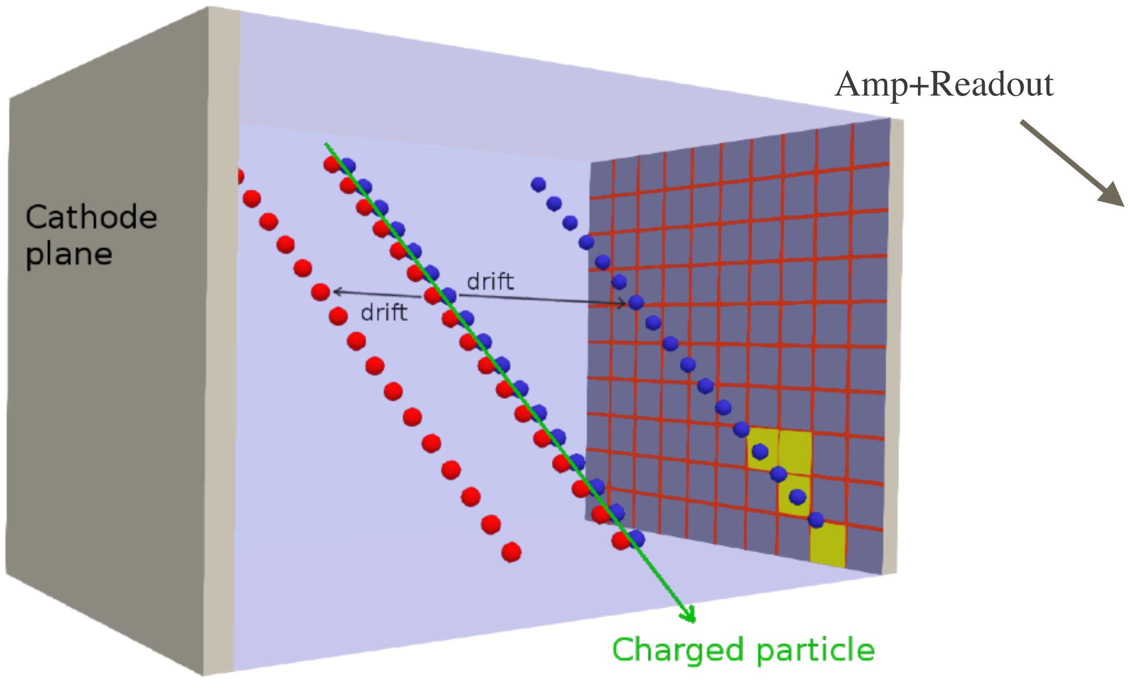
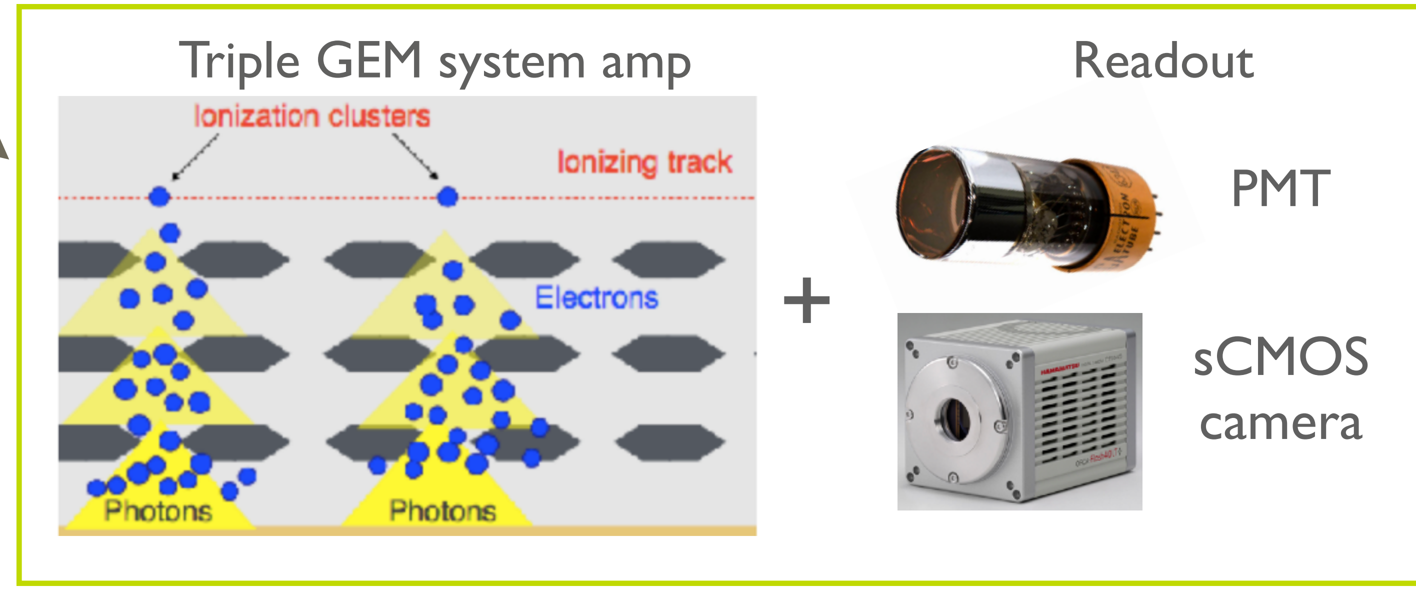
# Energy linearity in the LIME prototype of the CYGNO experiment

S.Torelli - On behalf of the CYGNO collaboration

RD51 Collaboration meeting 14/06/2021

# The CYGNO tecnique



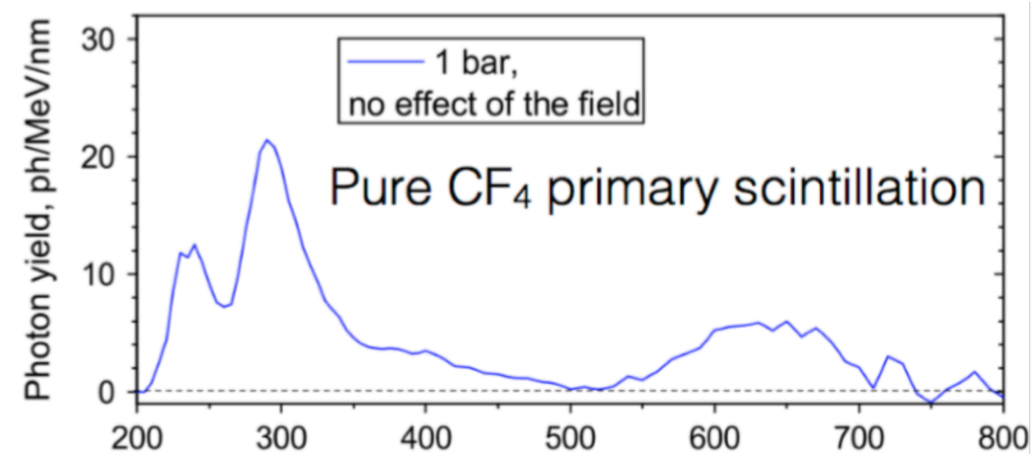



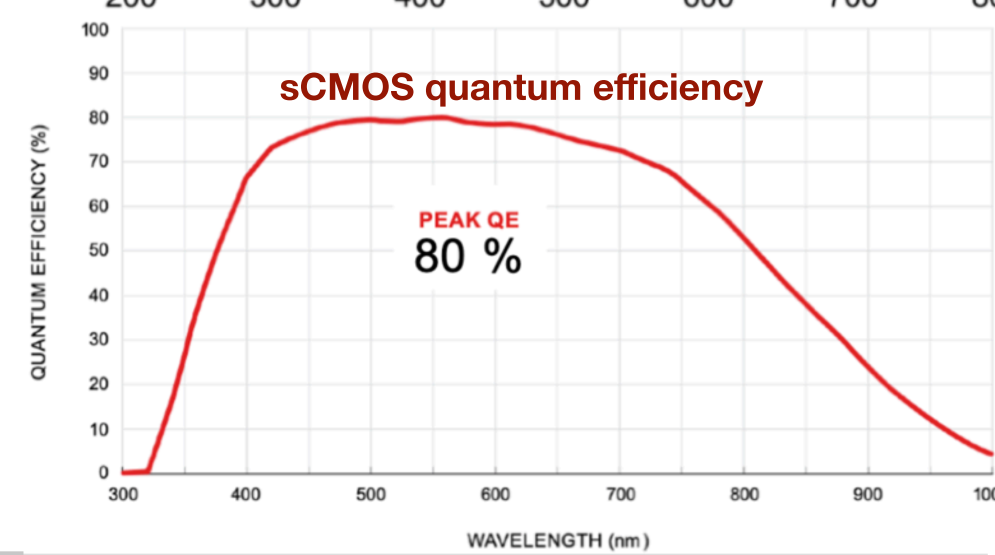

- Time projection chamber filled with He:$CF_4$ (60:40) at atmospheric pressure

- The trail of electrons produced in the TPC is transported to the readout

- Primay ionisation electron are amplified by triple thin GEMs, where light is produced together with electron avalanche (0.07 photon/electron)

- Light is readout from a sCMOS and a PMT



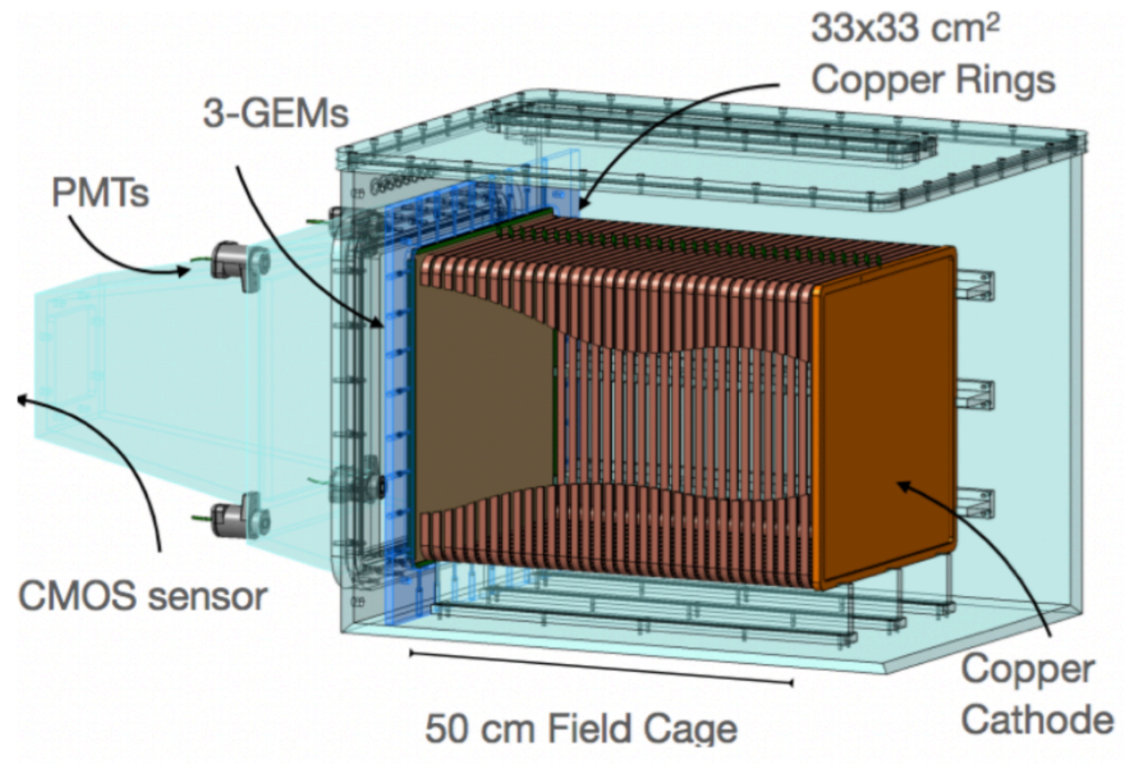



# The LIME prototype: CYGNO Phase 0

- Last prototype developed is the Large Imaging ModulE (LIME):
  - 50 cm drift
  - 33 x 33 $cm^2$ GEMs
  - 50 liters sensitive volume (0.05 $m^3$)
  - 35 copper ring field cage
  - 1 sCMOS camera (ORCA Fusion)
  - 4 PMTs

HIGH RESOLUTION
2304 × 2304
5.3 Megapixels

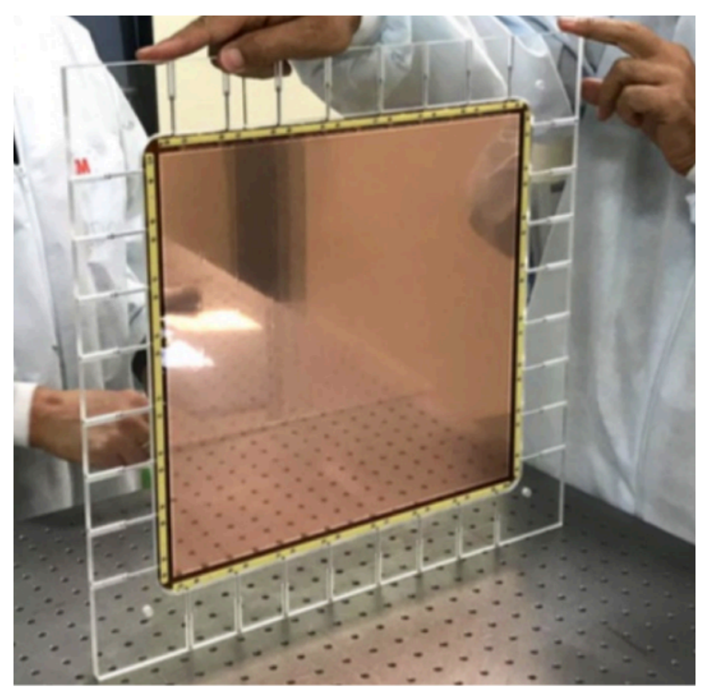
READOUT NOISE
0.7 electrons rms
Ultra-quiet Scan

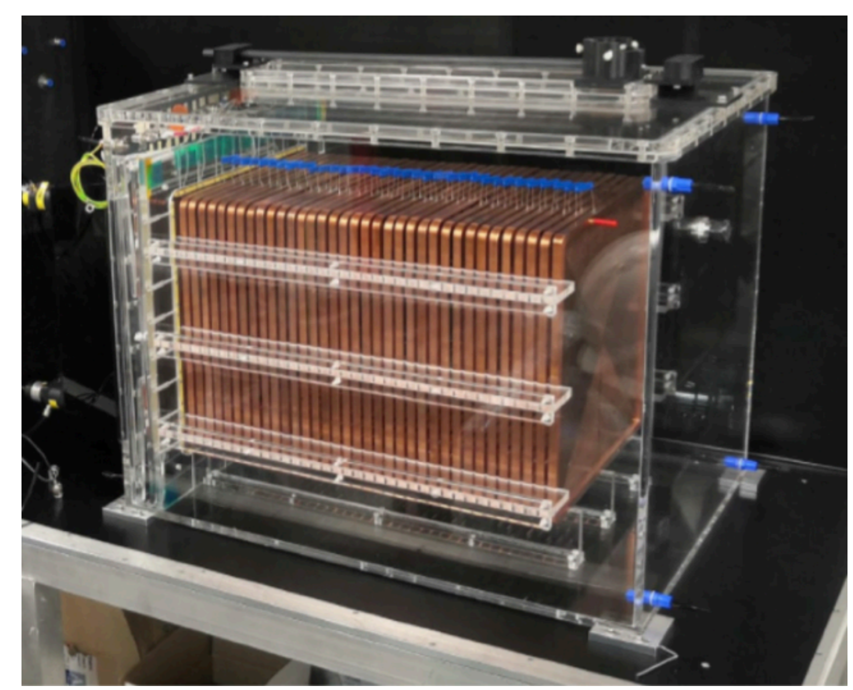



- Light response of 650 ph/keV

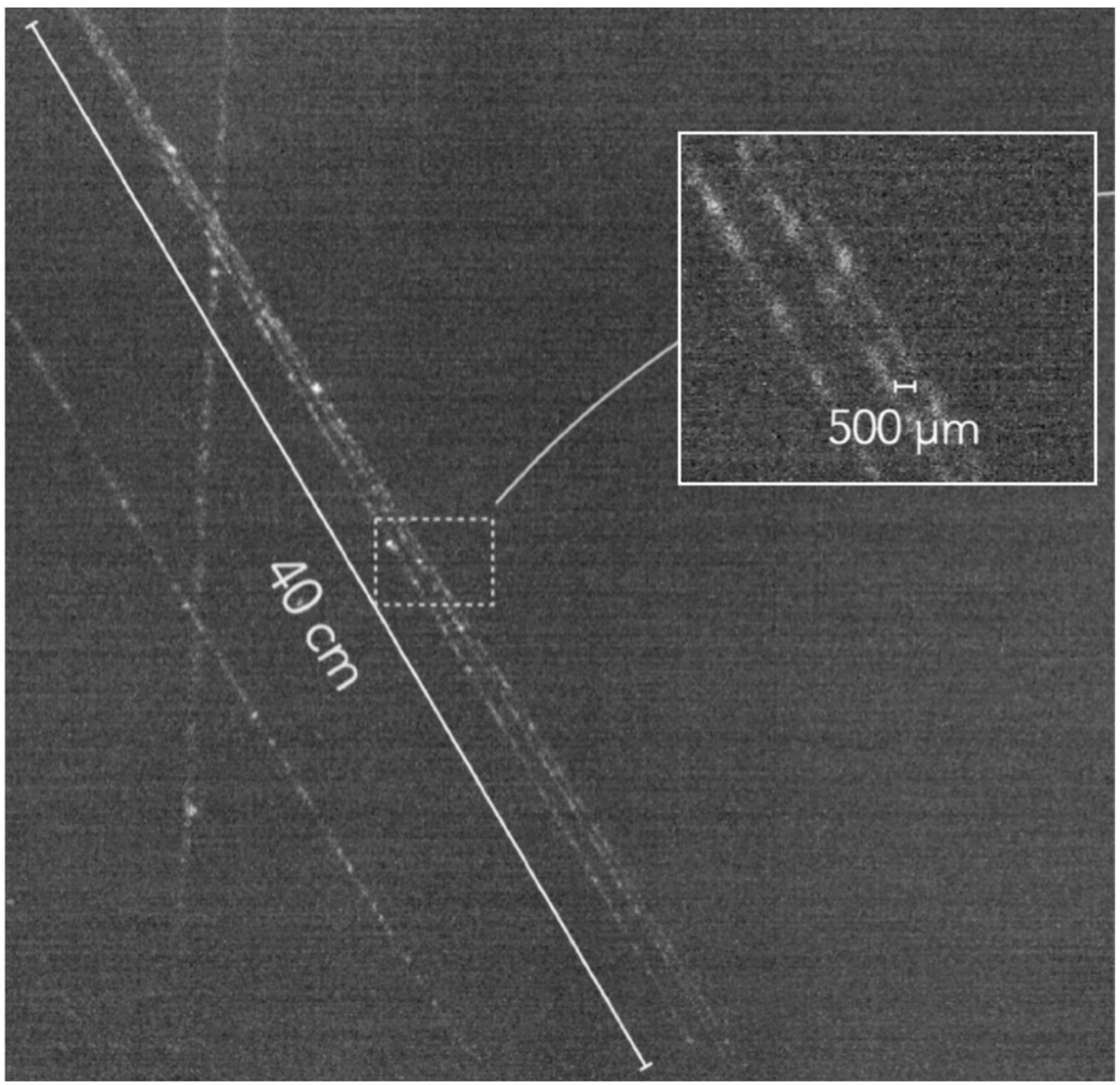
- Full detection efficiency in the whole 50 l

- 0.5 keV threshold with the new camera

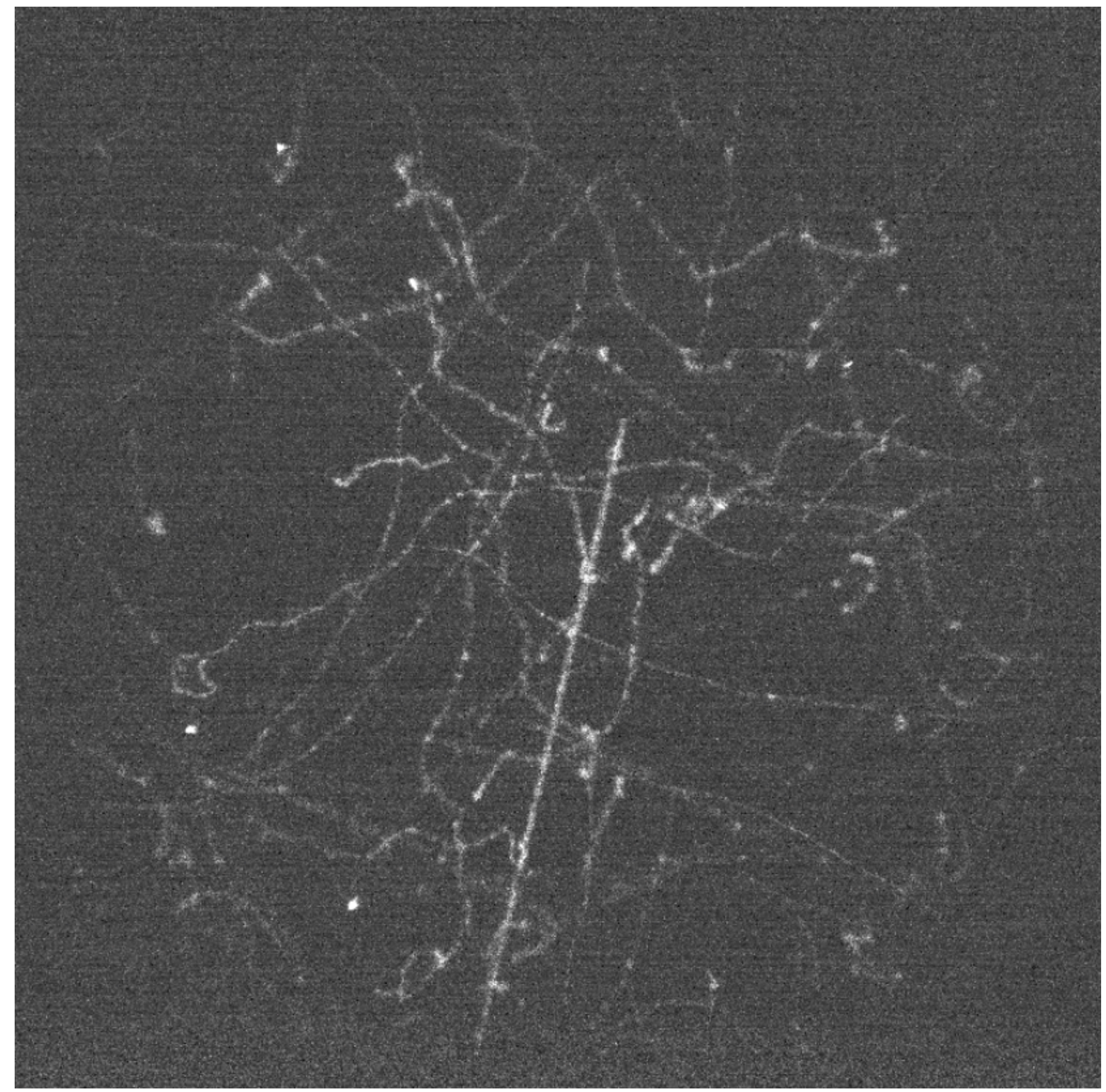




# Images from LIME




Cosmics overground with LIME

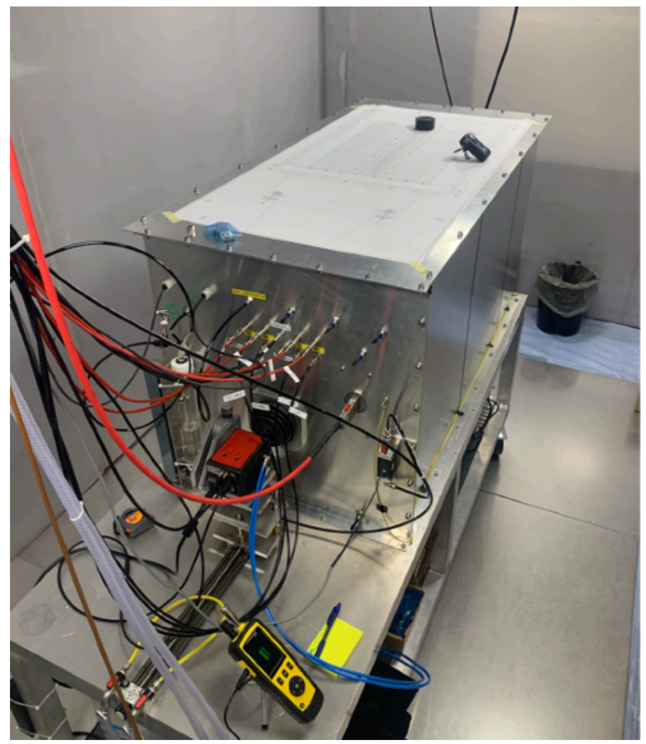


Long exposure natural radioactivity unshilded

# LIME underground installation

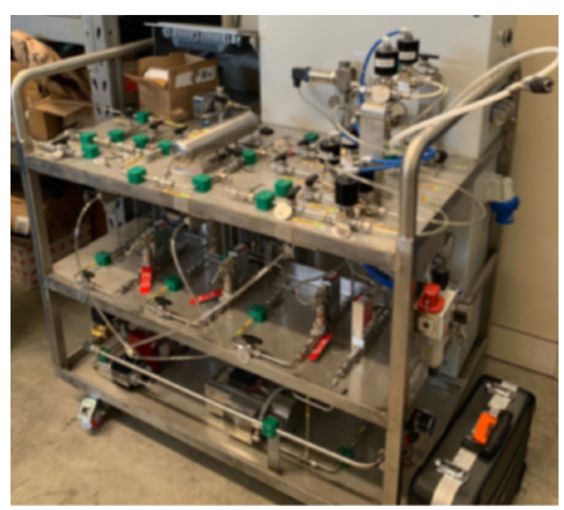
- After the initial phase of tests overground (part shown in this presentation), since few days, LIME is taking data underground

HV, VME, NIM crates

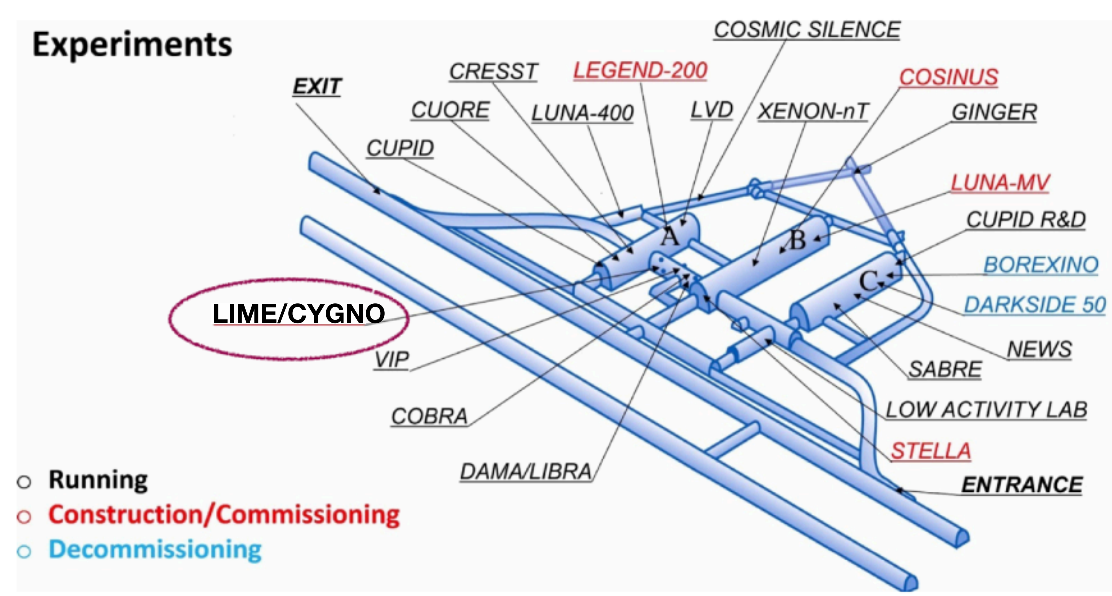


LIME inside the faraday cage

DAQ



Gas System

# Analysis with multi X-Ray source

# Multi-source X-Ray runs

- Study of linearity and energy resolution overground performed with different X-Ray source

- Gamma @ 6 keV produced using a $^{55}Fe$ source

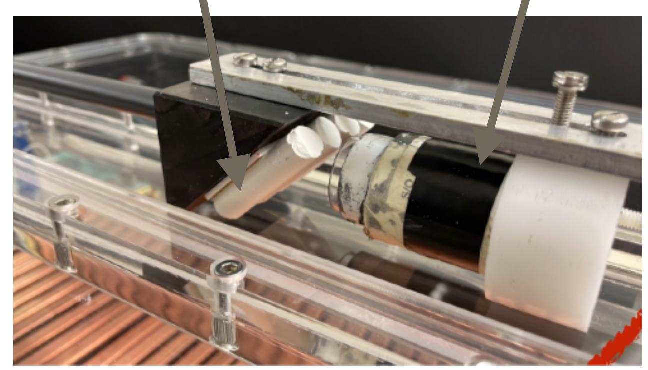
- Other energies done using an $^{243}$Am impinging on different Materials

- Lowest energies $^{55}Fe$ impinging on Gypsum (Ca) + Titanium foil (Ti)

| Target Selected | Energy (keV) K_alpha | K_beta | Photon Yield (#/sec/steradian) |
|---|---|---|---|
| Cu | 8.04 | 8.91 | 2,500 |
| Rb | 13.37 | 14.97 | 8,800 |
| Mo | 17.44 | 19.63 | 24,000 |
| Ag | 22.10 | 24.99 | 38,000 |
| Ba | 32.06 | 36.55 | 46,000 |
| Tb | 44.23 | 50.65 | 76,000 |

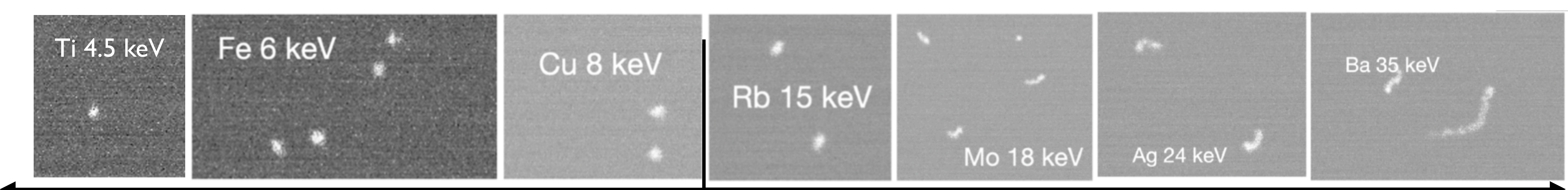
Gypsum

$^{55}Fe$ source



Data taken overground at LNF

- How tracks appear:



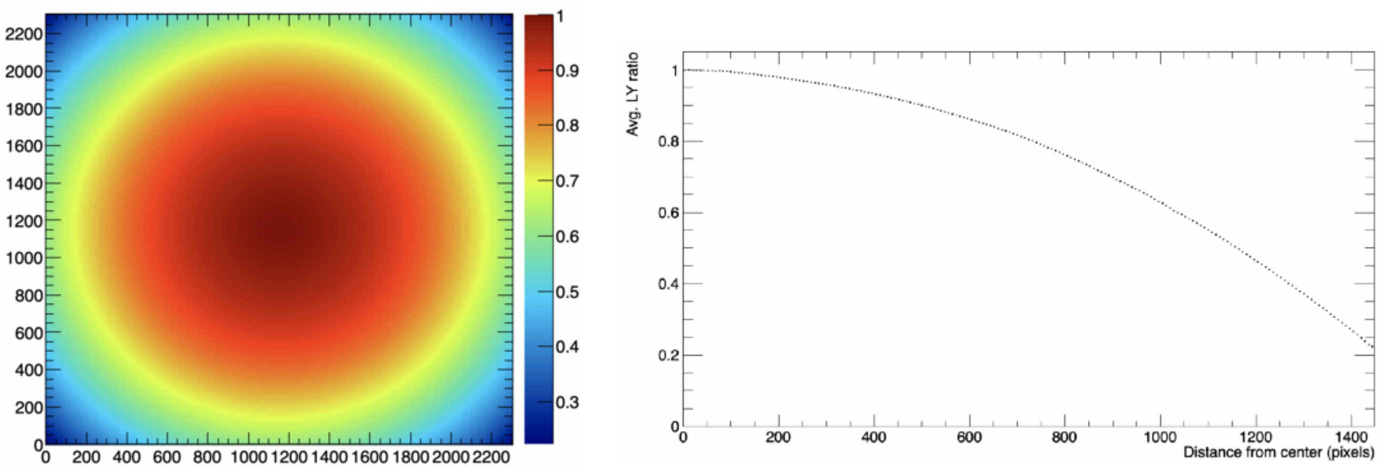

Spot like tracks

Extended tracks

# Track reconstruction code

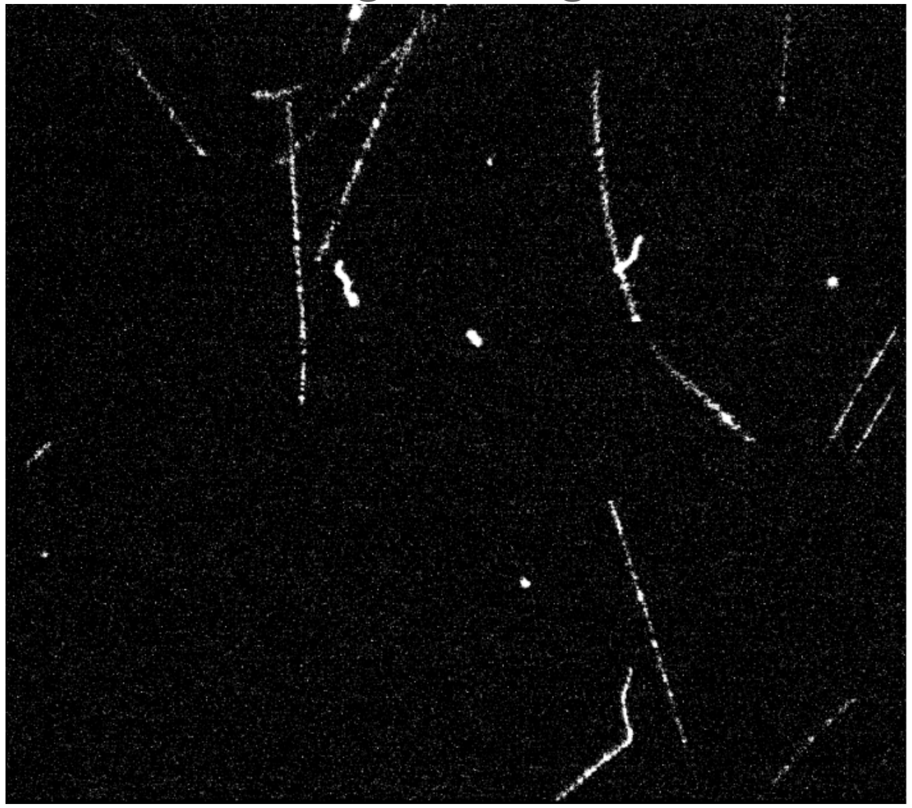
- High quantity of tracks with overlapping due to sensitive volume
- First iteration of directional iDBSCAN to reconstruct long and straight tracks
- Remaining tracks reconstructed with iDBSCAN

+ Vignetting correction:

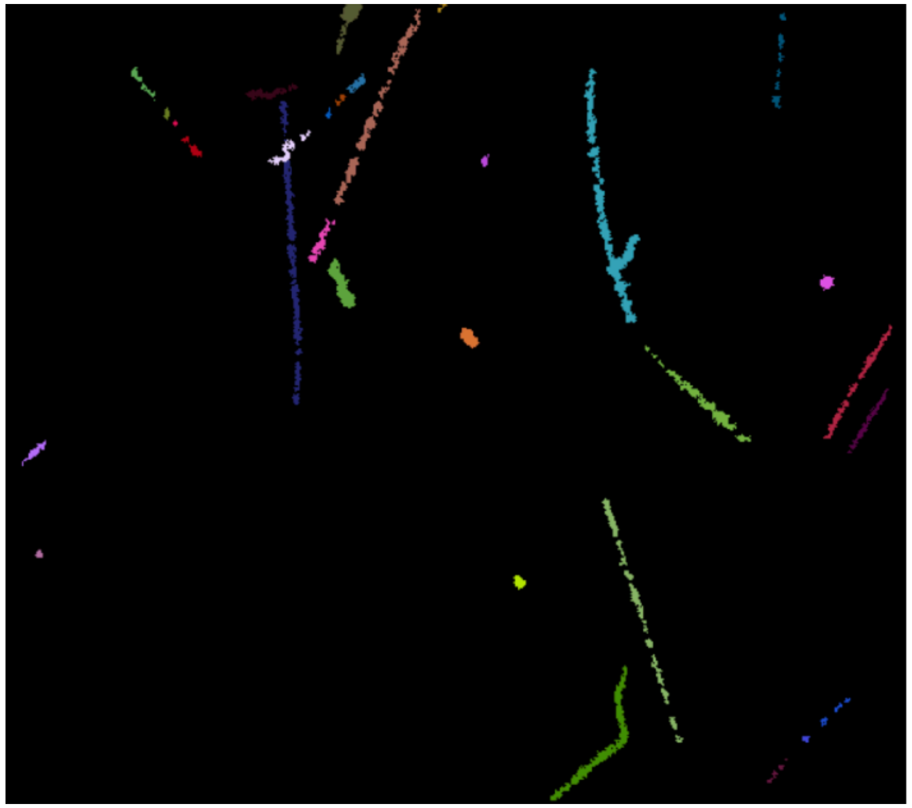



- Light Collection down up to 20% on the border of the images
- Saved information: pixels, light content, lenght, width, transverse and longitudinal rms …

Original image

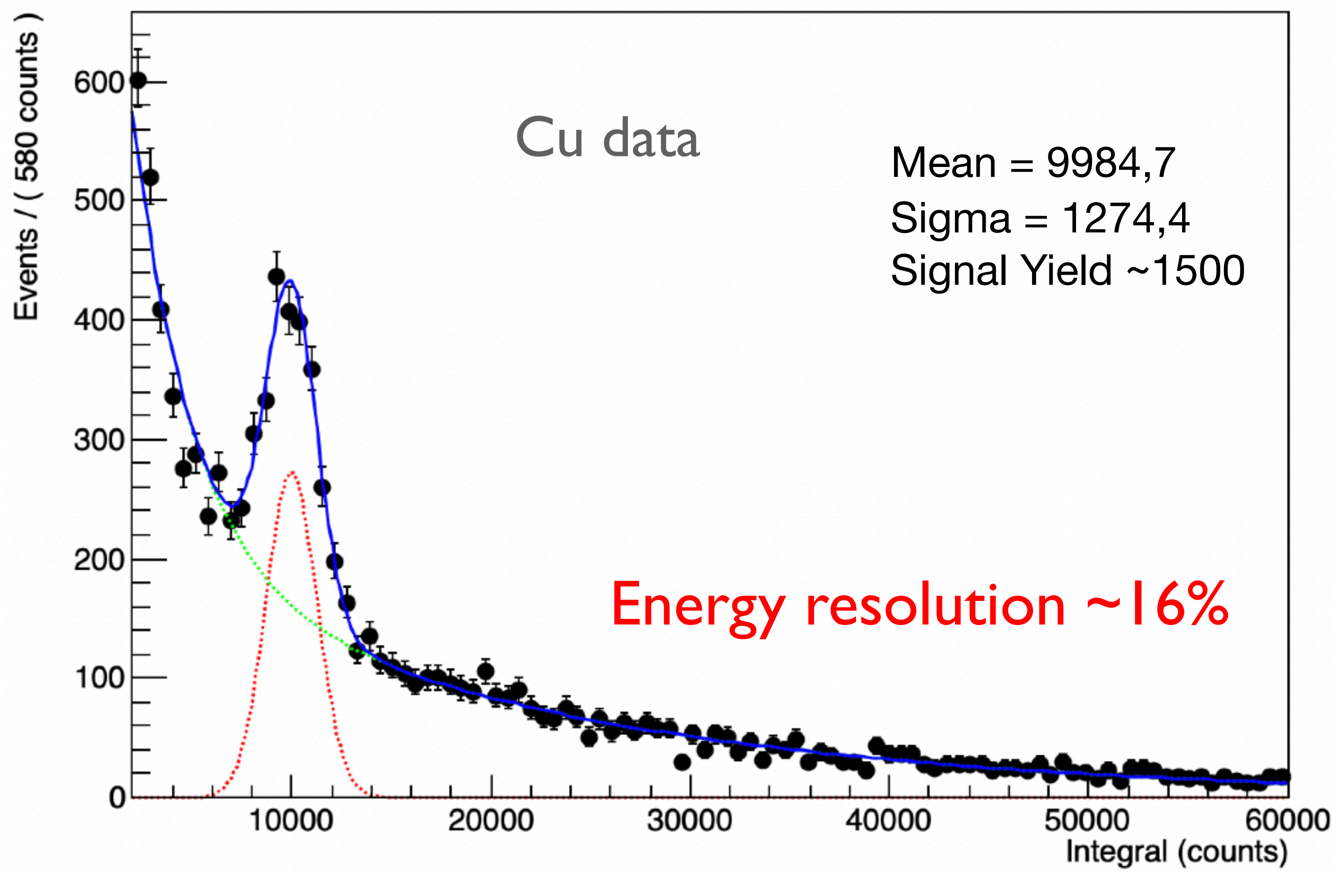


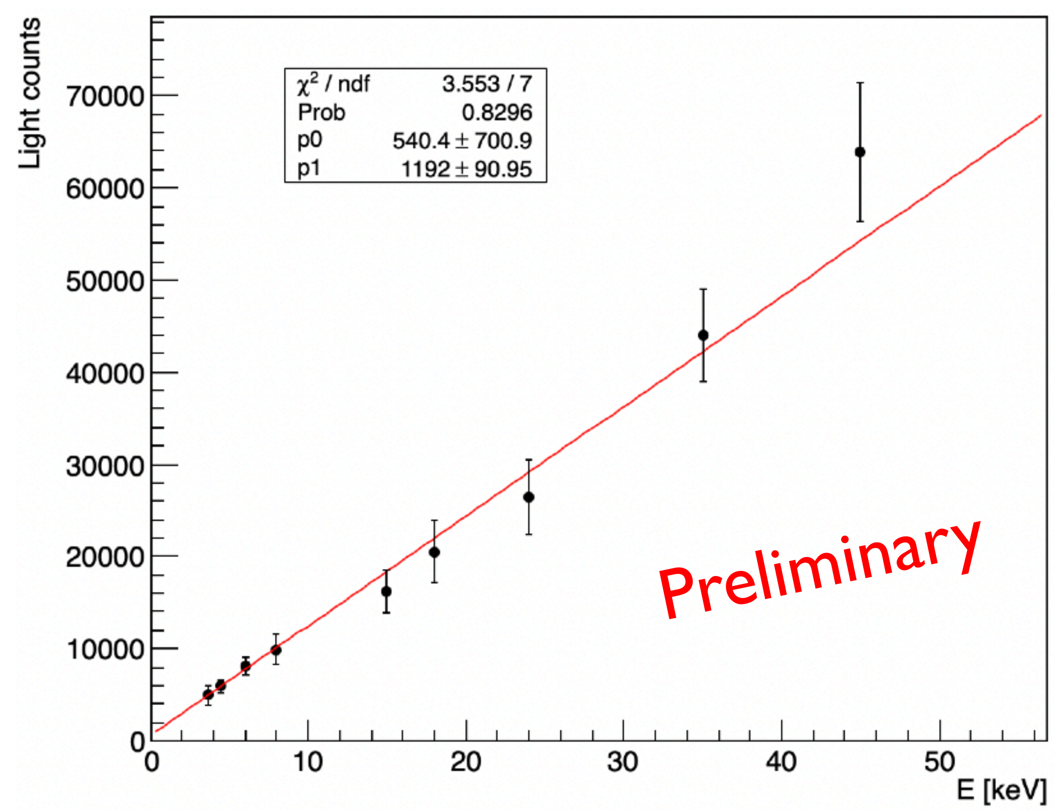
Tracks reconstructed



# Multi-source X-Ray analysis

- Data fitted with two exponentials to model the background + guassian to model the signal
  - First esponential to model fake clusters (steeper, at lower energies)
  - Second exponential to model the Physics (less steep, model up to high energies)



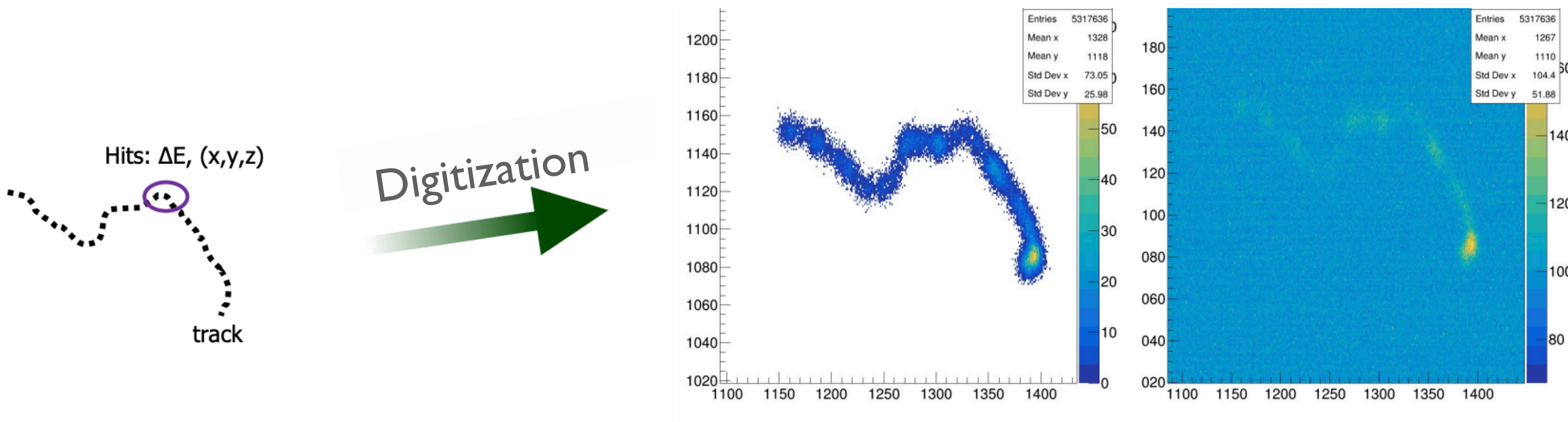

- Model fits well the data

- Data shows good linearity

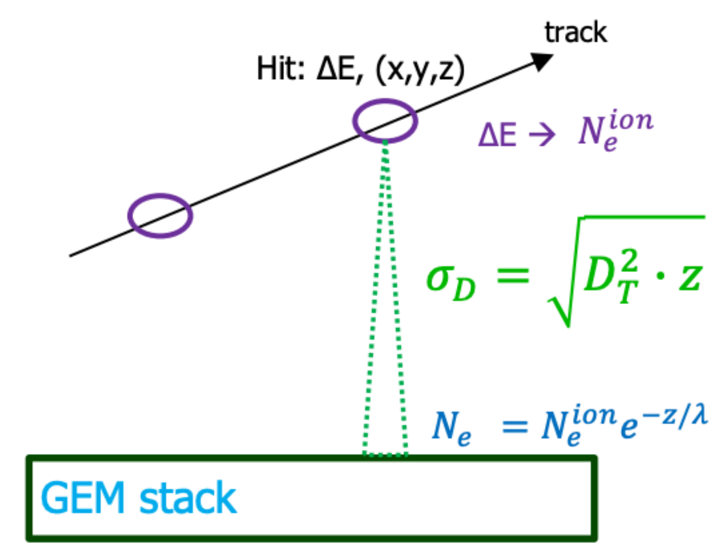
# Data-MC comparison

# Tracks simulation production

From a GEANT4 track → To a sCMOS-like image

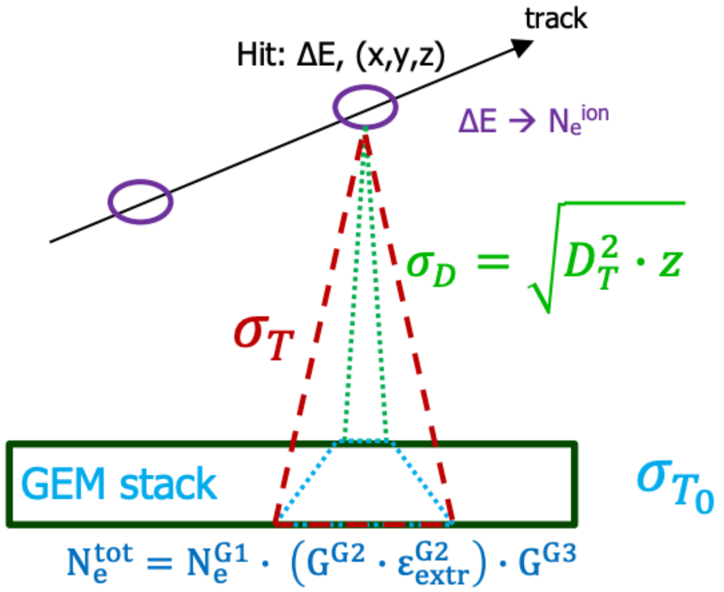



- For each hit of the track:
  - A mean number of ionization electrons are produced: $\bar{N}_e^{ion} = \Delta E/W$ (W =46.2 eV/pair in He/CF4 60/40)
  - The actual number $N_e^{ion}$ of ionization electrons is obtained from a Poisson distribution with mean = $\bar{N}_e^{ion}$
  - Ionization electrons diffuse in the drift region on the x-y plane of the GEM stack: $\sigma_D^2 = D_T^2 \cdot z$
  - Ionization electrons are partially absorbed in the gas: $N_e = N_e^{ion} e^{-\frac{z}{\lambda}}$ where z is the distance from the GEM stack



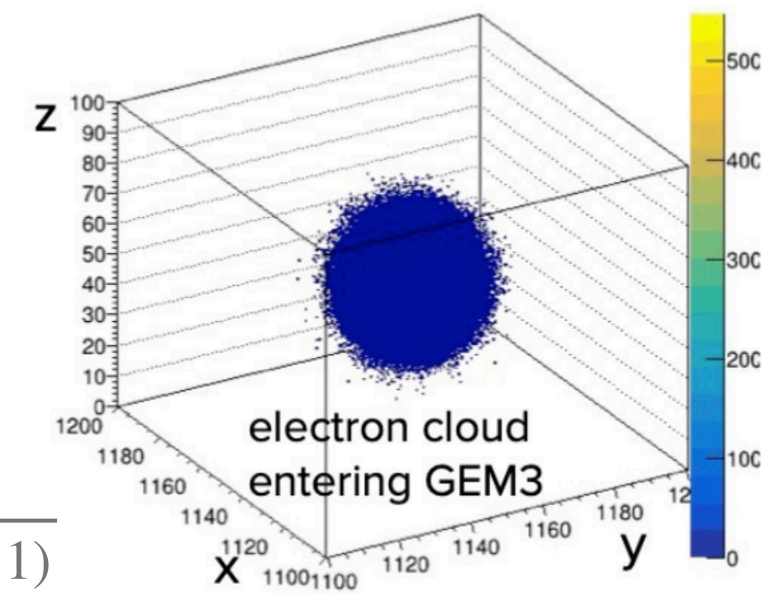
# Tracks simulation production

- GEM gain fluctuation and diffusion
  - Gain fluctuations in the first foil only are relevant:
  - For each ionization electron $N_e^{G1,k}$ multiplication electrons in the first GEM (k=1, $N_e^{ion}$) are extracted using an exponential distribution with mean = $G^{G1}$ ($G^{G1}$ is the gain of the first GEM foil)
  - Total number of multiplication electron for the first foil: $N_e^{G1} = \sum_k N_e^{G1,k} \cdot \epsilon_{extr}^{G1}$ ($\epsilon_{extr}^{G1}$ : extraction efficiency for the first GEM)
  - The total number of multiplication electrons computed considering the gain of other GEM foils and the extraction efficiency of the second foil: $N_e^{tot} = N_e^{G1} \cdot (G^{G2} \cdot \epsilon_{extr}^{G2})$



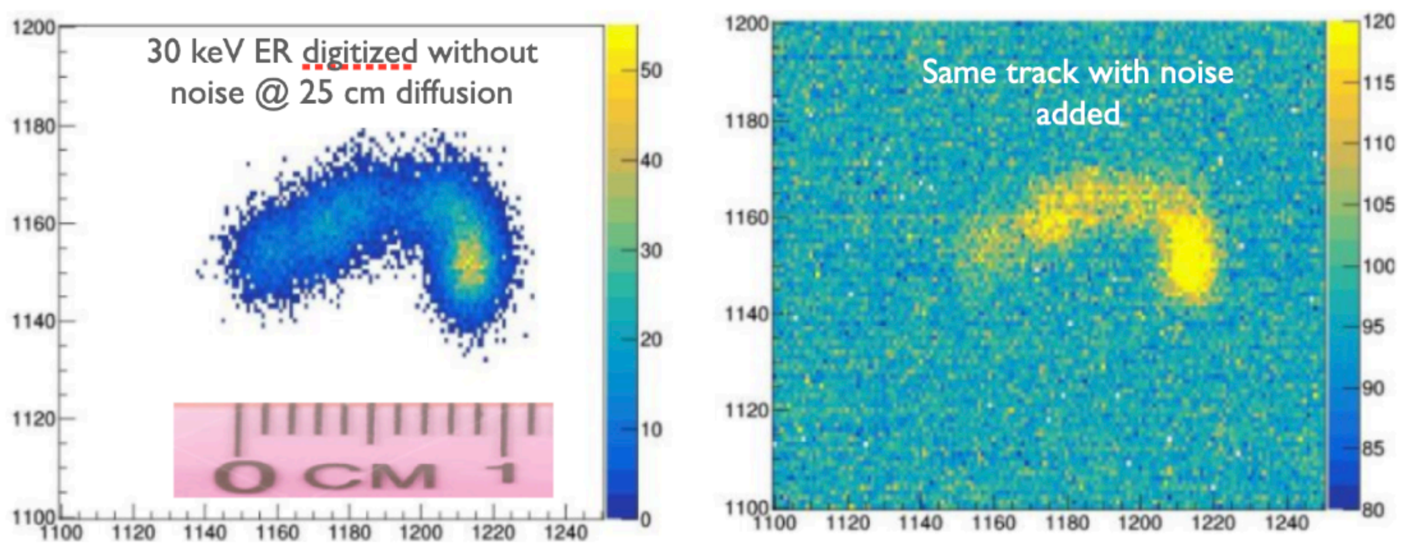

- Saturation:
  - Electrons from G1/2 diffused in 3D voxels: $\sigma_T = \sqrt{\sigma_{T_0}^2 + \sigma_{D,T}^2}$ $\sigma_L = \sqrt{\sigma_{L_0}^2 + \sigma_{D,L}^2}$
  - The number n of electrons in each voxel is multiplied by a gain $G^3 = A \frac{g}{1 + \frac{n}{n_h}(g-1)}$

    (where g is the non-saturated gain and A is an overall free parameter)
  - Finally the total number of electron is the sum of the electrons in all the voxels along the drift direction



# Tracks simulation production

- Photon collection:
  - The mean total number of photons is obtained using 0.07 $\gamma/e$ : $\bar{N}_\gamma^{tot} = N_e^{tot} \cdot 0.07\ \gamma/e$
  - The number of total photons $N_\gamma^{tot}$ extracted from a Poissonian distribution with mean value $\bar{N}_\gamma^{tot}$
  - The number of photons hitting the sensor depends on the solid angle ratio $N_\gamma = N_\gamma^{tot} \cdot \Omega$ where $\Omega = \frac{1}{(4 \cdot (\delta + 1)a)}$; where $\delta = \frac{image\ size}{sensor\ size}$ and a=0.95 aperture
  - The sensor noise is added to the simulation as an image from a real pedestal file



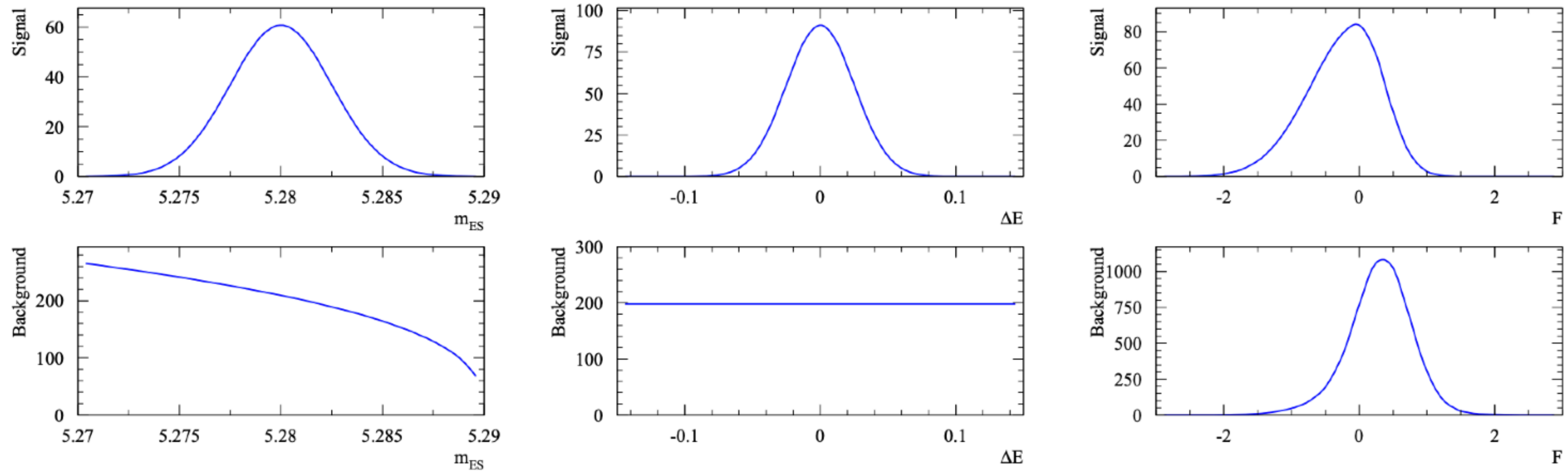

- For the Data-MC comparision tracks are produced at 8,15,18,24,35,47 keV
- In a range of 20-30 cm in z, since in data the source was placed at 25 cm.

# sPlots: a statistical tool to unfold data distributions

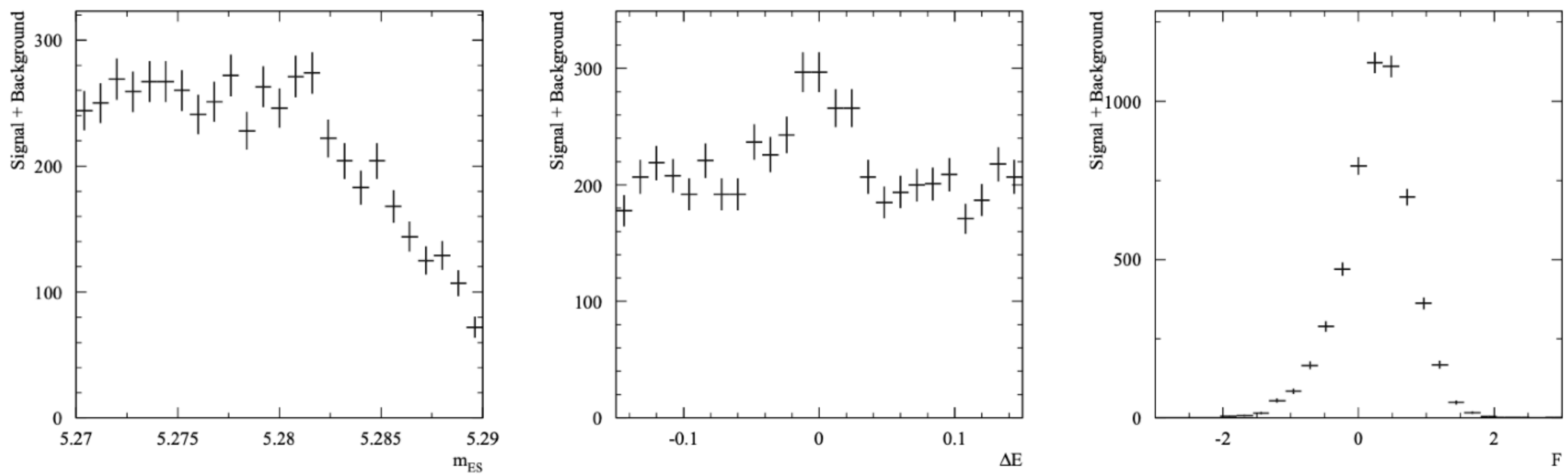
- Suppose to have a dataset containing three variables (Signal and background)
- By fitting one/two distribution (with signal + bkg model) it can be assigned at each event a weight proportional to the probability of being background or signal
- The other can be unfolded by weighting each entry with the probability that that event is signal or background

*Nucl.Instrum.Meth.A 555 (2005), 356-369*

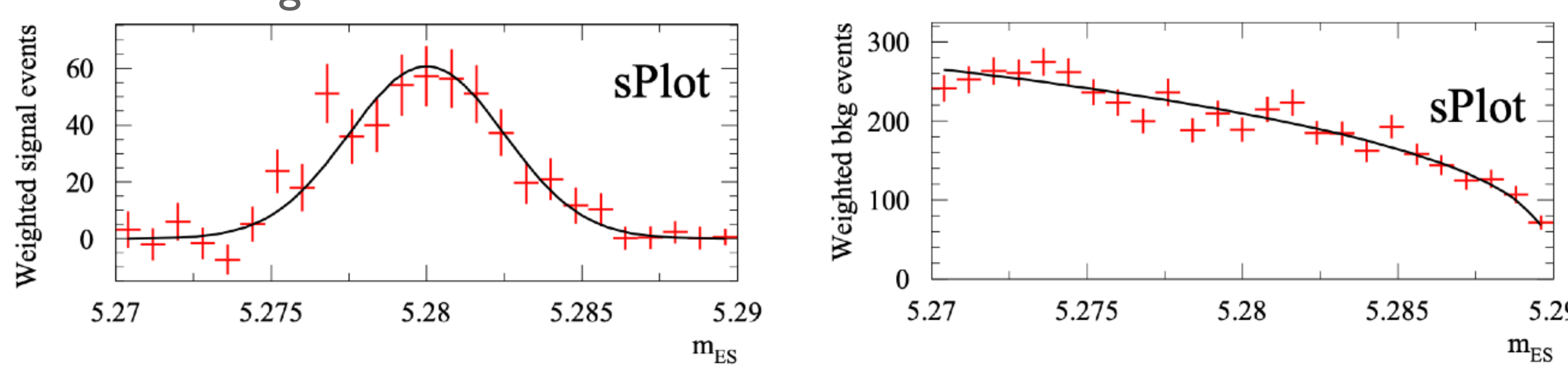
Theoretical distributions




Distributions from MC

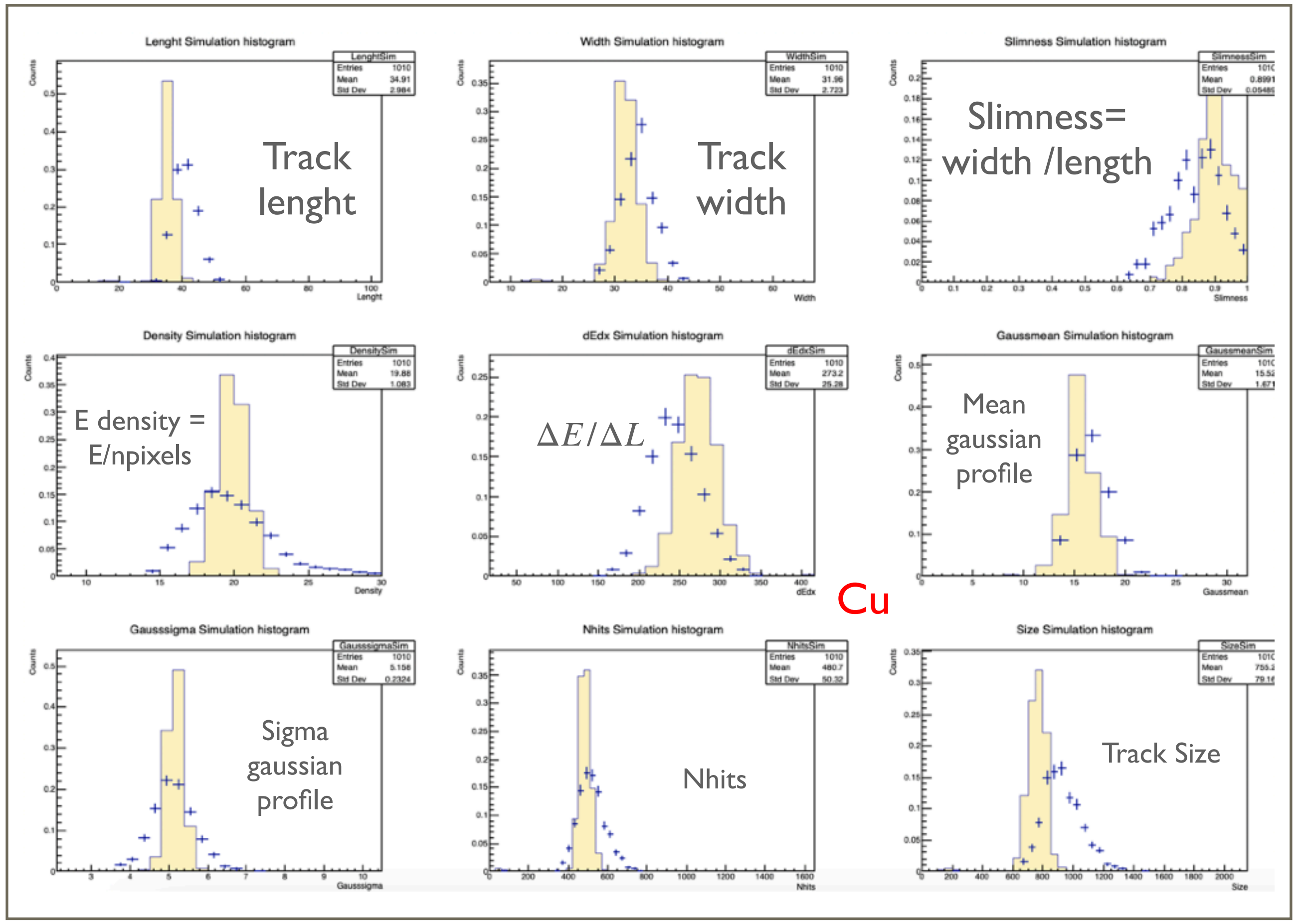


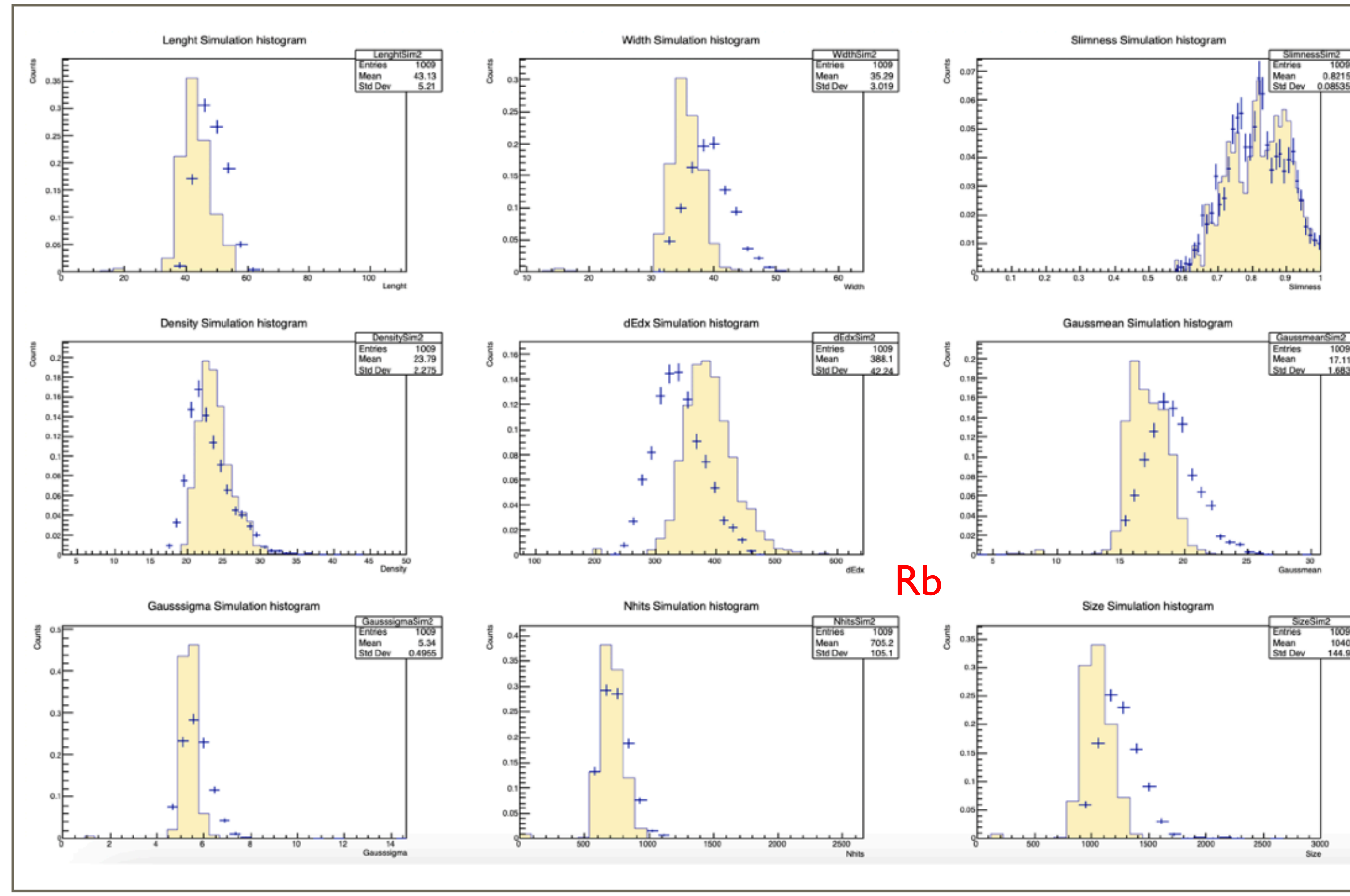

S-weightd distribution based on the fit of the other variable/s

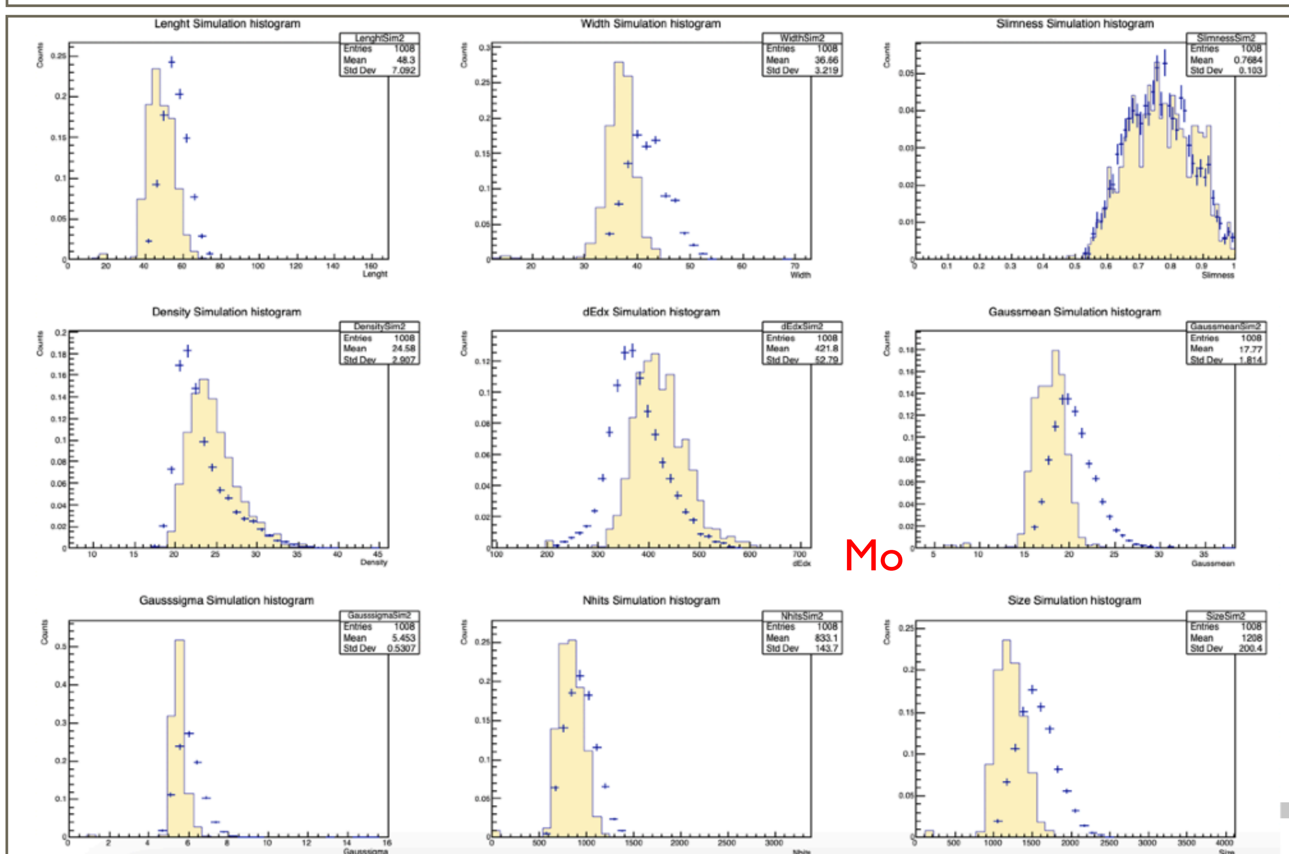


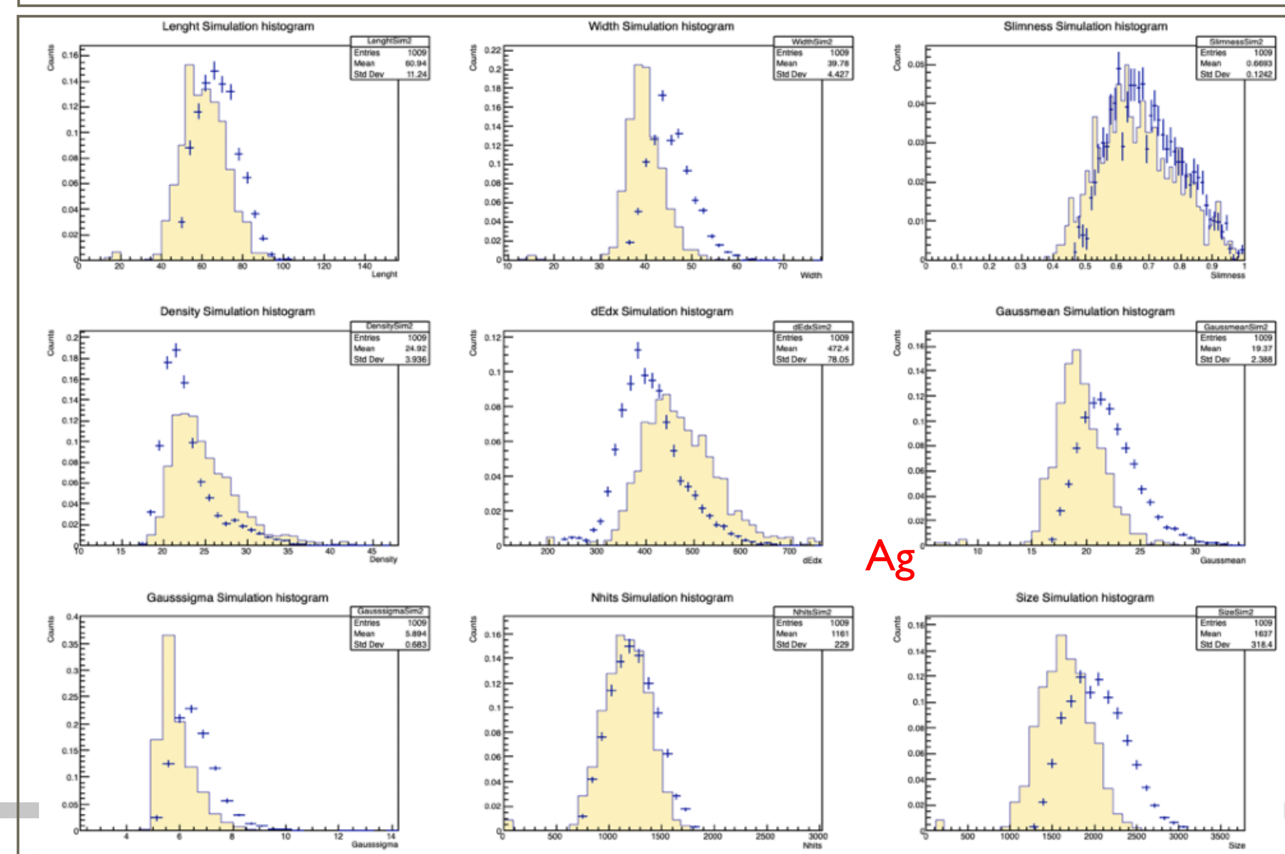
# Track shape parameters comparison

Simulation Data



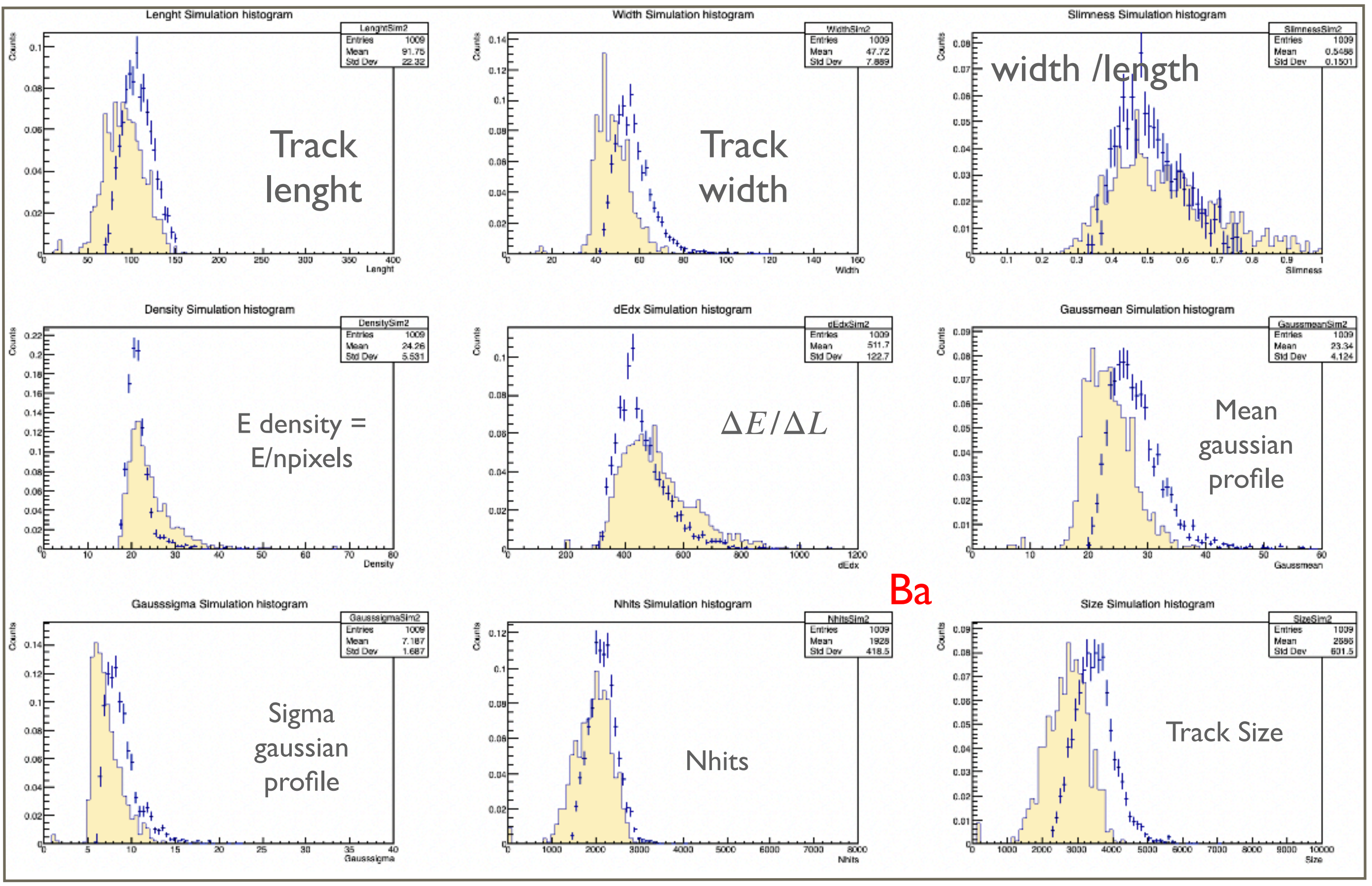



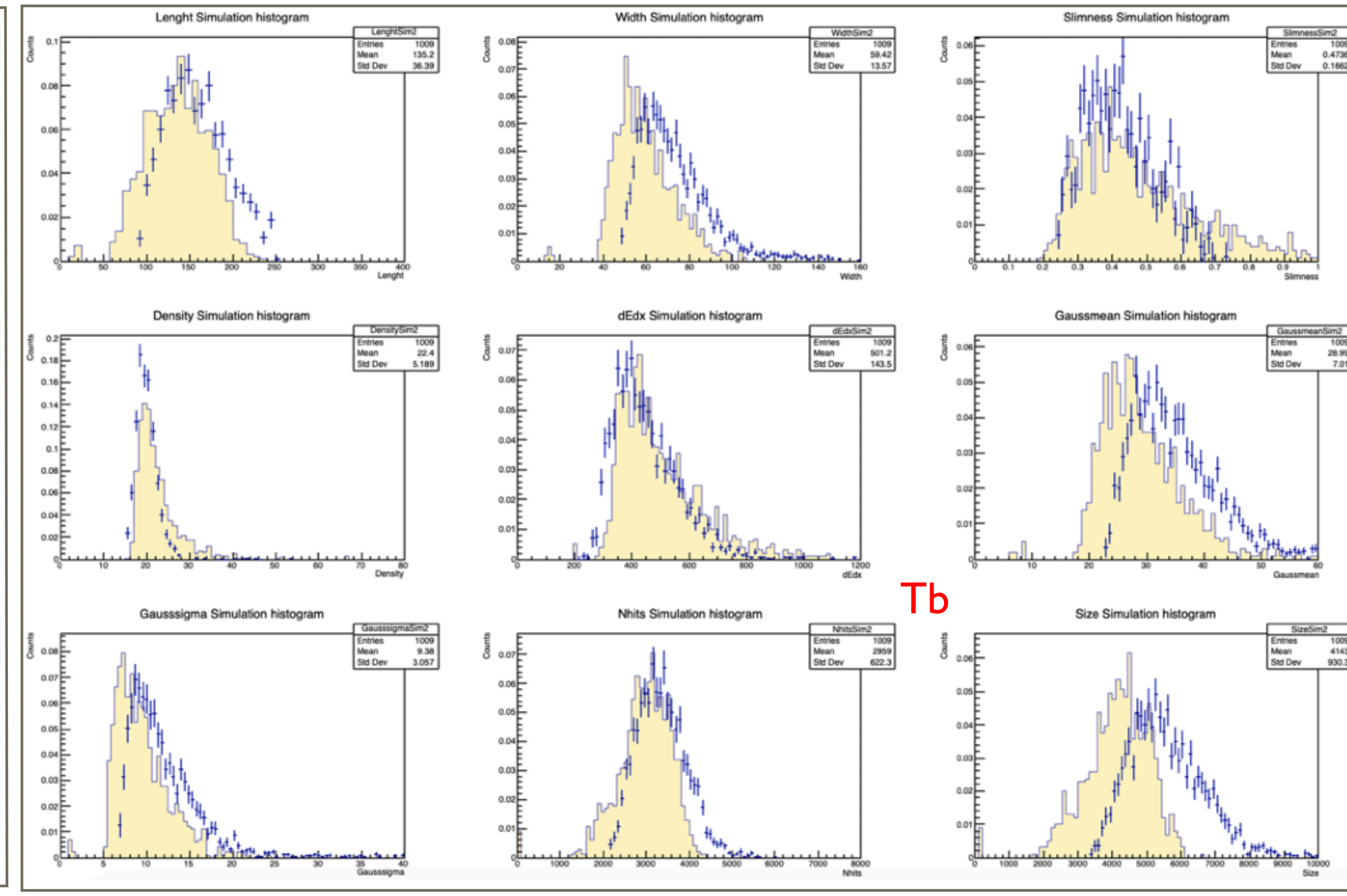



# Track shape parameters comparison

Simulation    Data

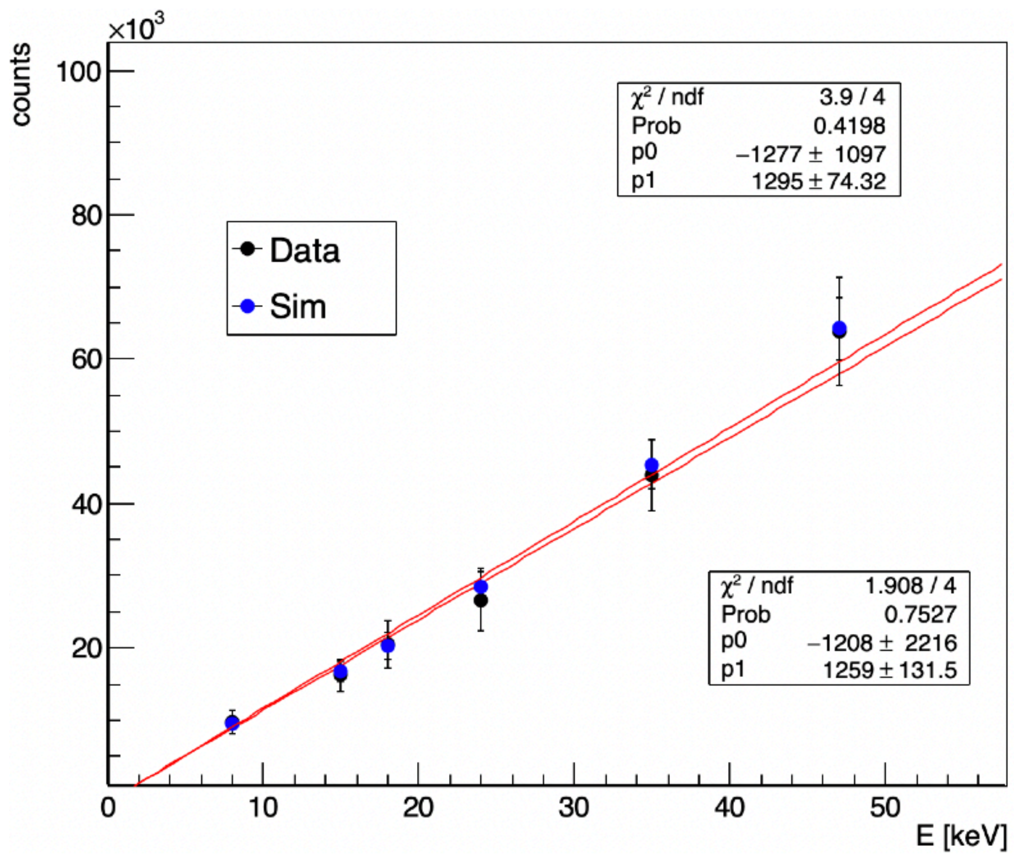



Not perfect agreement on all the shapes variables but we are on the good way

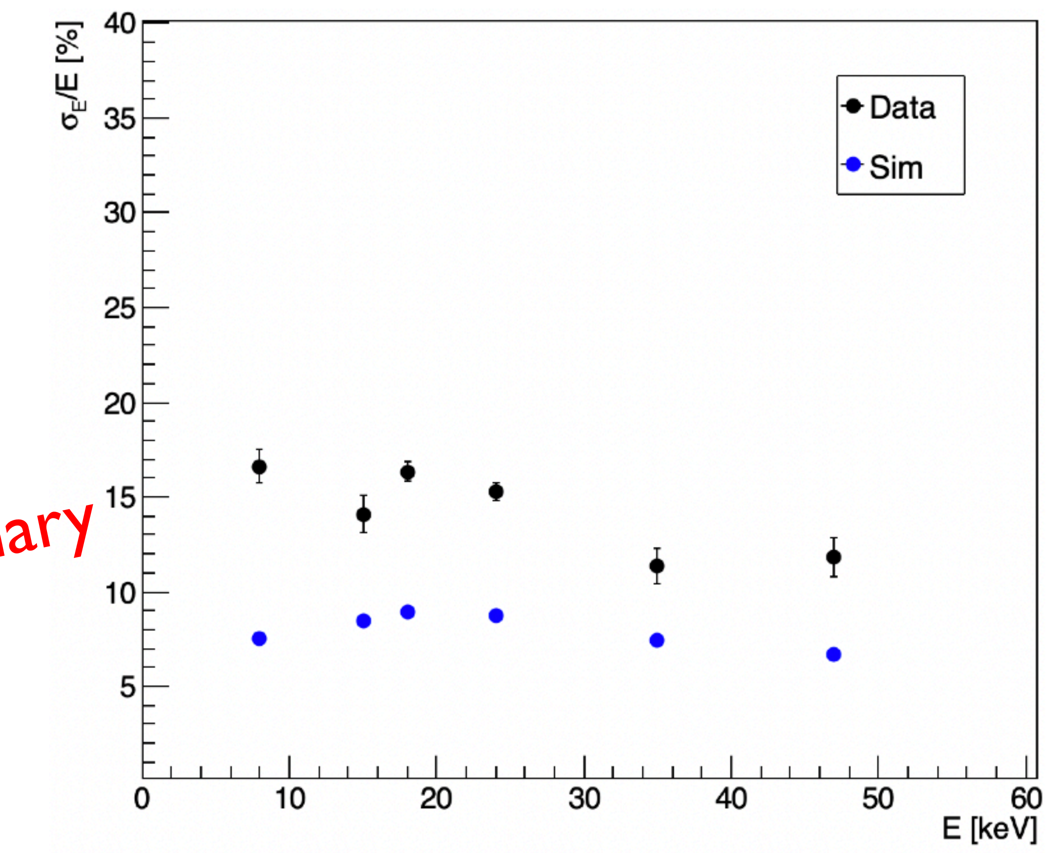
# Linearity and Energy resolution comparison

Linearity: counts vs E




Preliminary

Energy resolution: $\sigma_E/E$ vs E

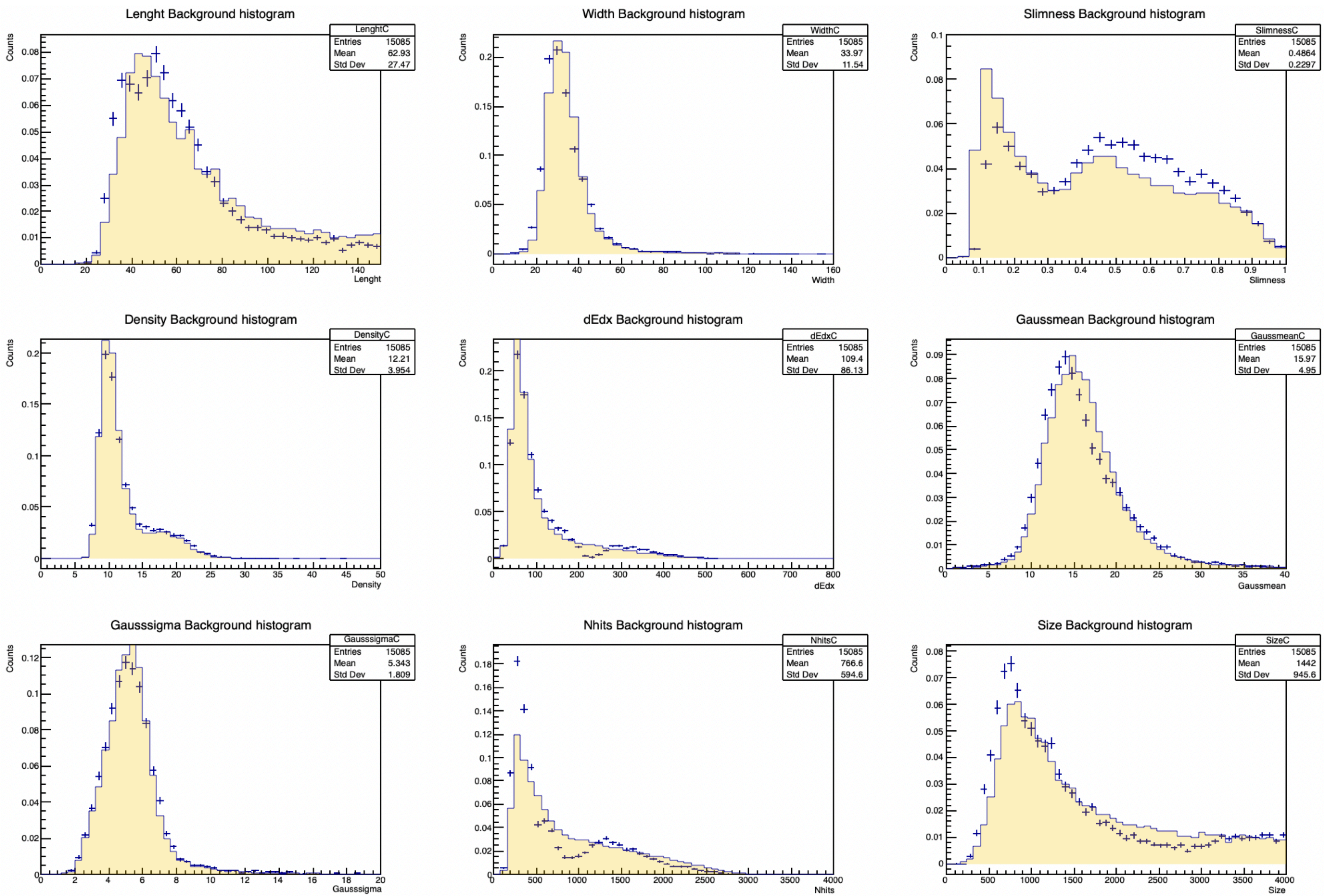



- Agreement in Linearity within data and MC
- Energy resolution still to be improved:
  - Maybe it could be some residual non-uniformity in gem GAIN along the GEM surface

# Conclusions

- LIME is the latest prototype we developed in our collaboration and it’s currently taking data underground
- To study the linearity in the energy response we took data with different sources of X-Ray
- From the data analysis we obtained a linear response and an energy resolution compatible with the typical resolution of a gas detector
- A track digitization code has been developed to produce tracks as equal as possible to the data
- Good agreement within data and MC

# Backup

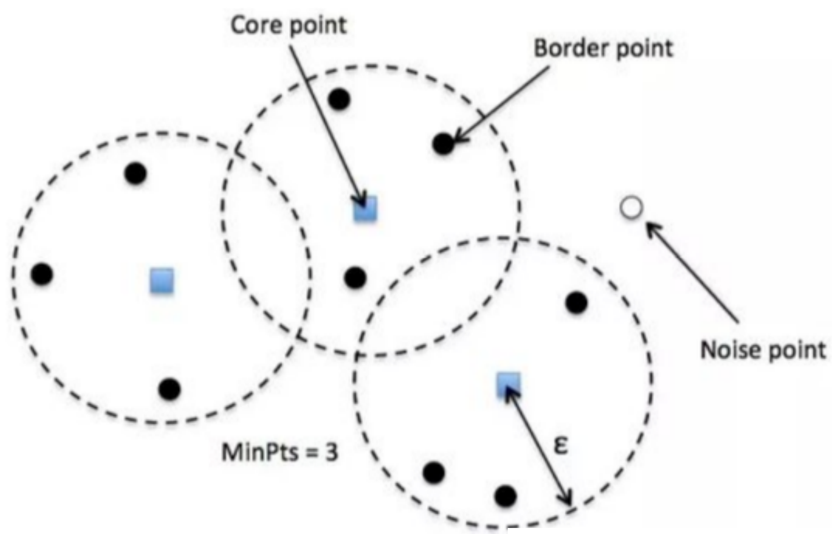


Lenght Background histogram
LenghtC
Entries 15085
Mean 62.93
Std Dev 27.47
Counts
Lenght
Width Background histogram
WidthC
Entries 15085
Mean 33.97
Std Dev 11.54
Counts
Width
Slimness Background histogram
SlimnessC
Entries 15085
Mean 0.4864
Std Dev 0.2297
Counts
Slimness
Density Background histogram
DensityC
Entries 15085
Mean 12.21
Std Dev 3.954
Counts
Density
dEdx Background histogram
dEdxC
Entries 15085
Mean 109.4
Std Dev 86.13
Counts
dEdx
Gaussmean Background histogram
GaussmeanC
Entries 15085
Mean 15.97
Std Dev 4.95
Counts
Gaussmean
Gausssigma Background histogram
GausssigmaC
Entries 15085
Mean 5.343
Std Dev 1.809
Counts
Gausssigma
Nhits Background histogram
NhitsC
Entries 15085
Mean 766.6
Std Dev 594.6
Counts
Nhits
Size Background histogram
SizeC
Entries 15085
Mean 1442
Std Dev 945.6
Counts
Size

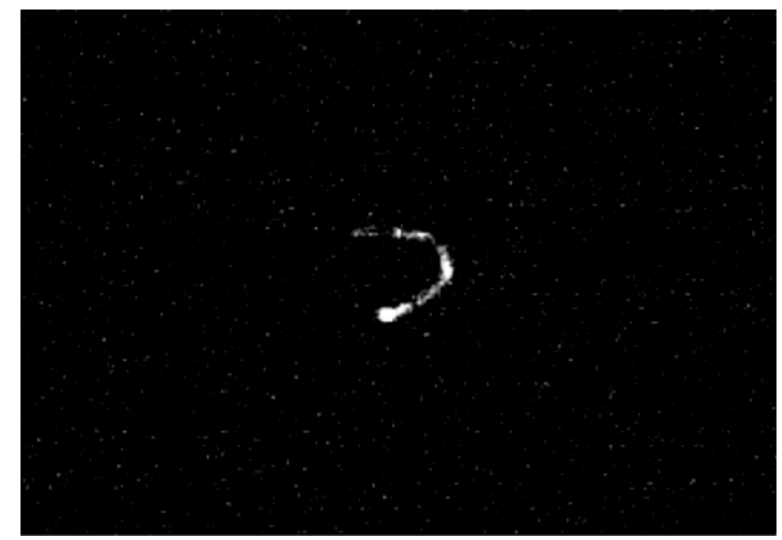
# The reconstruction algorithm

A density-based clustering algorithm for the CYGNO data analysis E. Baracchini et Al.

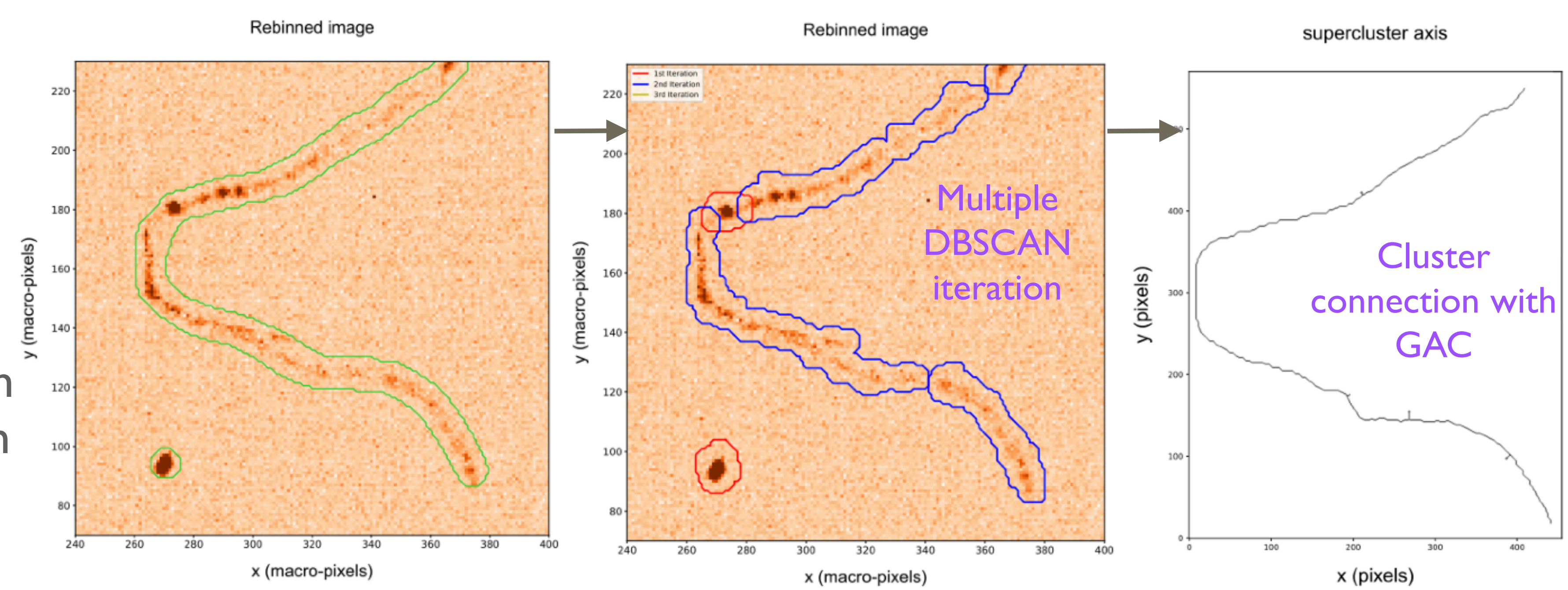
- The official CYGNO reconstruction code is based on an iterative version of the DBSCAN (Density-Based Spatial Clustering of Applications with Noise) algorithm after noise subtraction: iDBSCAN
- iDBSCAN identifies high density regions in the image based on two parameters:
  - $\epsilon$: radius of search region
  - $MinPts$ : minimum amount of points to form a cluster




Applied to



- Many iterations of iDBSCAN searching for different ionization patterns (ER, NR, cosmics)
- Clusters are merged together with Geodesic active contour algorithm



# CYGNO timeline

**CYGNO R&D** | **PHASE 0** | **PHASE 1** | **PHASE 2**

**ORANGE @ ROMA1**
- $10x10\ cm^2$ GEMs
- 1 cm drift
- $100\ cm^3$ volume
- First feasibility studies

**LEMOn @ LNF**
- $20x24\ cm^2$ GEMs
- 20 cm drift
- $0.01\ m^3$ volume
- 3D printed
- First studies of performances of the tecnique

**MANGO @ LNF / LNGS**
- $10x10\ cm^2$ GEMs
- variable drift
- performance studies
- gas mixture tests
- Parallel R&D on different research lines

**LIME @ LNF / LNGS**

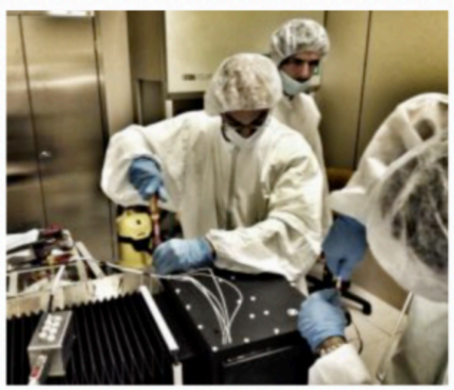
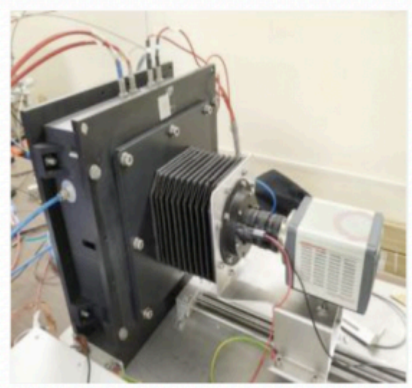
We are here
- **$30x30\ cm^2$ GEMs**
- **50 cm drift**
- **$0.05\ m^3$ volume**
- **performance and stability test**
- **underground**
- **shielding**
- **data-taking**

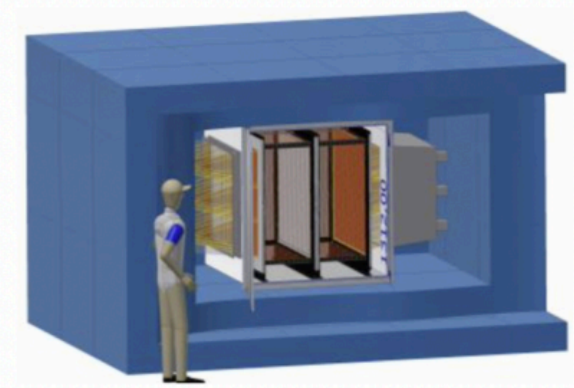
**CYGNO demonstrator @ LNF / LNGS**
- 9x2 back-to-back LIME modules
- $1\ m^3$ volume
- material tests
- background assessment
- underground installation & commissioning
- gas purification
- scalability

**CYGNO 30-100 $m^3$**

R&D results from Lemon shown in the following

2015-2016 | 2017-2019 | 2019-2022 | 2019-2022 | 2023 | 2023



**+ $SF_6$ for negative ion drift**

erc European Research Council

INITIUM

- Parallel research lines with MANGO (evolution of NITEC):
  - Different GEM configuration
  - Different gas mixtures
  - Electroluminescence studies
  - Different gas pressures
  - Negative ions drift

E. Baracchini et. al, JINST 13 (2018) no.04, P04022