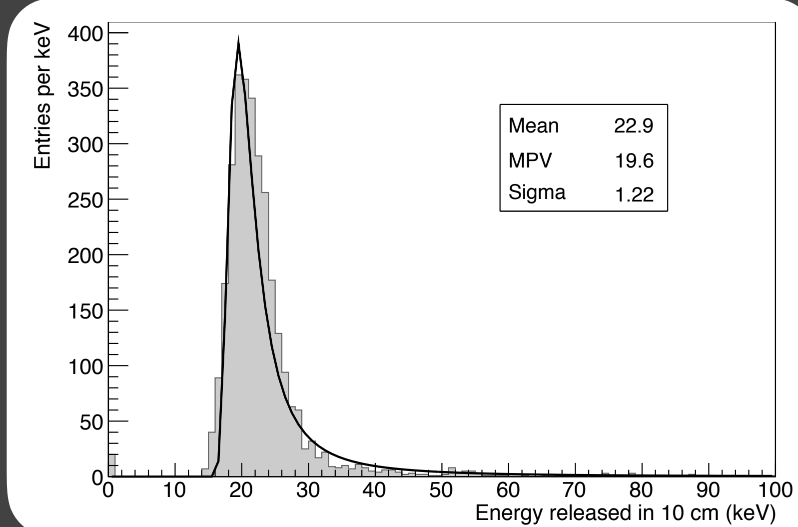
The amount of photons produced in the channels was evaluated and compared with the electron number. A constant ratio of 0.07 γ/e was found almost independent from the gas gain.



ENERGY RESOLUTION

Tracks were subdivided in "slices" of various widths (0.8 mm - 2 cm);
The energy released in the slices was simulated by Garfield (200 eV - 4.8 keV) and the behaviour of the energy resolution was evaluated;





An energy resolution of about 25% is achieved for releases of few keV;

LEMON: COSMIC RAYS