Clustering & Tracking with a Single Event-Driven SOI Pixel Detector for Axion Search Experiment

ALEJANDRO MORA[1], AYAKI TAKEDA[2], HIROAKI AIHARA[1], KENTARO MIUCHI[3], TAKESHI GO TSURU[4], TAAKAKI TANAKA[4], TATSUKI OSE[1], YOSHIO KAMIYA[1], YOSHIYUKI ONUKI[1], YOSHIZUMI INOUE[1]

[1]THE UNIVERSITY OF TOKYO, [2]UNIVERSITY OF MIYAZAKI, [3]KOBE UNIVERSITY, [4]KYOTO UNIVERSITY

HSTD11-SOIPIX2 – OIST, OKINAWA, 15 OF DECEMBER OF 2017

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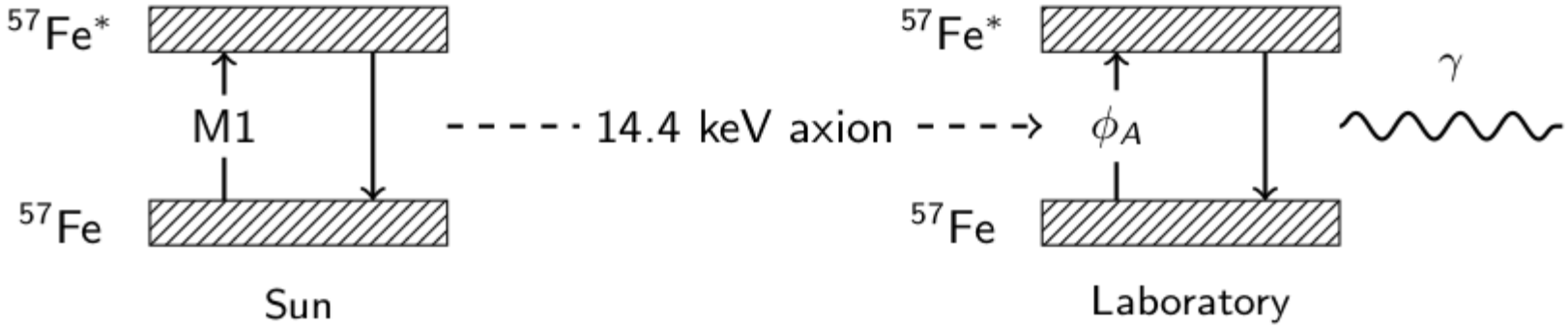
1. Axions from the sun
2. The experimental design
3. The clustering and tracking scheme
4. How well does everything work?
5. Future prospects

Axions from the sun

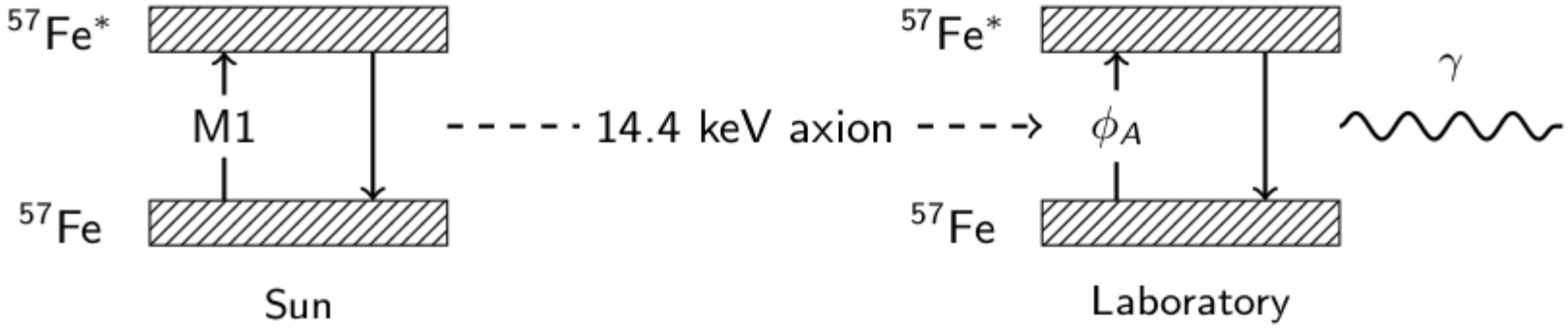


Interaction of photons with the sun's magnetic field may produce axions

Monochromatic photons produced copiously are what we need!

Phys .Rev. Lett, 75 (1995) 3222

Axions from the sun



Use the 14.4 keV line for the ^{57}Fe isotope!

Let the emitted axion couple to ^{57}Fe nucleus in the laboratory and look for an emitted photon of the same (14.4 keV) energy

Expected excitation rate:

$$R = 3C^4 \left(\frac{10^6\ \text{GeV}}{f_A}\right)^4 \times 10^2 \text{day}^{-1}\text{kg}^{-1}$$

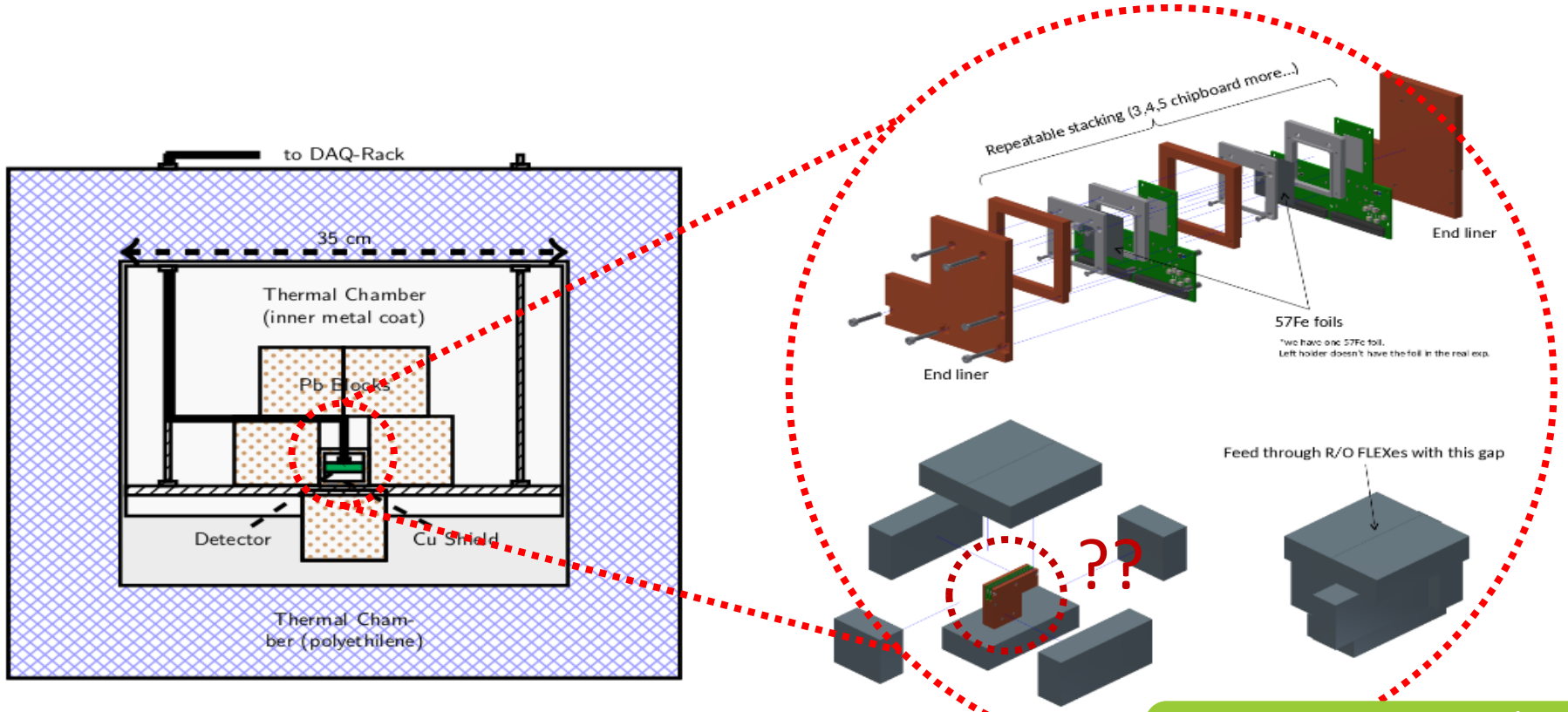
Phys .Rev. Lett, 75 (1995) 3222

OBJECTIVE

Obtain new constraints on the axion mass for the hadronic window:

$$1\ \mathrm{eV} < m_A < 20\ \mathrm{eV}$$

The experimental design



Y. Onuki presentation:
Low background radiation SOI pixel detector for Solar Axion search experiment (Friday)

The XRPIX detector

A series of monolithic SOI Pixel detectors originally designed for spatial γ search

With two operating modes	
Integration mode	Event-triggered mode
1. Reset 2. Time window 3. AD conversion 4. Storing	1. Reset 2. Trigger 3. AD conversion 4. Storing
What about the response to other particles?	

T. Tsuru presentation:
Overview of the X-ray astronomical imaging detectors (Monday)

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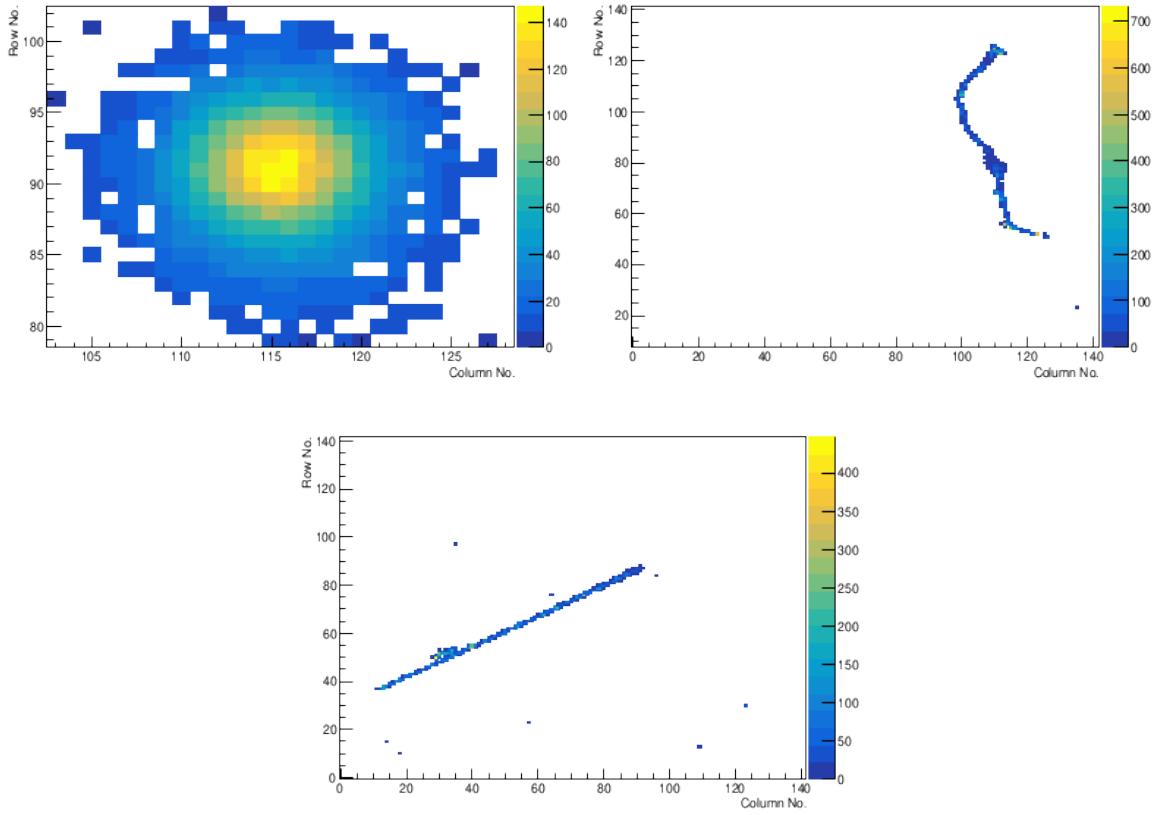


T. Tsuru presentation:
Overview of the X-ray astronomical imaging detectors (Monday)

Can we analyze the background of this experiment in a systematic and efficient way?

Can we analyze the [illegible] ex[illegible]y?

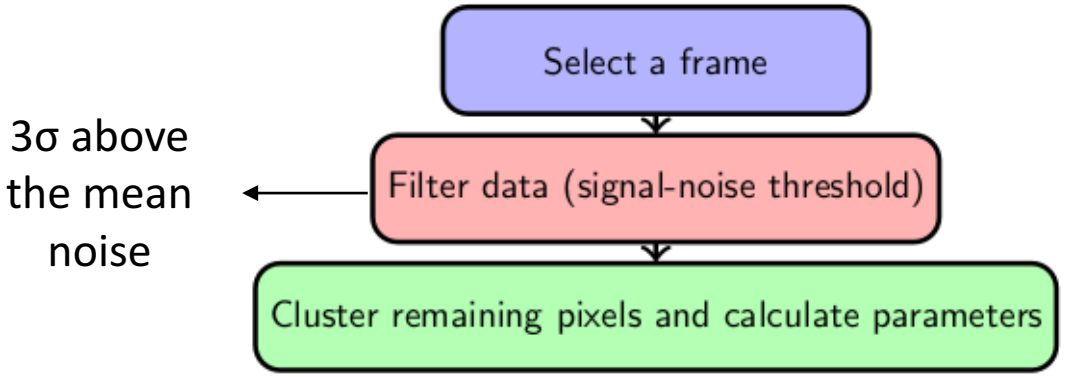
Can we efficiently study other types of radiation with the XRPIX?*

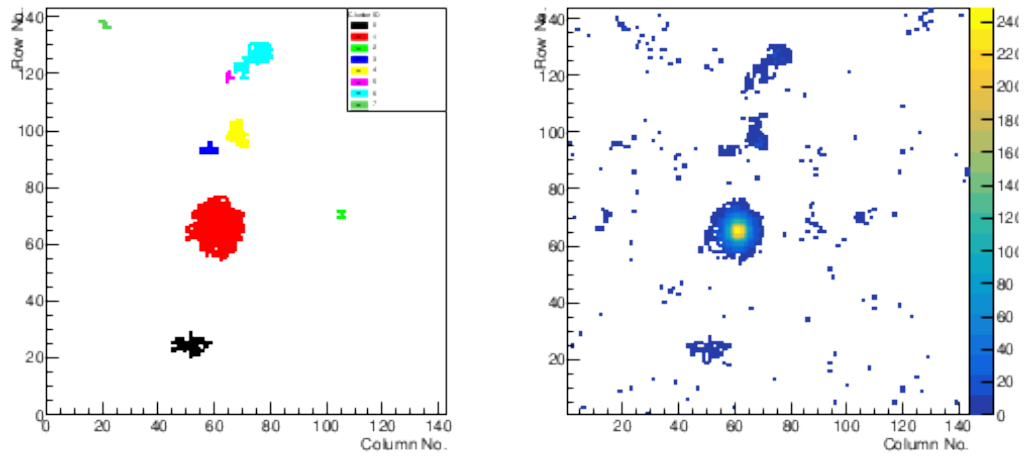
If we can identify the type of radiation interacting with the detector…

Y. Kamiya presentation:
Imaging Detector for Ultracold Neutrons using SOI Pixel Sensors and its Application to an Experimental Test of the Weak Equivalence Principle (Friday)

The clustering (DBSCAN Algorithm)

Define a cluster like a group of pixels such as that for each pixel in the group, there is at least another one in the close vicinity of the first. Then...





Example of the clustering process in Am-241 data. The minimum number of pixels required to form a cluster is 3, and the maximum distance between two pixels within a cluster is 30 μm

How to determine the particle of each cluster?

Used radioactive sources to generate characteristic clusters for each type of radiation.

(usually) when a human looks at the clusters, easily distinguish the source.

Objective:

Find simple properties that allow a computer to discriminate between clusters from different sources

How?

Use **Gaussian-like** distributed parameters from the samples to write the likelihood of a cluster to a radiation *p* as

$$L_p(\boldsymbol{x}_p) = \exp\left[-\left(\boldsymbol{x_p} - \boldsymbol{\mu_p}\right)^{\mathrm{T}} \boldsymbol{\Sigma_p^{-1}} \left(\boldsymbol{x_p} - \boldsymbol{\mu_p}\right)\right]$$

Where

- $x_p =$ Vector of the cluster parameters for radiation *p*
- $\mu_p =$Vector with the most probable values of the parameters for radiation *p*
- $\Sigma_p =$Covariance matrix for the parameters of radiation *p*

Parameters

Proposed cluster properties to be used as parameters

- Dimensions' difference
- Centers' distance
- Linearity
- Occupation fraction

… obtained using the XRPIX-2b in the integration mode

Characteristic	Value
Total size (mm2)	6 × 6
Sensitive size (mm2)	4.6 × 4.6
Pixel size (µm2)	30 × 30
Readout channels	144 × 144
Readout noise (rms)	68 e^-
Sensor layer thickness (µm)	500
FWHM at 13.95 keV (Am-241)	1.28 keV

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Determine the characteristics of each type of radiation

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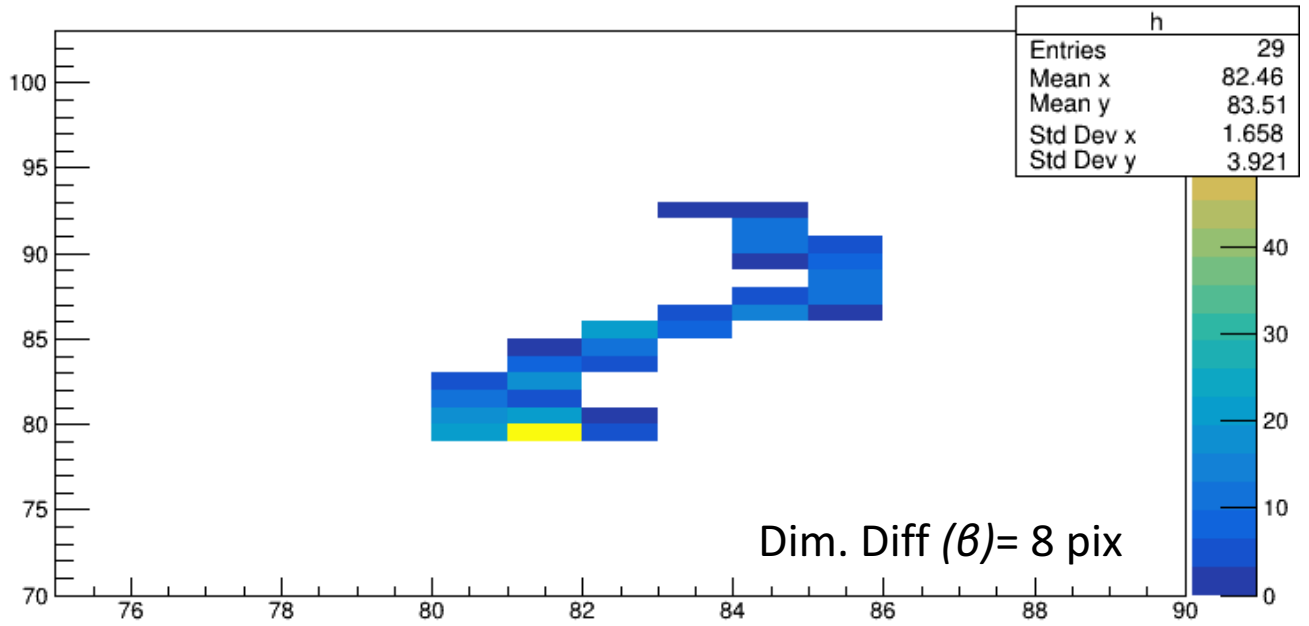
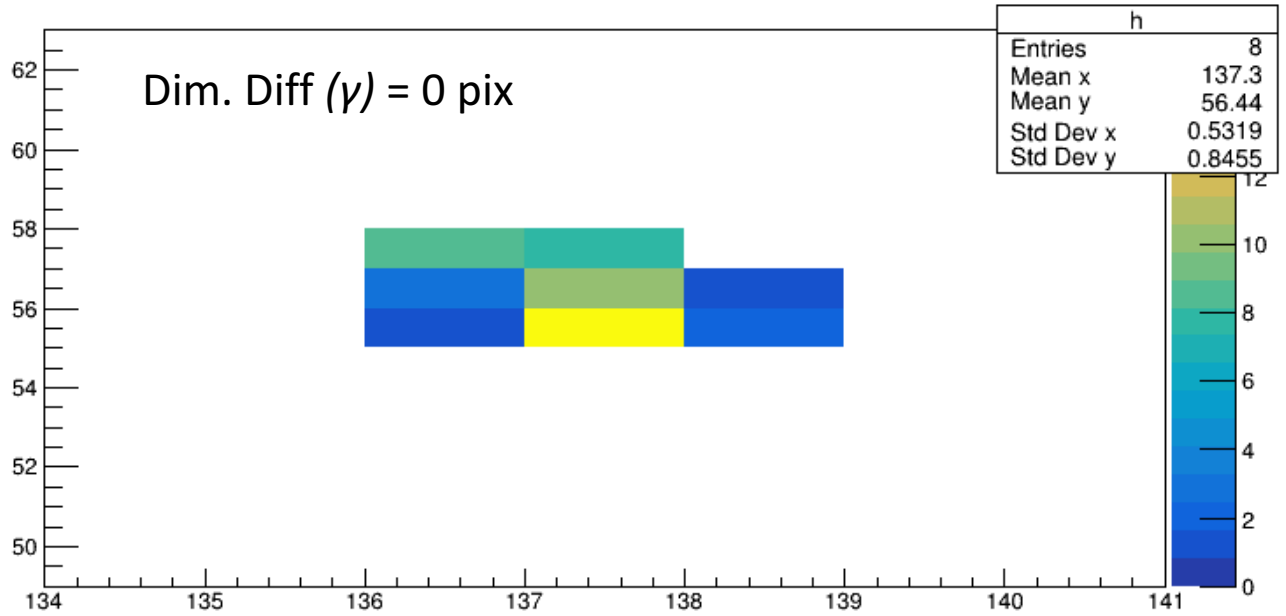
	Alpha	Beta	Gamma	Muon
Source	Am 241	Sr 90	Am 241	CR (Env)
Bias Voltage [V]	100	200	200	180
Temperature [K]	278	253	183	223
Integration time [ms]	0.3	1	1	10
Initial cut	Size > 100 Clusters in the border excluded	Likelihood value for alpha, gamma and muon < 0.75 Occ. Frac. < 1	Size < 50	Size > 10 Linearity > 0.95
Samples (after cuts)	4402	3.422×10^6	2.844×10^6	121

Dimensions' difference

Absolute difference in the number of columns and rows spanned by the cluster

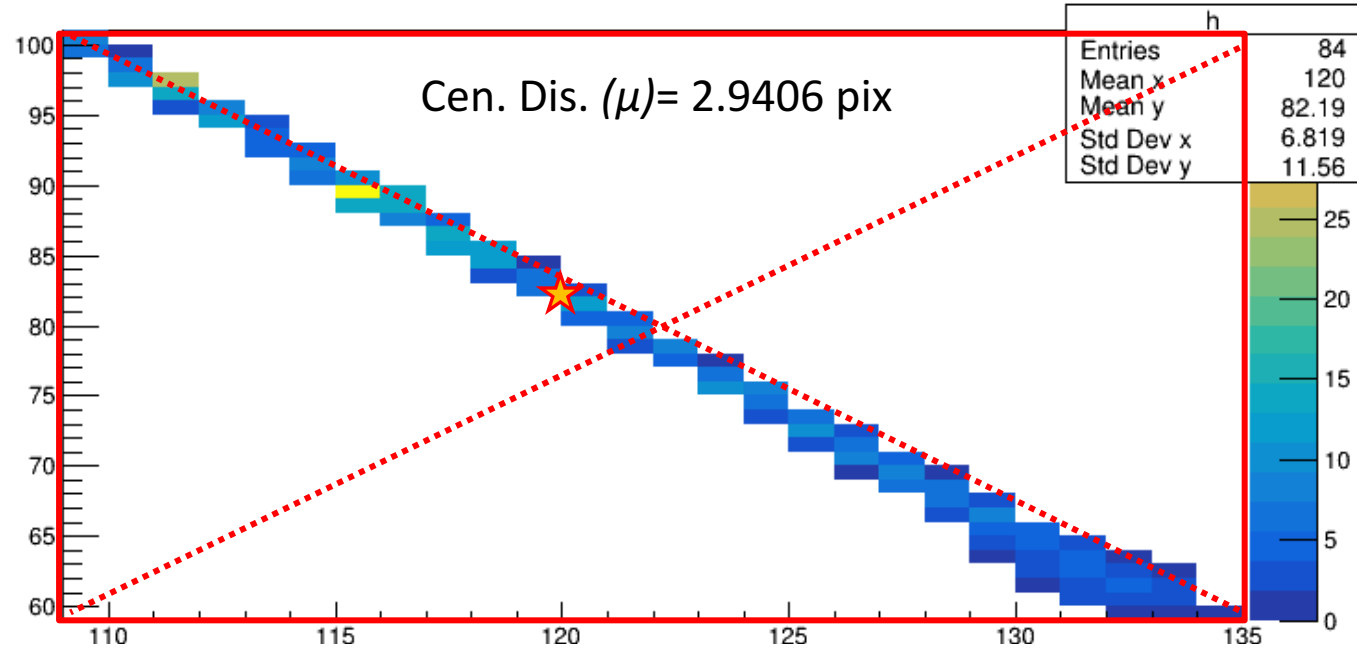


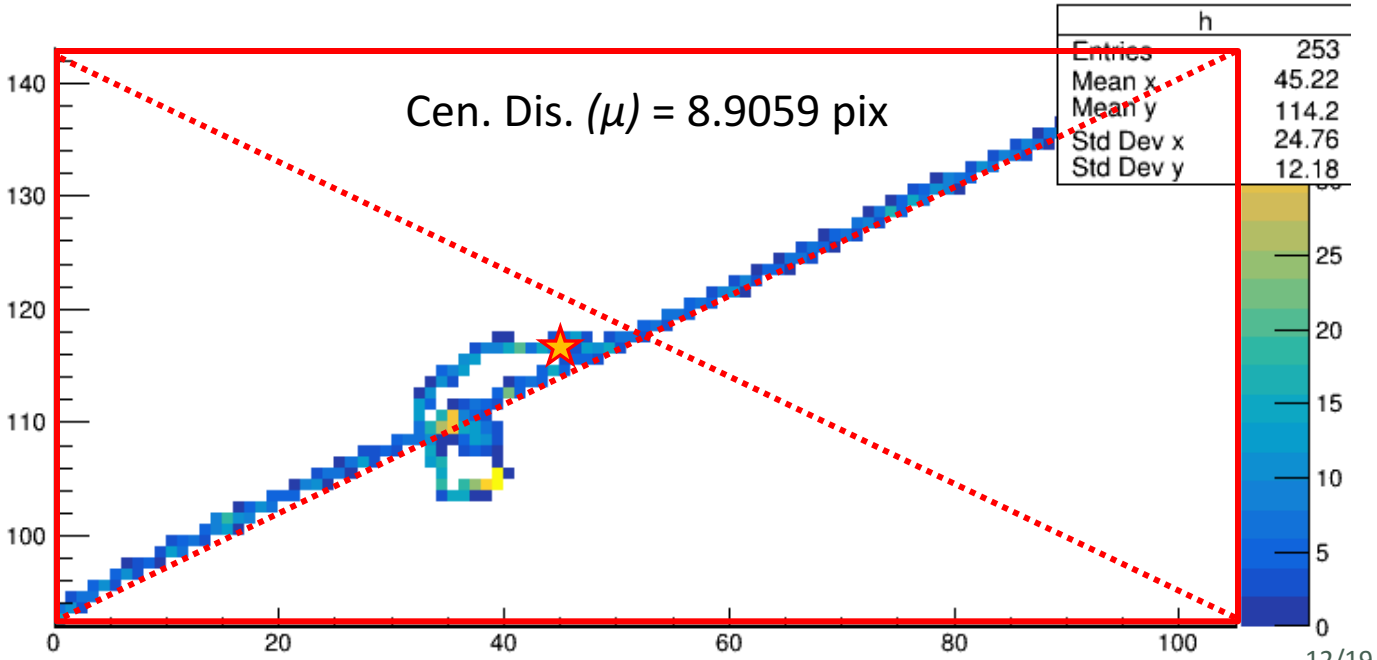


Centers' distance

Distance between the cluster weighted center and the center of the bounding box of the cluster

Way to detect δ electrons!



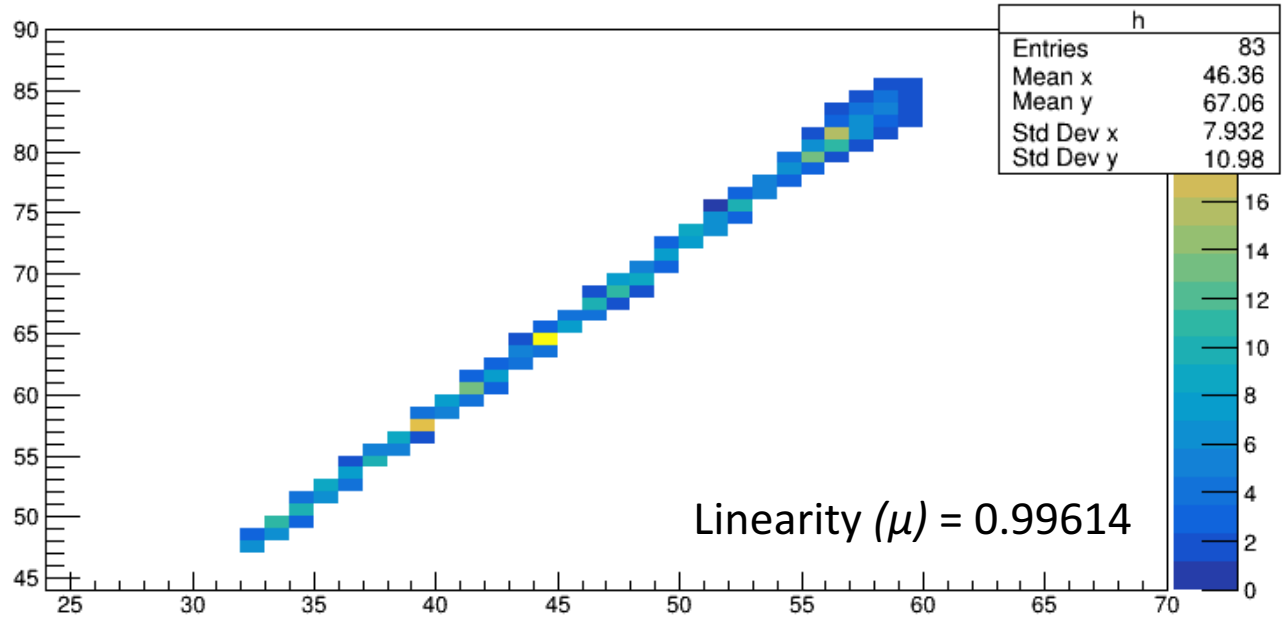


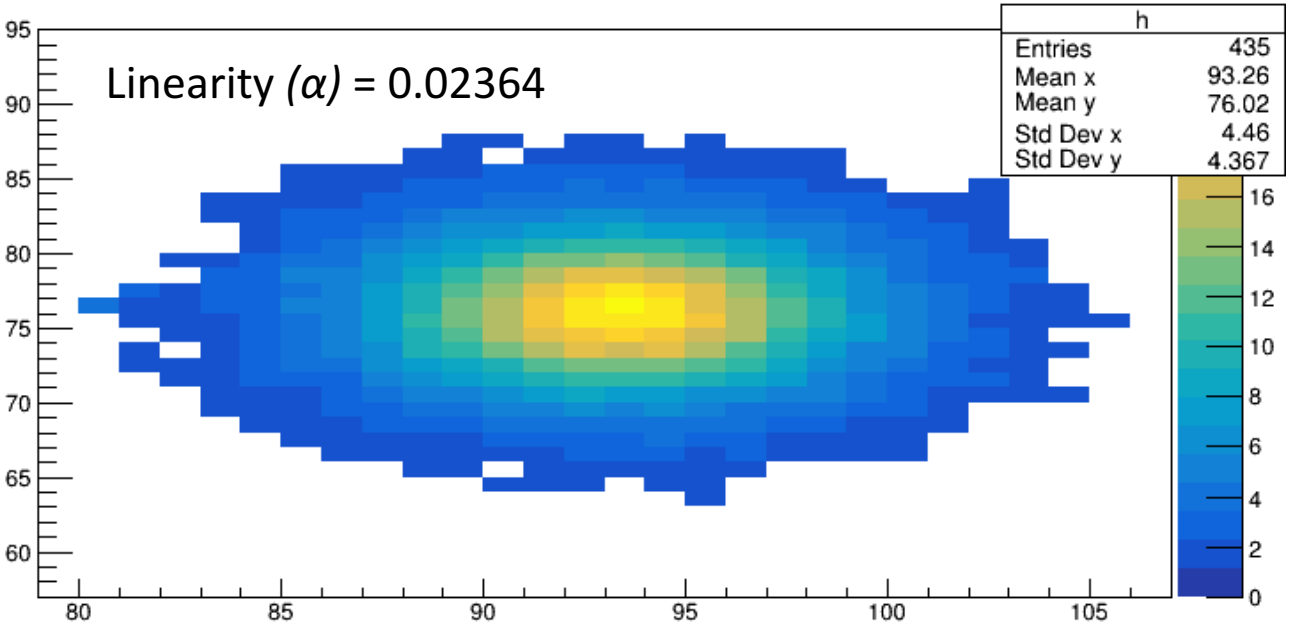
Linearity

Pearson correlation coefficient between the column and row of each pixel

$$\rho = \frac{\sigma_{\mathrm{col,\,row}}}{\sigma_{\mathrm{col}}\sigma_{\mathrm{row}}}$$

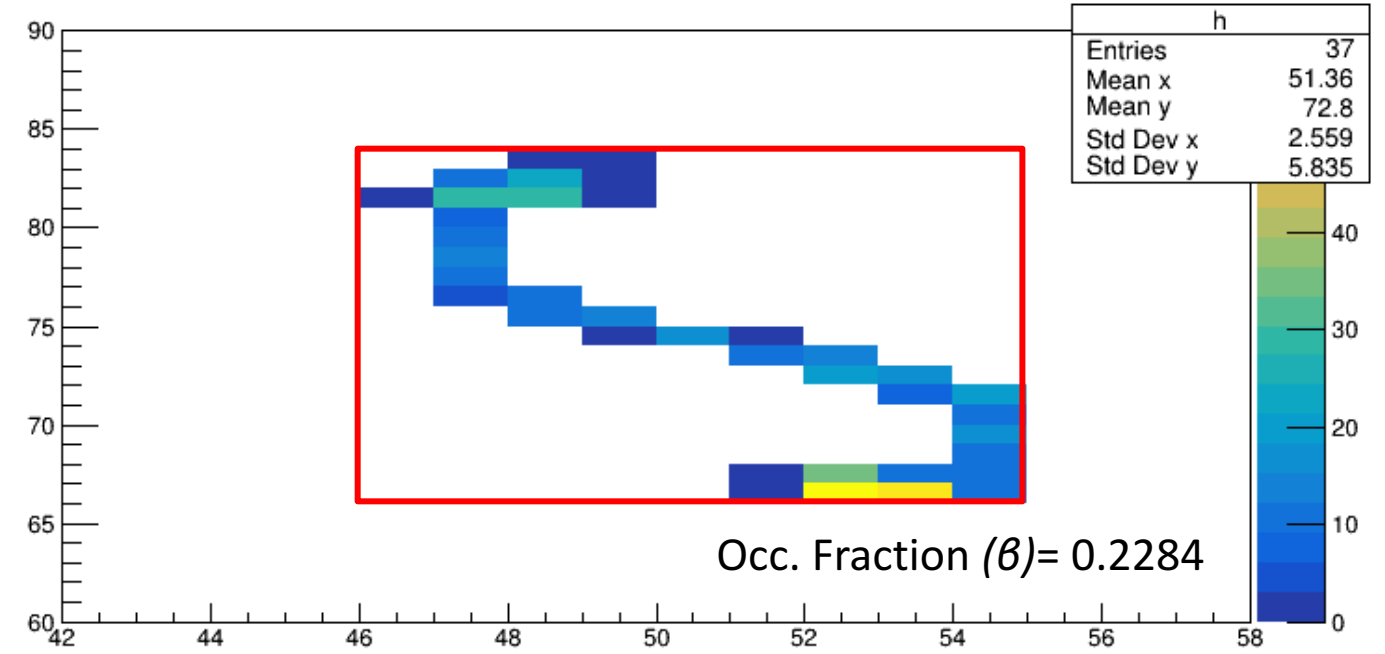
Equal to 1 if the coefficient is undefined ($\sigma_{\mathrm{col}}\sigma_{\mathrm{row}} = 0$)

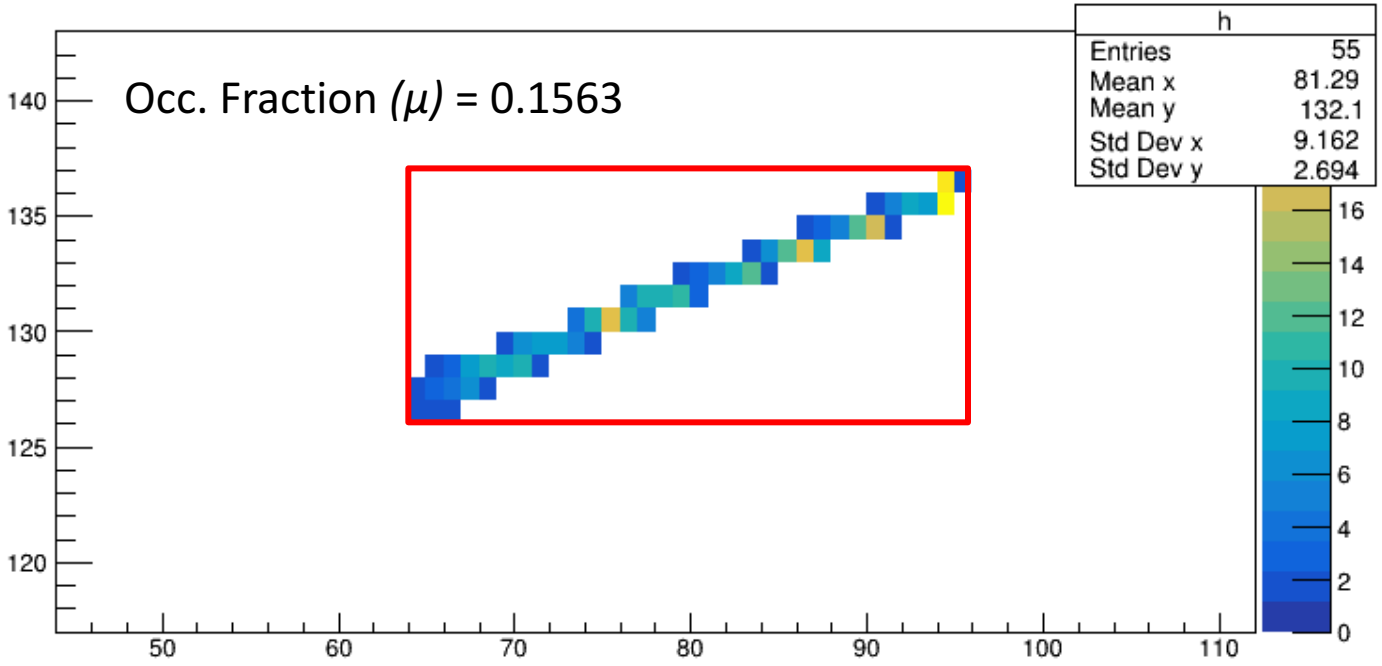




Occupation fraction

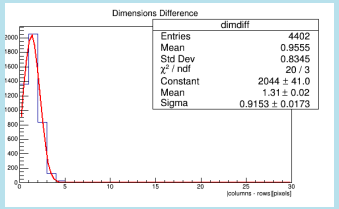
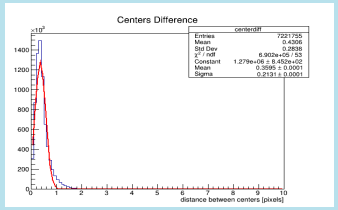
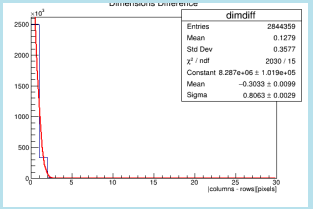
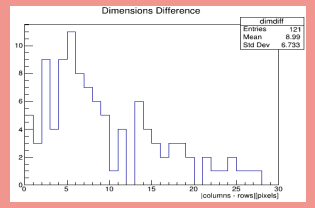
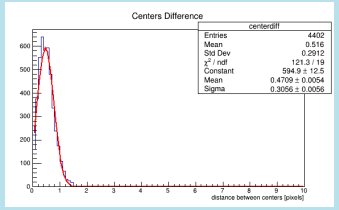
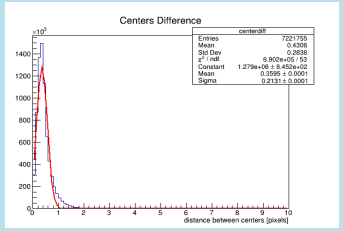
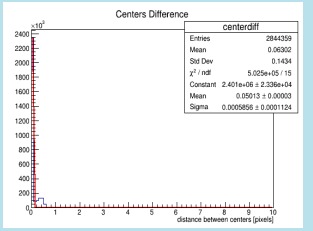
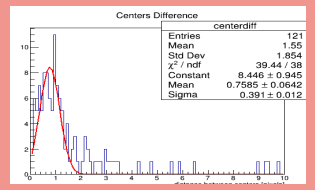
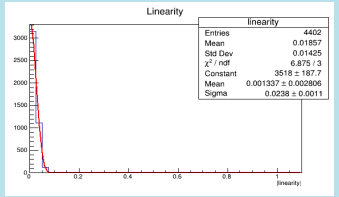
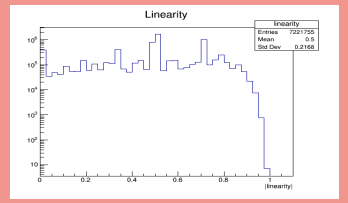
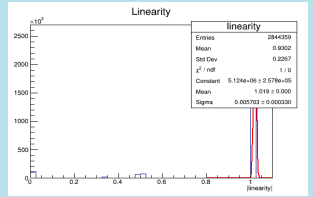
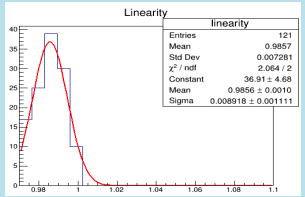
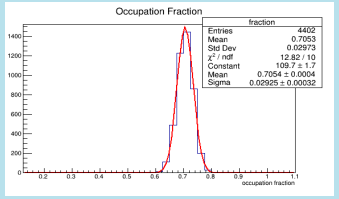
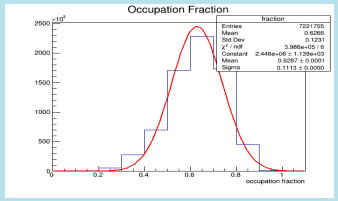
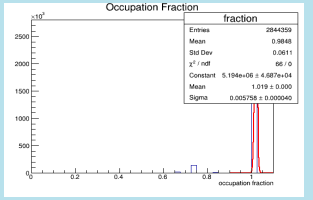
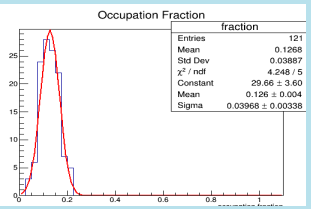
Ratio between the size of the cluster and the size of its bounding box





In concrete…

Used as parameter of the Likelihood function of …

	α	β	γ	μ
Dimensions difference				
Centers difference				
Linearity				
Occupation Fraction				

How well do these properties work?

1

All likelihood function use the same group of properties

Calculate the likelihoods of the most probable values of each radiation

Since the likelihood functions can be interpreted as probabilities:

$$\sum L_i = 1$$

$L_a(\mu_b)$	L_α	L_β	L_γ	L_μ
μ_α	1	0.4451	0	0
μ_β	0	1	0	0
μ_γ	0	1.11E-5	1	0
μ_μ	0	0	0	1

2

Calculate the likelihoods for the clusters in environment's data

Make a scatter plot of each likelihood pair

Are all the points under the line $y = 1 - x$?

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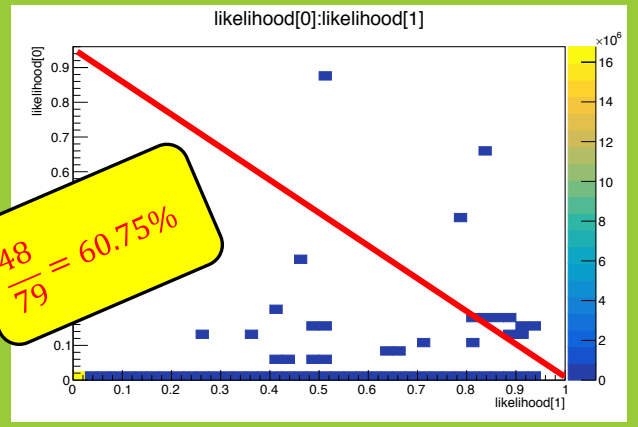
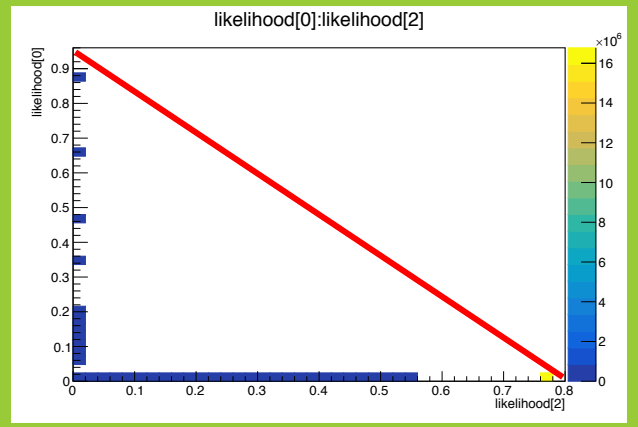


$L_\alpha : L_\beta$



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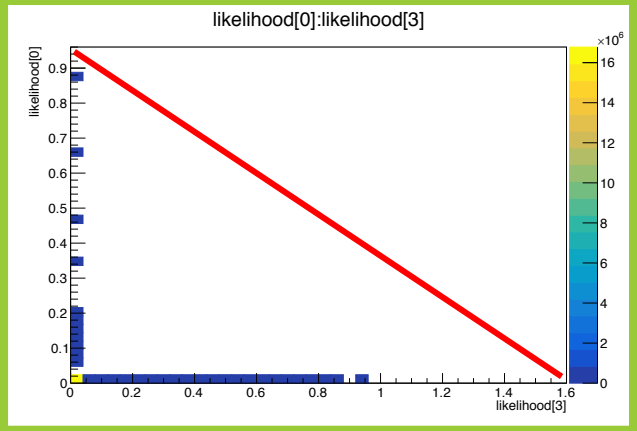
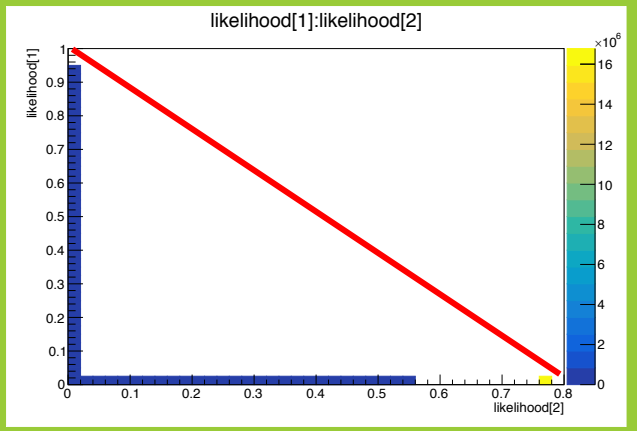


$L_\alpha : L_\mu$



$L_\beta : L_\gamma$

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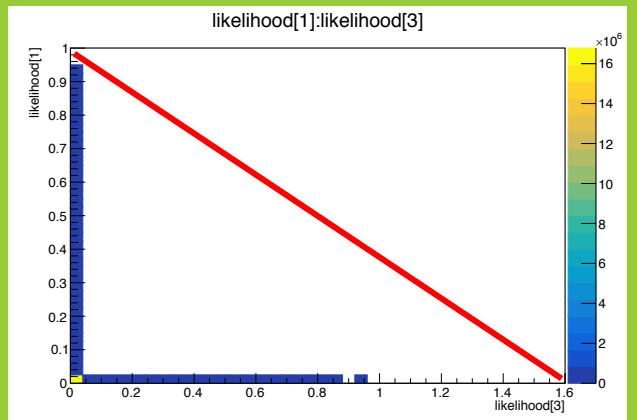
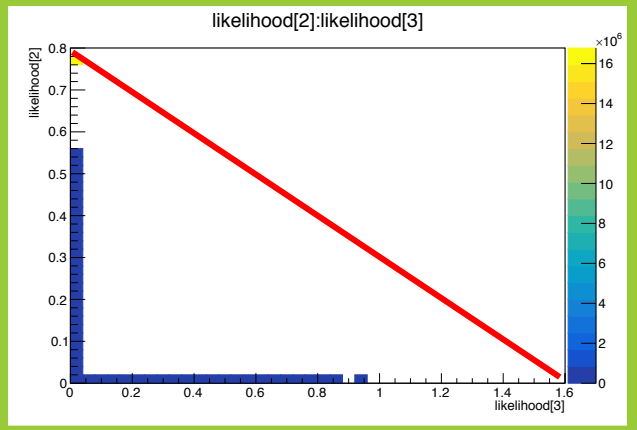


$L_\beta : L_\mu$



$L_\gamma : L_\mu$

Conclusions and prospects

A fast cluster analysis is possible

- A mean of 8.26 seconds for a data file of 15 MB (root file) ~ 1000 seconds of environmental data
- Output in root format

However…

- The distinction between alpha and beta must be improved
  - Evaluate beta source and data taking conditions
  - Limit search to a certain energy region (take into account XRPIX design purposes)
  - Look for a new parameter?
  - Implement the same cuts as the ones used when deriving the likelihoods
- The likelihood functions should be evaluated with data from other sources
  - Are they really likelihood function for particles, or for radioactive sources?
- The gamma cluster is basically a 1 pixel cluster
  - 20.83% of gammas in ^{241}Am larger than this
  - Include other shapes…
- Try to include non-Gaussian profiles in the likelihood functions…

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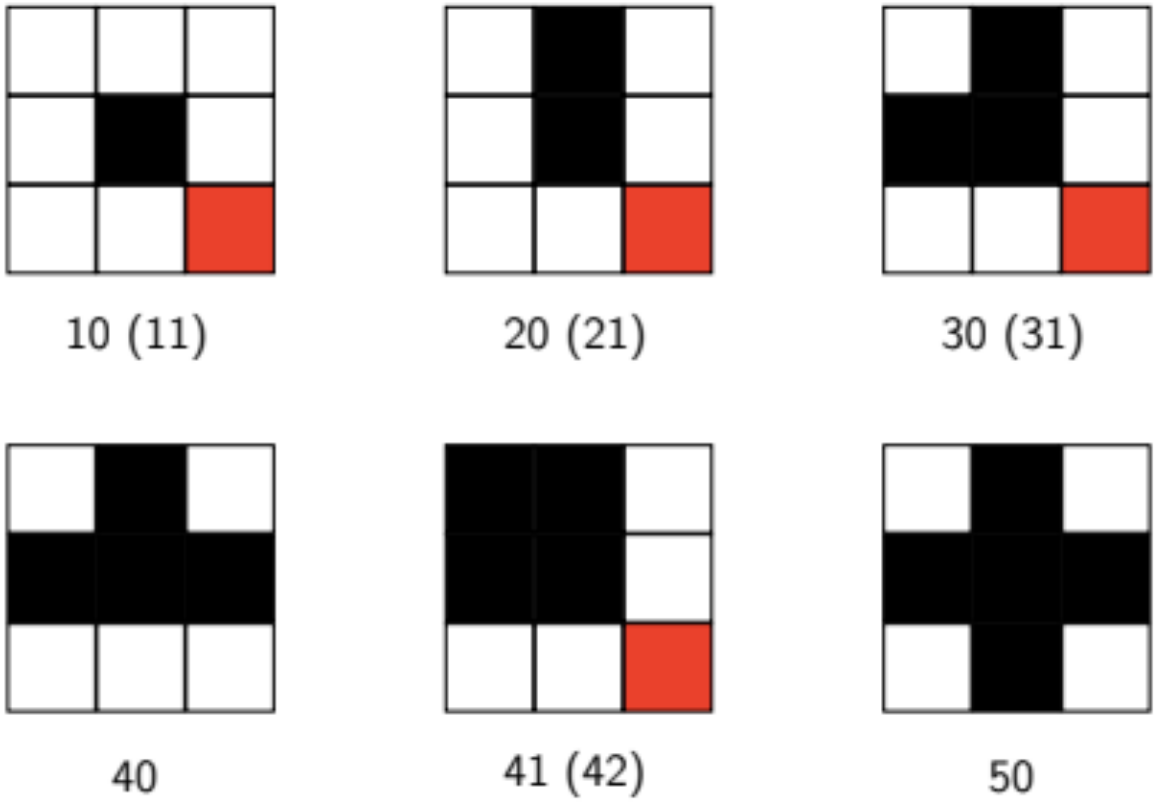
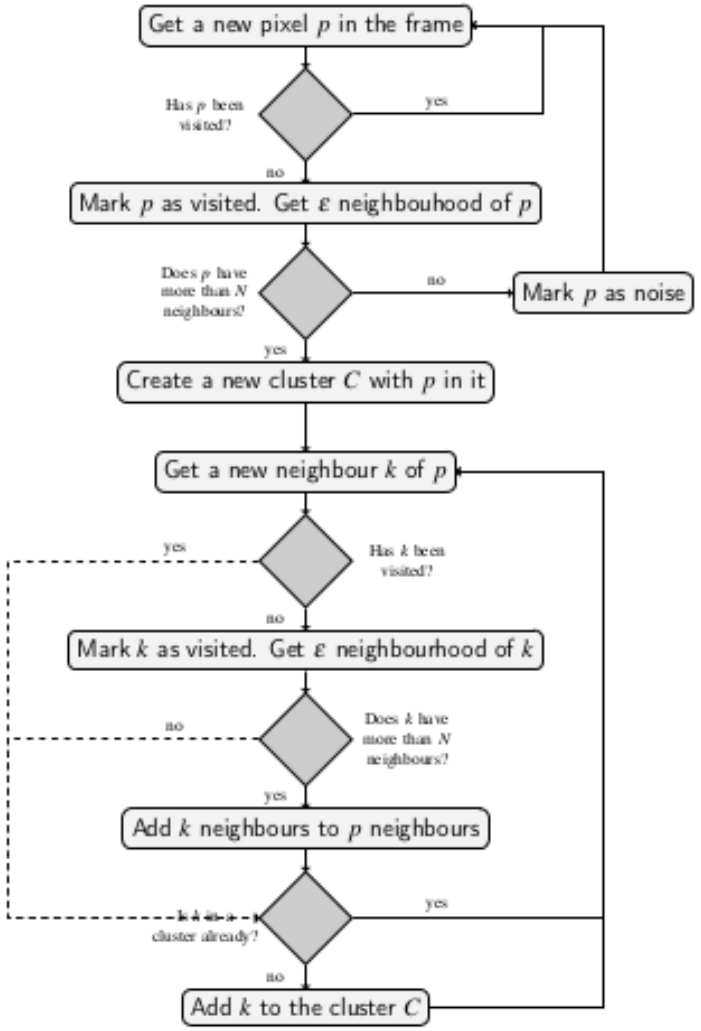
Thank you very much… and have a happy new year!

Comparison with former experiments

	Namba (2007)	Derbin et al (2011)	Current
Background rate $[\times 10^{-3}\mathrm{mm}^{-2}\mathrm{h}^{-1}\mathrm{keV}^{-1}]$	1.76	1.09	< 1.23
Energy resolution @ 14.4 keV $[\mathrm{keV}]$	2.36	1.48	0.58
Required temperature $[\mathrm{K}]$	205	77.35	223.15
Detector	Si photoscintilator	Si	SoI XRPIX
Shielding	• Lead (10 cm)	• Lead (5 cm) • Copper (10 mm cube, +40 mm bottom) • Iron (35 mm)	• Lead (5 cm) • Copper (10 mm) • Muon veto

Events explored by the XRPIX in the trigger mode





DBSCAN: the clustering algorithm

Correlation factors for each type of radiation

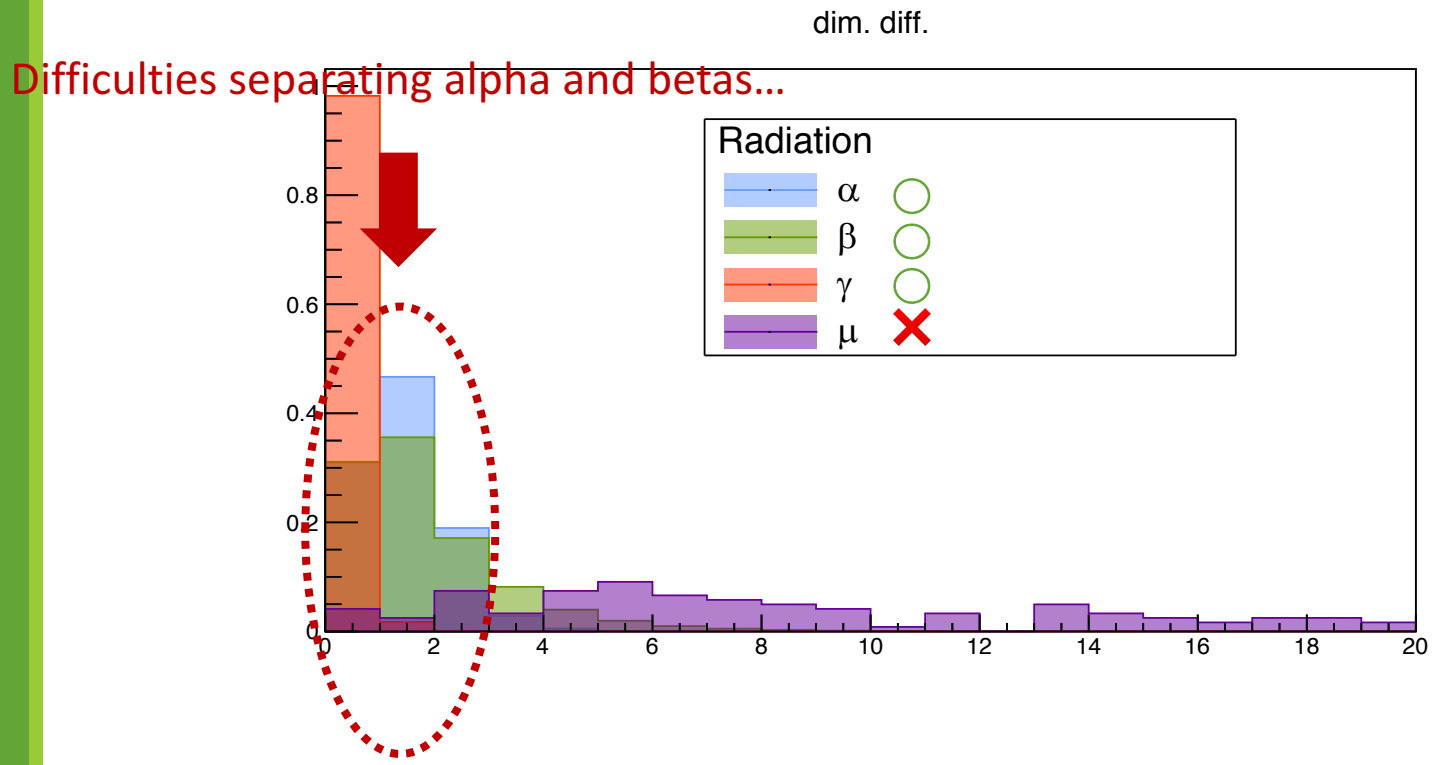
	Alpha	Beta	Gamma	Muon
L – OF	-0.0478	-0.3152	0.5447	-0.5117
L – DD	0.0494	-0.0320	-0.0011	0.2299
L – CD	0.0337	-0.0416	-0.6211	0.0662
OF – DD	-0.0527	-0.3675	-0.0259	-0.2079
OF – CD	-0.0305	-0.4698	-0.6676	-0.2454
DD – CD	0.0476	0.3850	0.4337	0.1488

χ^2/ndf for the fitting of the parameters' distributions to a Gaussian function

	Alpha	Beta	Gamma (peak)	Mu
Linearity	6.875 / 3	-	1 / 0	2.064 / 2
Occupation Fraction	12.82 / 10	3.98e6/6	66 / 0	-
Dimensions' Difference	20 / 3	2.596e5/23	2030 / 0	23.11 / 24
Centers' Distance	121.3 / 19	6.902e5/53	5.025e5 / 0	39.44 / 38

Dimensions difference

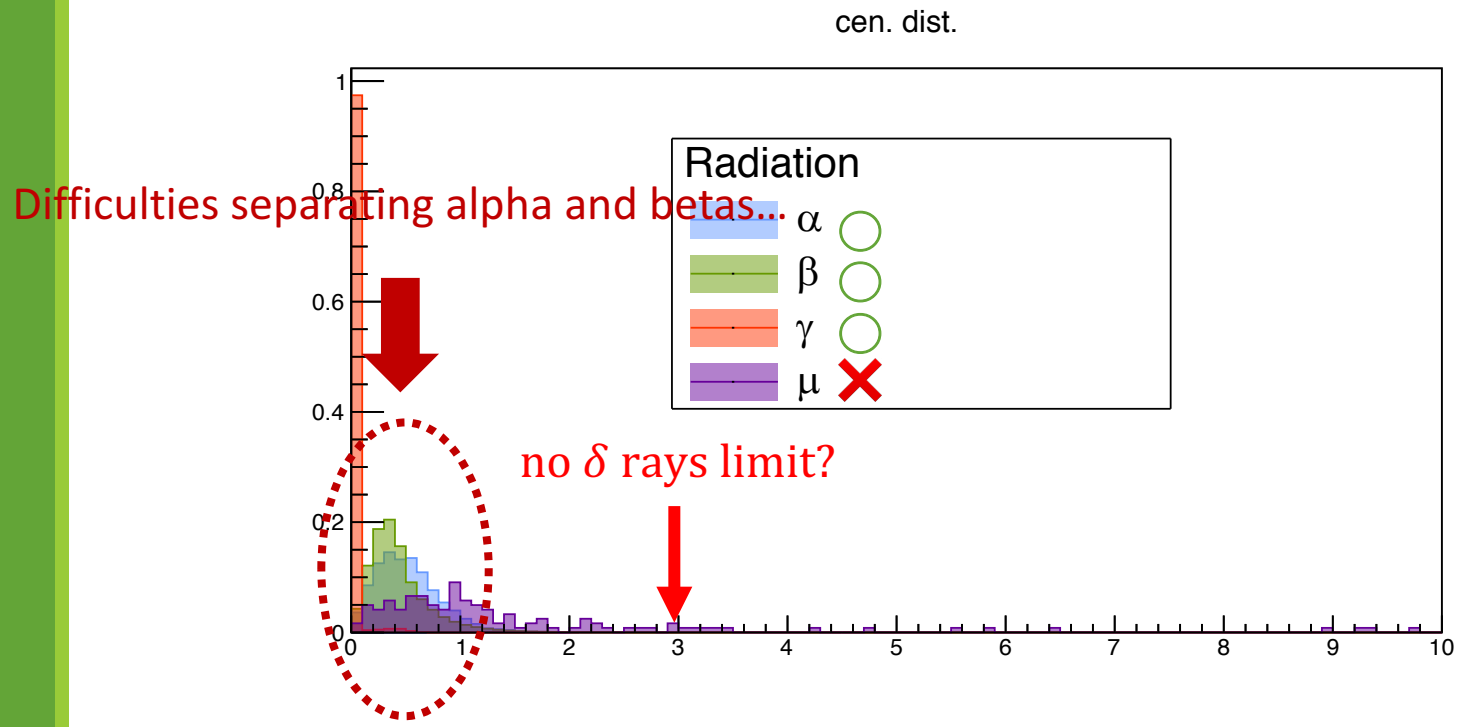
Difference in the number of columns and rows spanned by the cluster



Centers' distance

Distance between the cluster weighted center and the center of the bounding box of the cluster

Way to detect δ electrons!



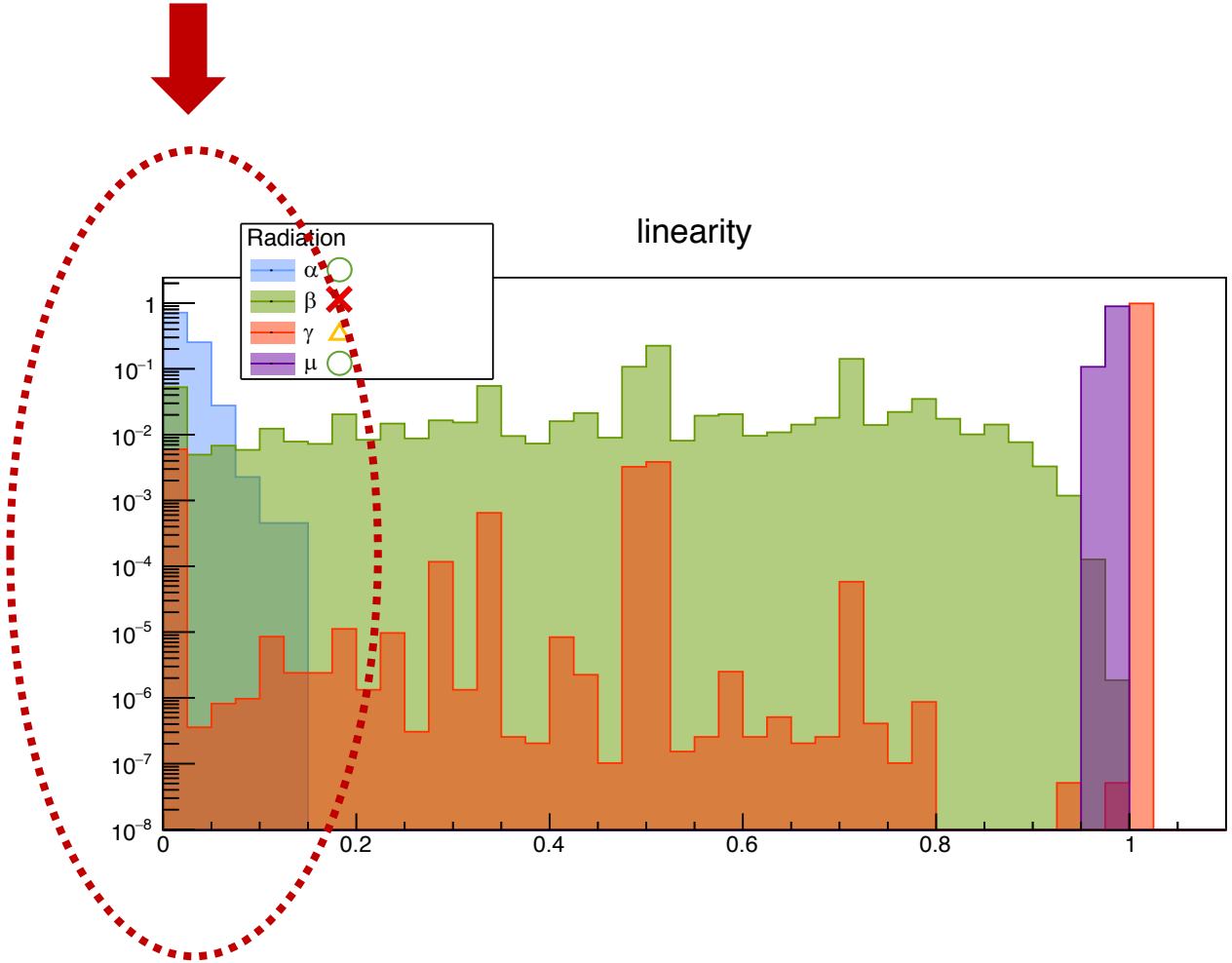
Difficulties separating alpha and betas…

Linearity

Pearson correlation coefficient between the column and row of each pixel

$$\rho = \frac{\sigma_{\mathrm{col,\,row}}}{\sigma_{\mathrm{col}}\sigma_{\mathrm{row}}}$$

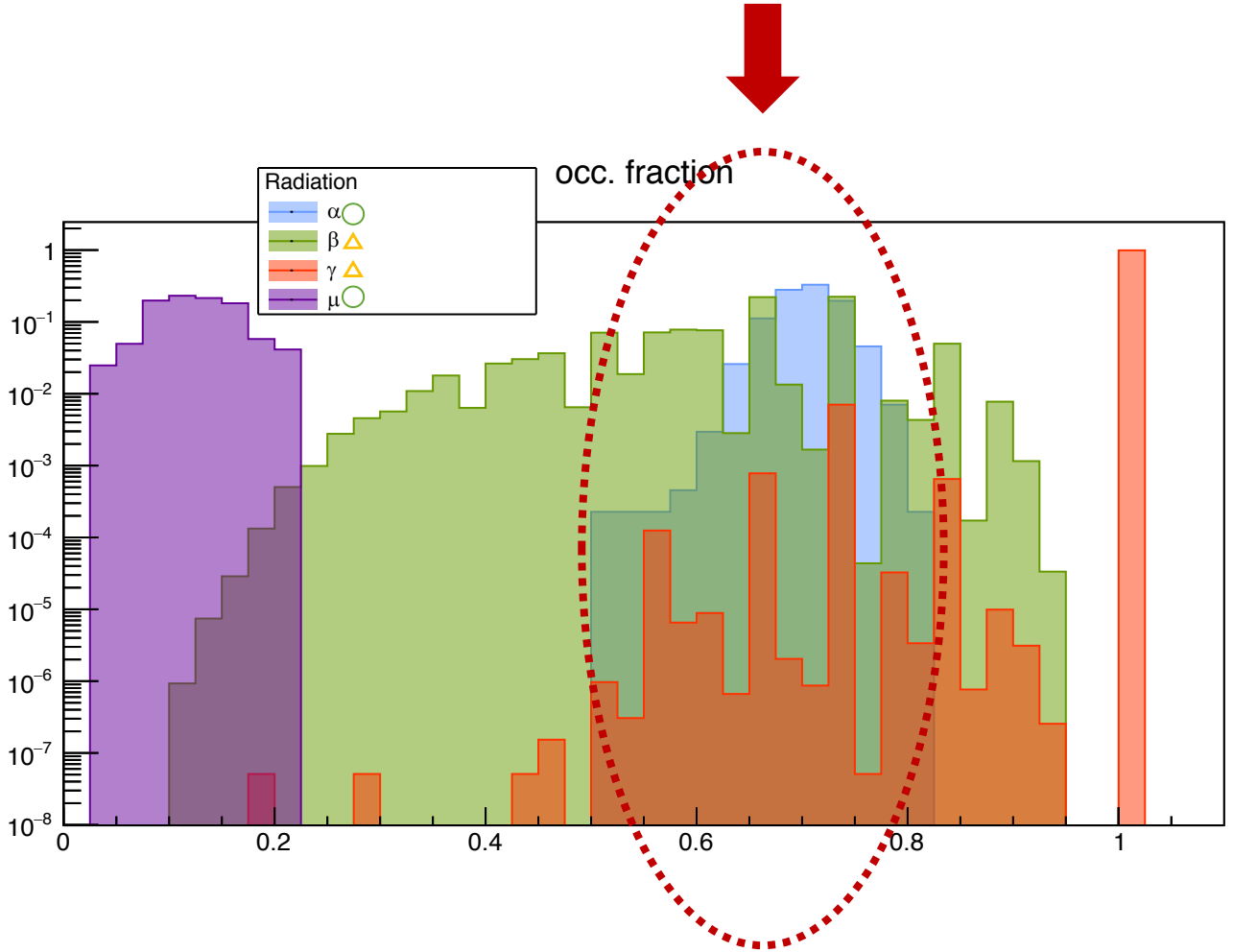
Equal to 1 if the coefficient is undefined ($\sigma_{\mathrm{col}}\sigma_{\mathrm{row}} = 0$)



Occupation fraction

Ratio between the size of the cluster and the size of its bounding box

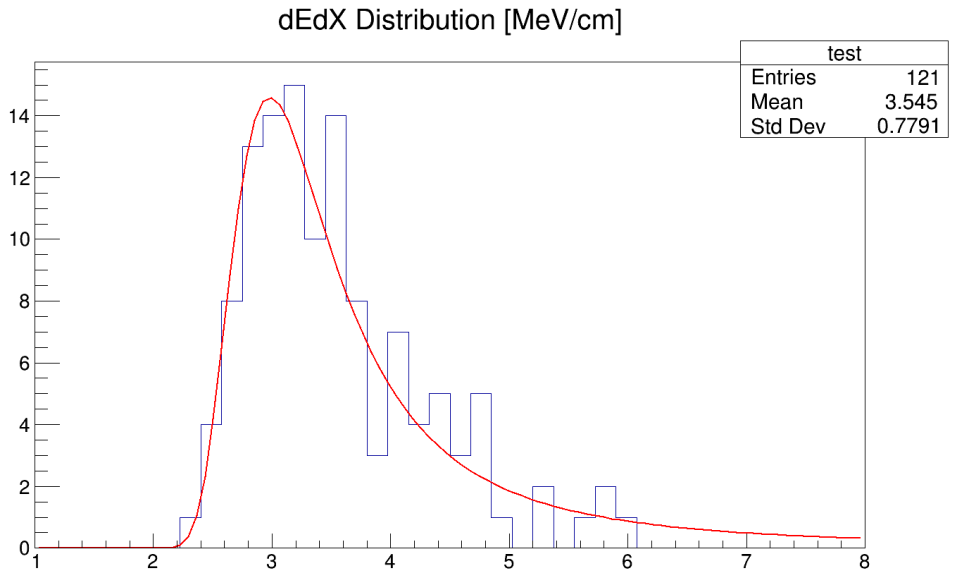
Difficulties separating alpha and betas…



Where do the cuts for muons come from?

Filtered environmental data until the dE/dx distribution followed a Landau one with a MPV close to 3.88 MeV/cm

- Chi square: 9.74
- NDF: 17
- Probability: 91.4%
- Size: 13
- Linearity: 0.97



What are those alpha-beta clusters?

```
======> EVENT:473810
 cluster          = (cluster*)0x33804c0
 TObject          = TObject
 ID               = 0
 run              = 2
 event            = 36597
 chip             = 1
 boxCenter[2]     = 71.5 , 4

 massCenter[2]    = 71.7566 , 3.49324

 size             = 21
 pixels           = (TClonesArray*)338b2a0
 signal           = 171.168
 likelihood[4]    = 0.876886 , 0.524482 , 0 , 0

 noRows           = 5
 noCols           = 6
 linearity        = 0.0132341
```

```
======> EVENT:12351155
 cluster          = (cluster*)0x33804c0
 TObject          = TObject
 ID               = 2
 run              = 34
 event            = 12789
 chip             = 1
 boxCenter[2]     = 115.5 , 43

 massCenter[2]    = 115.832 , 42.9207

 size             = 29
 pixels           = (TClonesArray*)33c7ab0
 signal           = 104.882
 likelihood[4]    = 0.66978 , 0.847063 , 0 , 0

 noRows           = 7
 noCols           = 6
 linearity        = 0.0247871
```