



**TREDI 2024 @ Torino, 20-22 February**

# **A Lightweight Algorithm for Modelling Radiation Damage effects in the MC events for HL-LHC experiments**

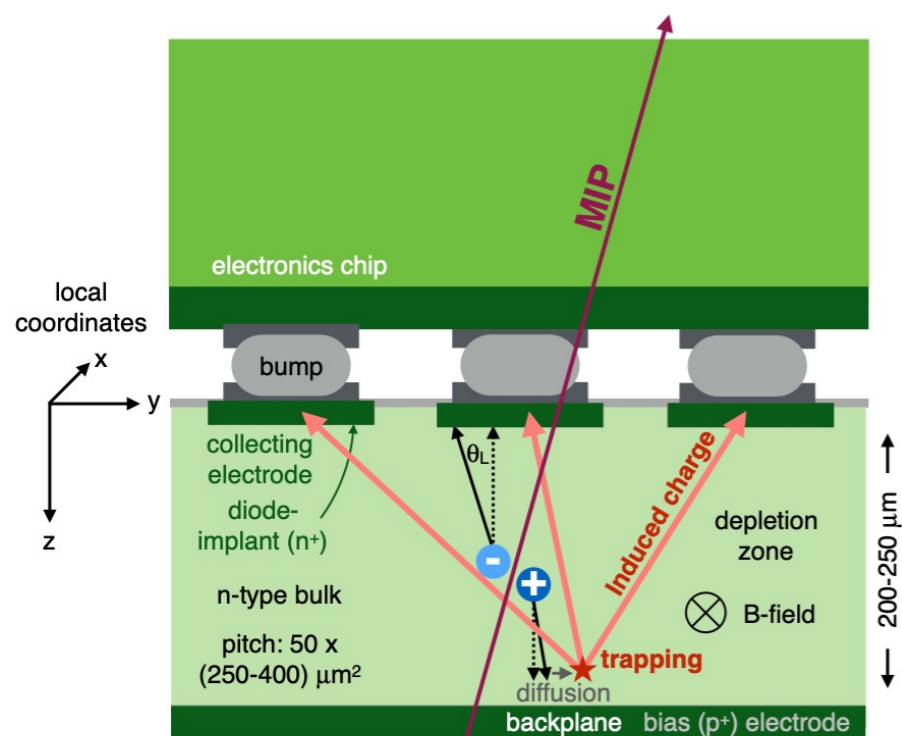
**Marco Bomben & Keerthi Nakkalil**  
**APC & Université de Paris**



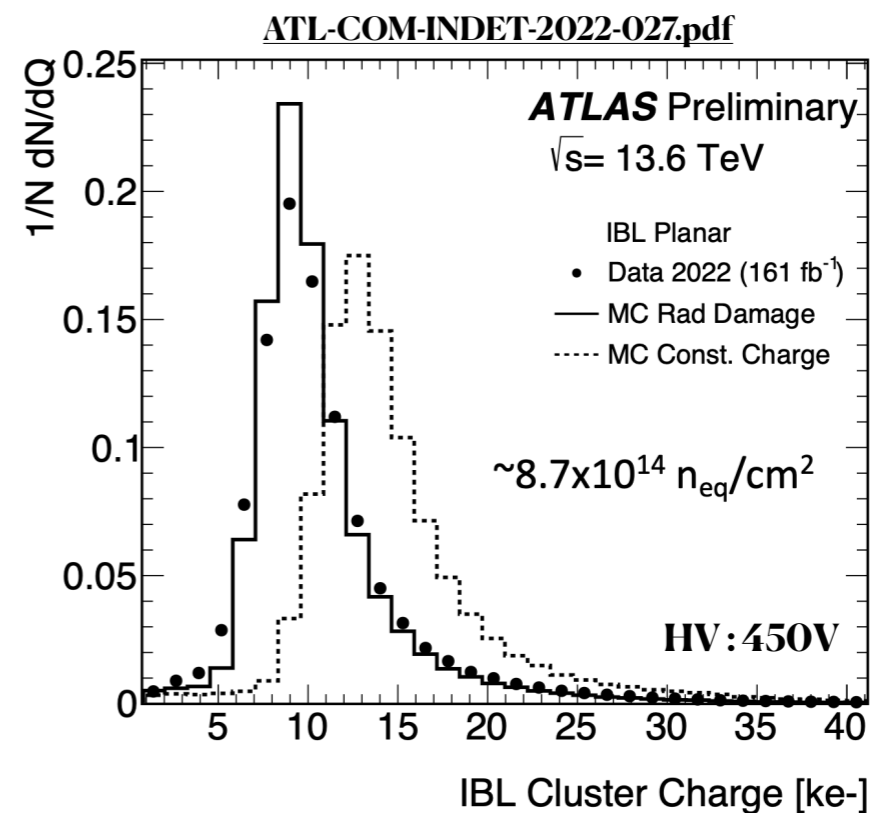
# Radiation damage modelling : ATLAS approach

## Run2 and Run3 strategy

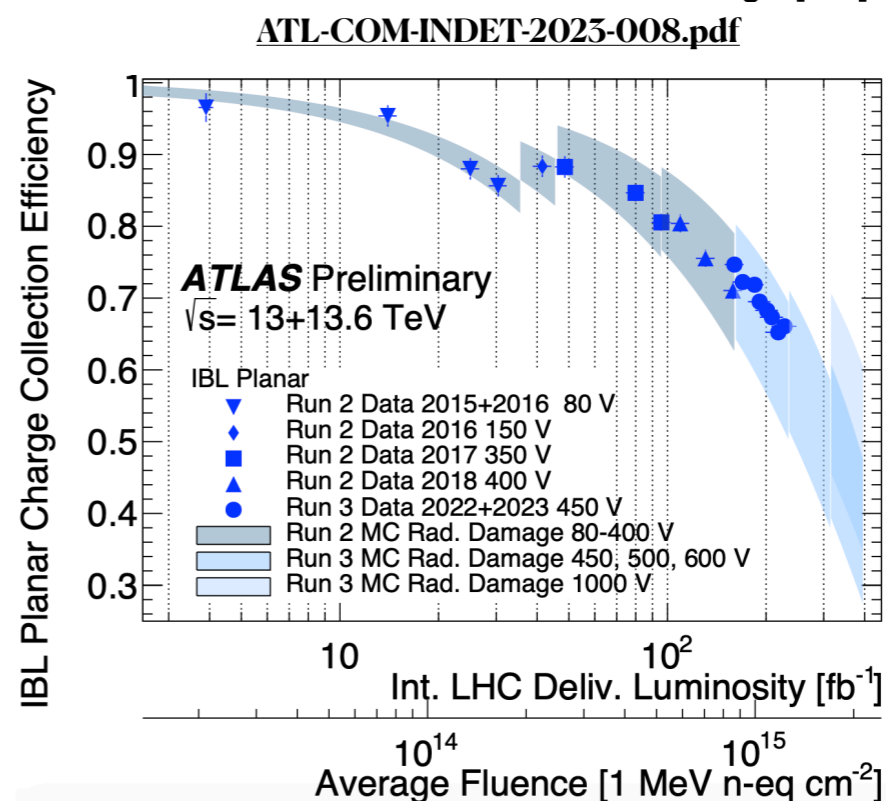
- Current strategy : Evaluate final position and induced signal of group of carriers in MC
- Inputs:
  - ◆ Precise electric field simulation (TCAD) to take into account radiation damage effects
  - ◆ Weighting potential (TCAD)
  - ◆ Trapping rates (literature)



<https://iopscience.iop.org/article/10.1088/1748-0221/14/06/P06012>



Most Probable Values match at 1% level!



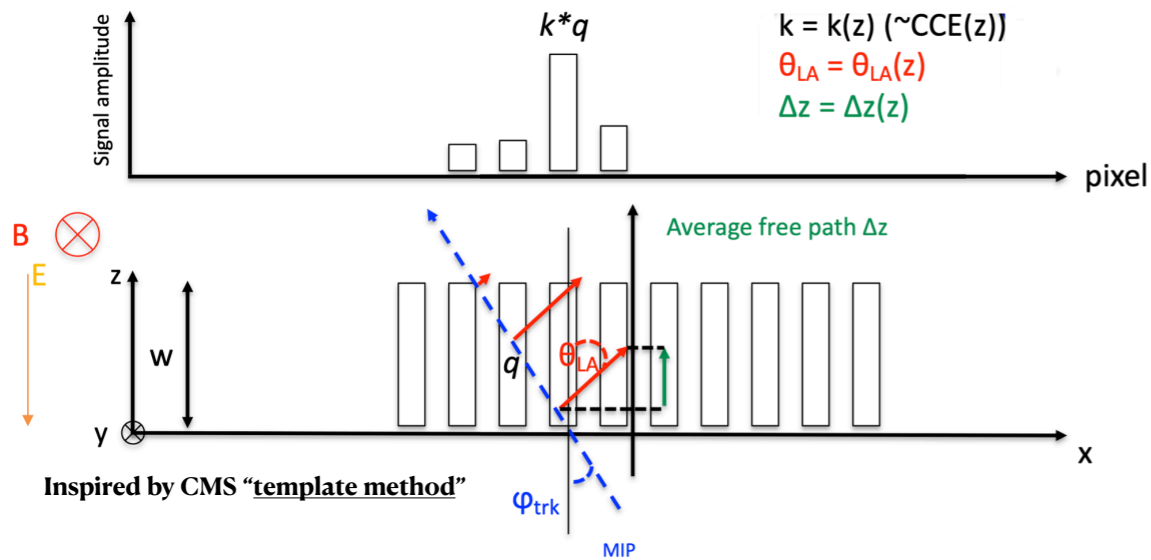
Excellent agreement over almost two order of magnitudes of fluence!

# Radiation damage modelling : ATLAS approach

## HL-LHC strategy

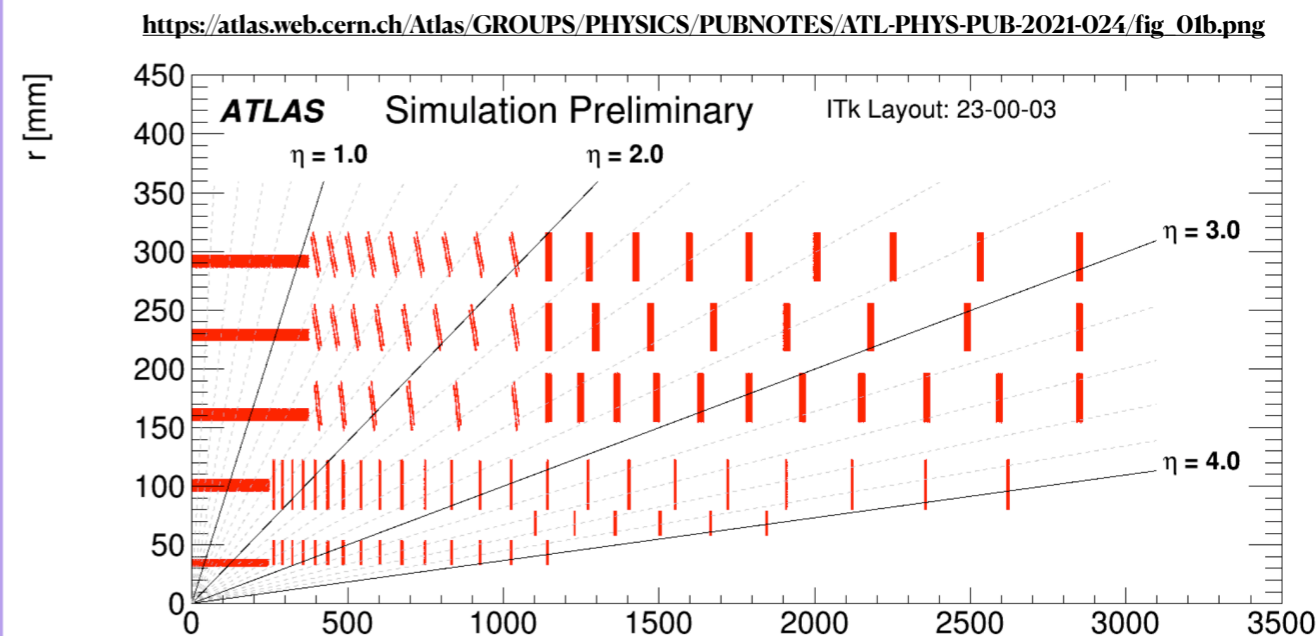
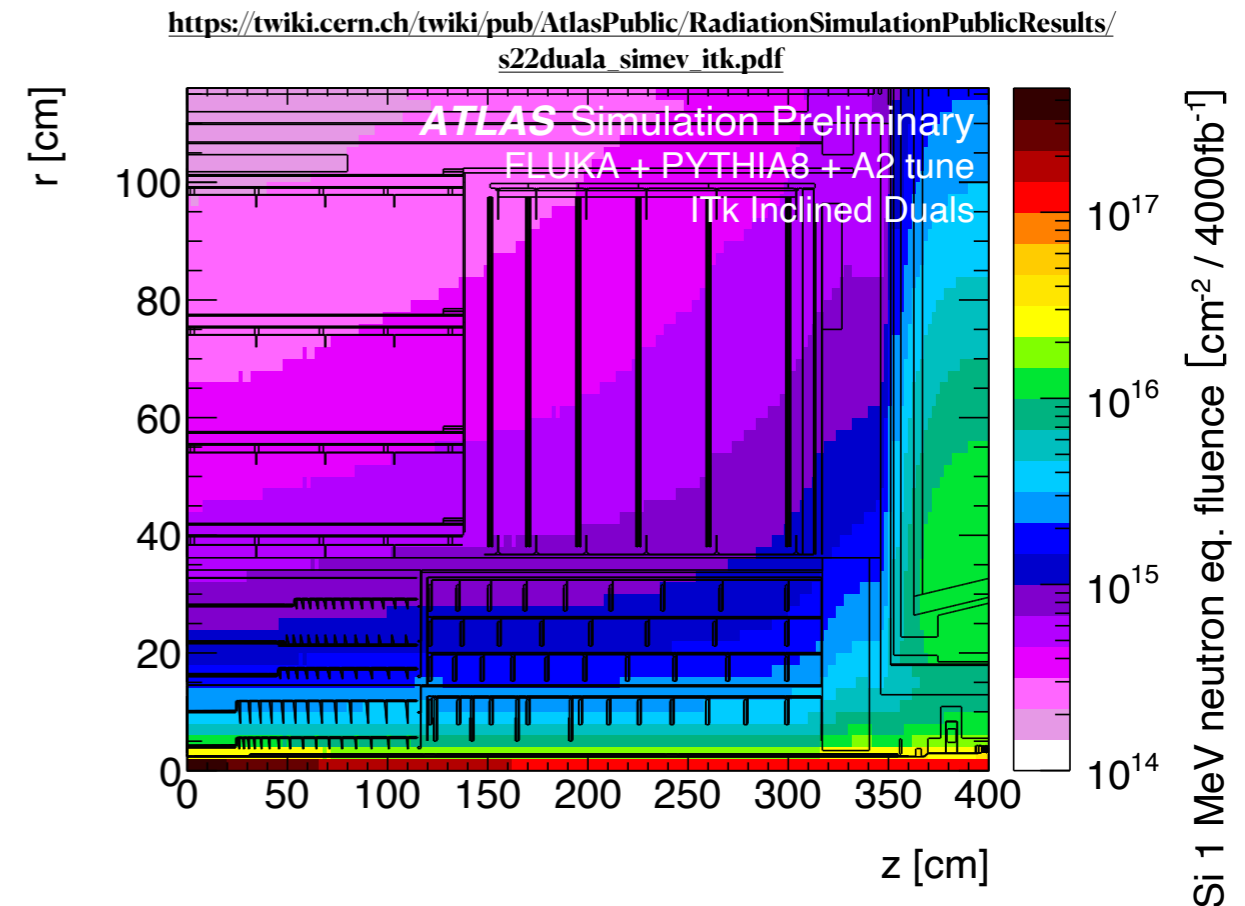
- HL-LHC : ATLAS/CMS pixel detectors exposed to unprecedented levels of radiation damage
  - ◆ Peak luminosity:  $1 \times 10^{34} \rightarrow 5 - 7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
  - ◆ Average collisions/BC:  $\sim 30 \rightarrow \sim 200$
  - ◆ Integrated luminosity:  $350 \rightarrow 4000/\text{fb}$
- Expected increase of particles density and rates in HL-LHC -> need for a faster algorithm

- ◆ New strategy is planned : charge reweighing from look-up tables (LUTs)



- Idea : For each simulated charge  $q$  at depth  $z$  find in **which pixel it will end up**, by how much ( $k$ ) the signal will be reduced

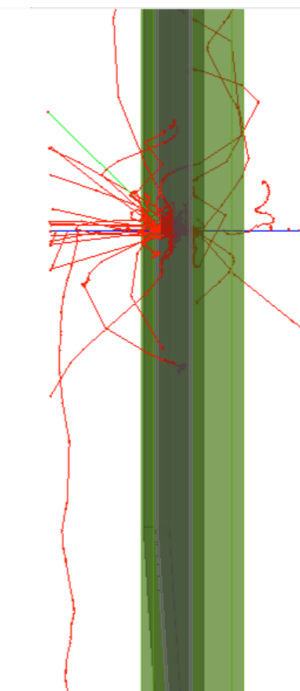
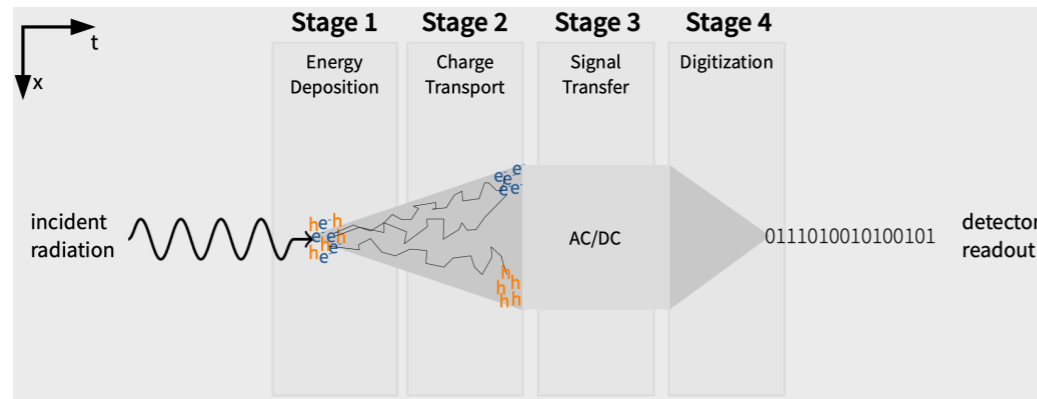
- ◆ Goal: Simulated pixels in MC is corrected using these information before digitisation -> correction scheme implemented using **Allpix-squared** (doi:10.1016/j.nima.2018.06.020)



# Allpix-squared framework

## Simulation flow

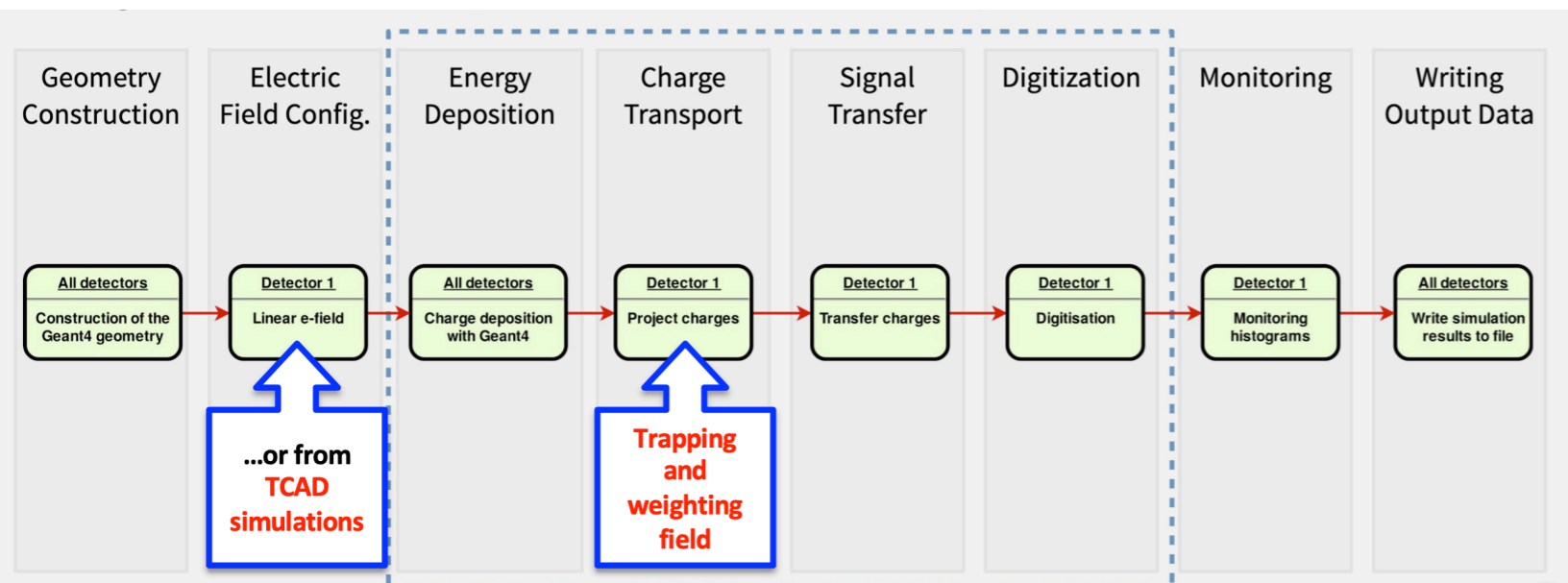
- Modular, generic simulation framework aiming at facilitating the different steps of the simulation of semiconductor detectors



- Visualization of an event in APSQ with 120 GeV  $\pi^+$  (blue track) incident on an RD53A detector
- Red tracks: secondary electrons
- Green track: secondary photons

- Building blocks follow individual steps of signal formation in detector

<https://allpix-squared.docs.cern.ch/>



```
[Allpix]
log_level = "INFO"
log_format = "DEFAULT"
detectors_file = "planar_detector.conf"
number_of_events = 125000
root_file = "histos_125kEvents_100um_4e15_600V"
random_seed = 0

[GeometryBuilderGeant4]

[MagneticFieldReader]
model="constant"
magnetic_field = 0T 2T 0T

[DepositionPointCharge]
log_level = DEBUG
model = "scan"
source_type = "point"
number_of_charges = 1000
output_plots = 1

[ElectricFieldReader]
model = "mesh"
file_name = "../TCAD_files/EFieldIpxel_ElectricField_100um_600V_4e15.init"
output_plots = 1

[WeightingPotentialReader]
model = "mesh"
file_name = "../TCAD_files/flipped_mirrored_shifted_Ramo_Potential-3D-map-rd53a-50x50-100um_ElectrostaticPotential.init"
output_plots = 1

#For TCAD Efield
[TransientPropagation]
temperature = 253K
charge_per_step = 10
mobility_model = "canali"
trapping_model = "cmstracker"
fluence = 4e15/cm/cm
induction_matrix = 3 3
output_plots = 1

[PulseTransfer]
max_depth distance = 5um
output_plots = 1

[DefaultDigitizer]
output_plots = 1

[DetectorHistogrammer]

[ROOTObjectWriter]
file_name = "trees_125kEvents_100um_4e15_600V.root"
include = "MCTrack", "MCParticle", "PixelCharge", "PixelHit", "PropagatedCharge", "DepositedCharge"
```



# LUTs from Allpix-Squared

## How to generate the LUTs

- Simulate **point** deposition using “**scan**” model ([DepositionPointCharge]) in AP2
  - ◆ Charge carrier deposition position change with every event, ensuring homogenous scanning of a single pixel cell
  - ◆ 125000 events simulated, deposit **1000** e-h pairs every 1um along x, y and 2um along z
  - ◆ Simulation for **100 μm** thick **planar** sensor at  $4 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$  and **600 V**

- **Creation of CCE LUT**

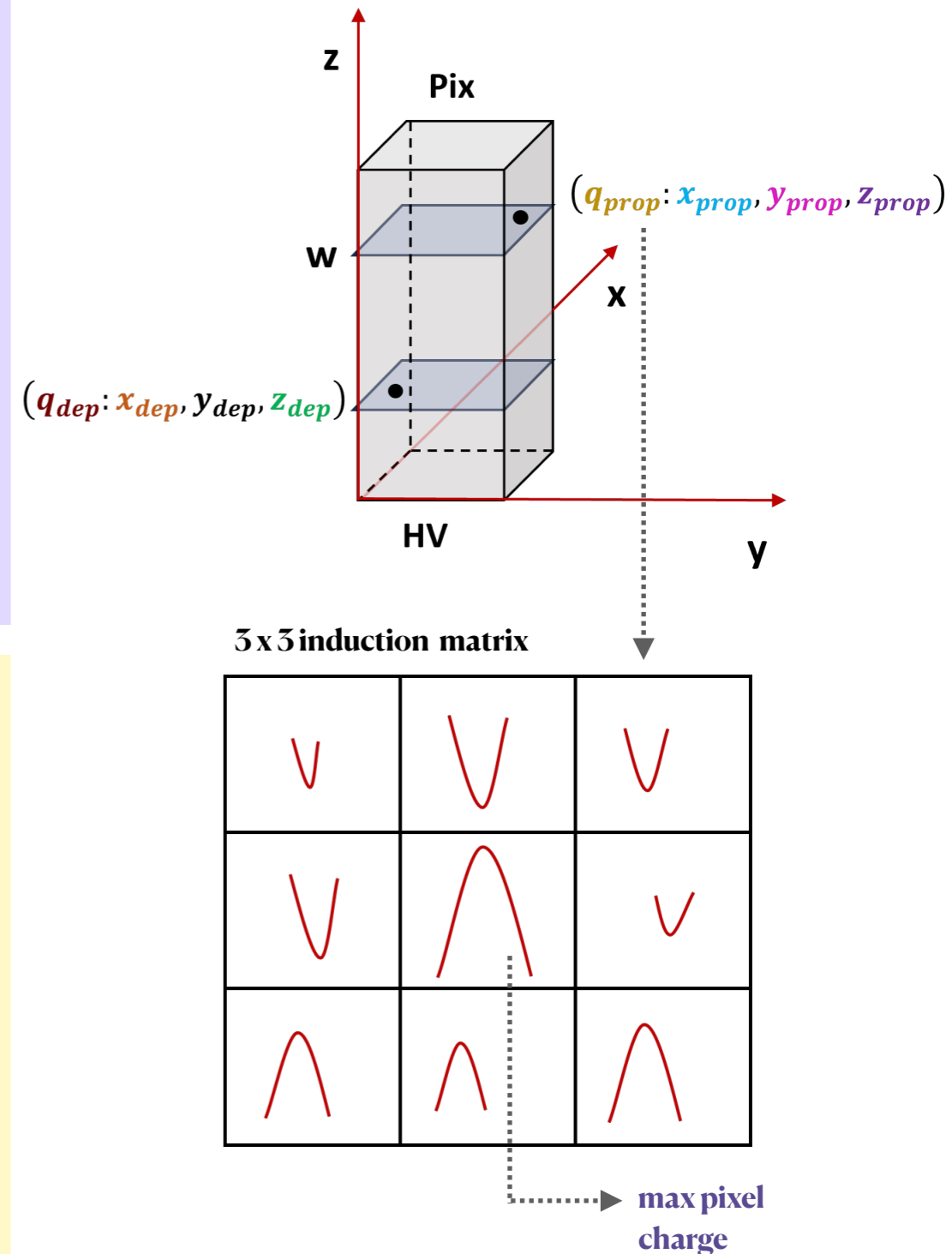
- ◆ CCE per event = (**max pixel charge**)/( $q_{\text{dep}}$ )
- ◆ CCE LUT obtained by taking the most probable CCE values (**MPV**) at various  $x_{\text{dep}}, y_{\text{dep}}$  for each  $z_{\text{dep}}$

- **Creation of tan(LA) LUT**

- ◆ Perform a pol1 fit to the distribution of electron drift for each z position ( $\Delta x$  vs.  $\Delta z$ ) to extract the tanLA

- **Creation of delZ LUT**

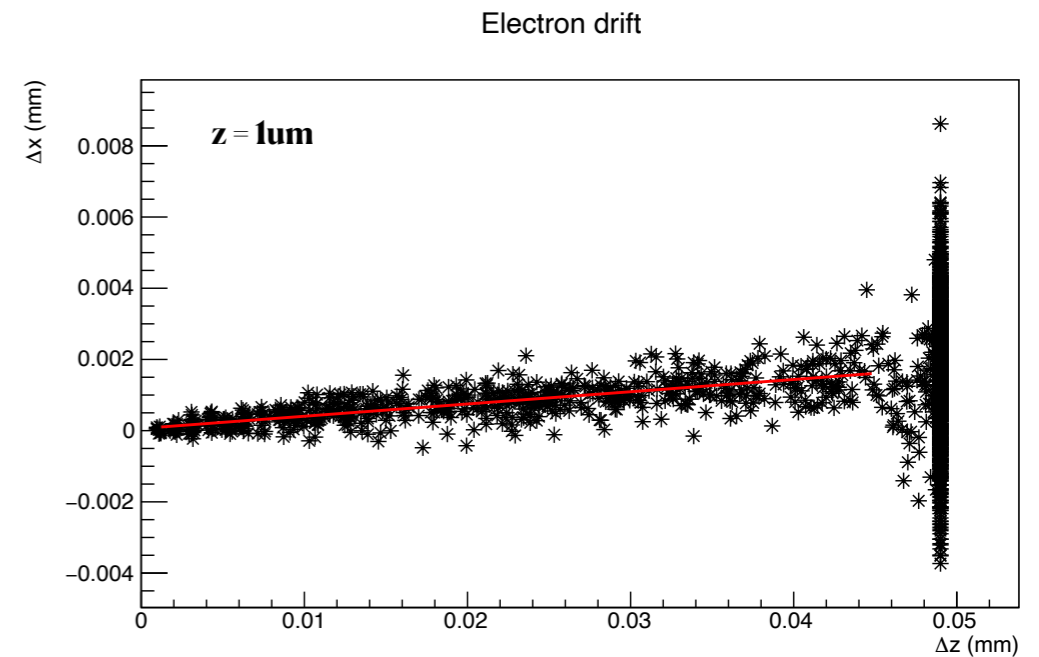
- ◆ Perform a pol4 fit to distribution of  $\Delta z(z_{\text{prop}} - z_{\text{dep}})$  vs z to fill  $\Delta z$  LUT



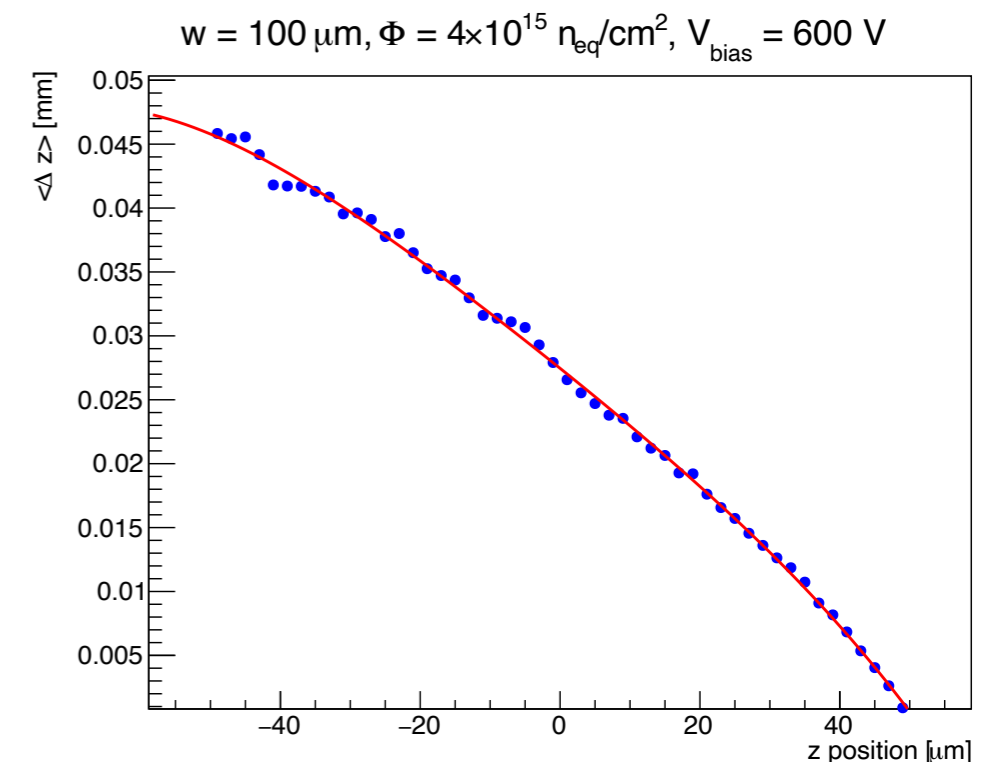
# LUTs from Allpix-Squared

## How to generate the LUTs

- Simulate **point** deposition using “scan” model ([DepositionPointCharge]) in AP2
  - ◆ Charge carrier deposition position change with every event, ensuring homogenous scanning of a single pixel cell
  - ◆ 125000 events simulated, deposit **1000** e-h pairs every 1 $\mu\text{m}$  along x, y and 2 $\mu\text{m}$  along z
  - ◆ Simulation for 100  $\mu\text{m}$  thick planar sensor at  $4 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$  and **600 V**



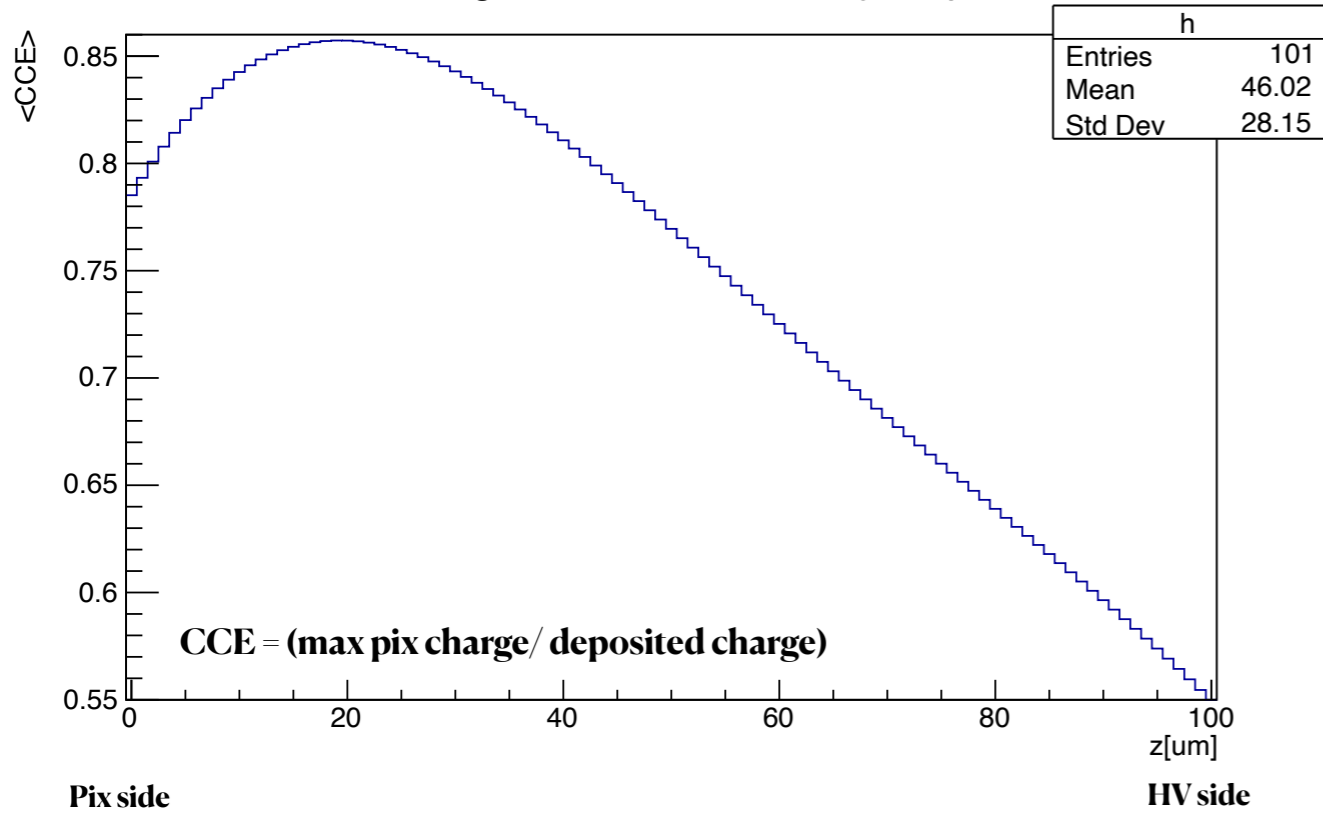
- **Creation of CCE LUT**
  - ◆ CCE per event = (**max pixel charge**)/( $q_{\text{dep}}$ )
  - ◆ CCE LUT obtained by taking the most probable CCE values (**MPV**) at various  $x_{\text{dep}}, y_{\text{dep}}$  for each  $z_{\text{dep}}$
- **Creation of tan(LA) LUT**
  - ◆ Perform a pol1 fit to the distribution of electron drift for each z position ( $\Delta x$  vs.  $\Delta z$ ) to extract the tanLA
- **Creation of delZ LUT**
  - ◆ Perform a pol4 fit to distribution of  $\Delta z(z_{\text{prop}} - z_{\text{dep}})$  vs z to fill  $\Delta z$  LUT



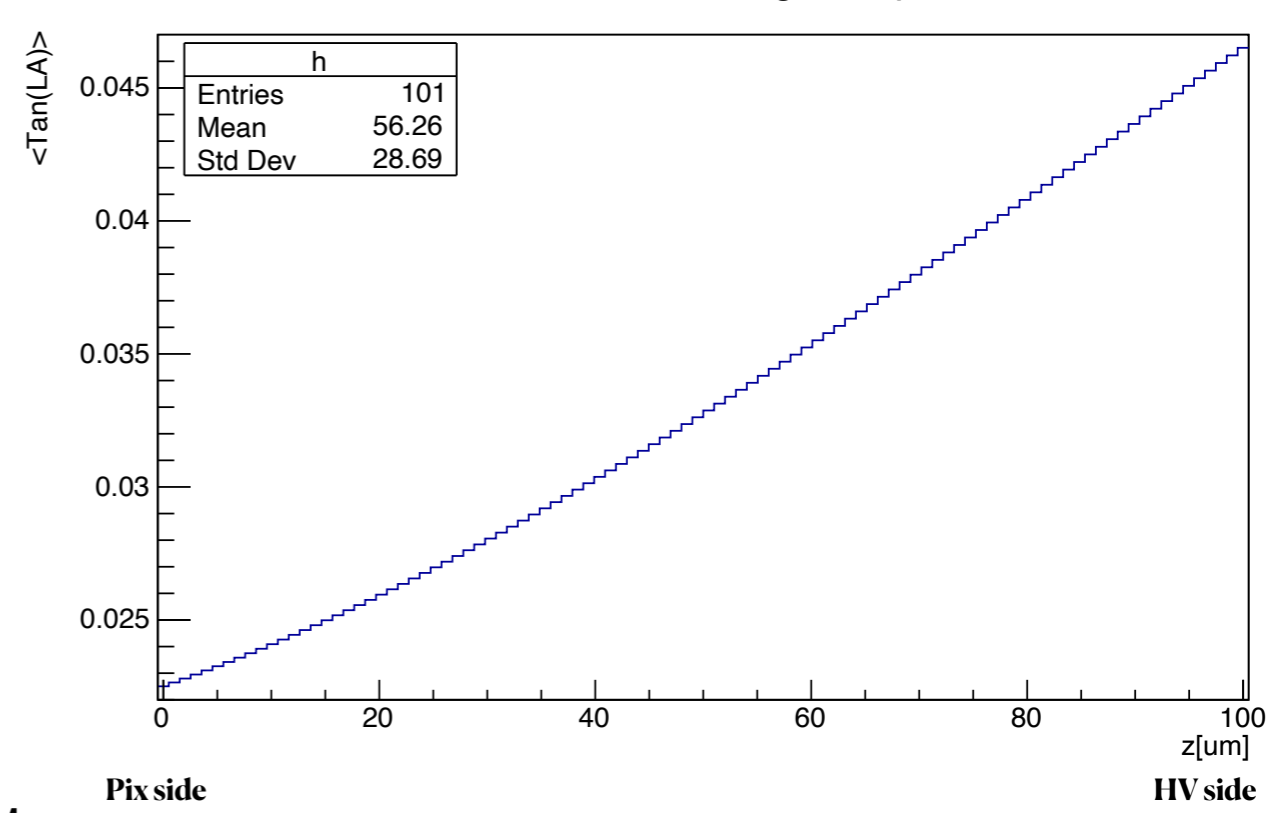
# LUTs from Allpix-Squared

## LUTs

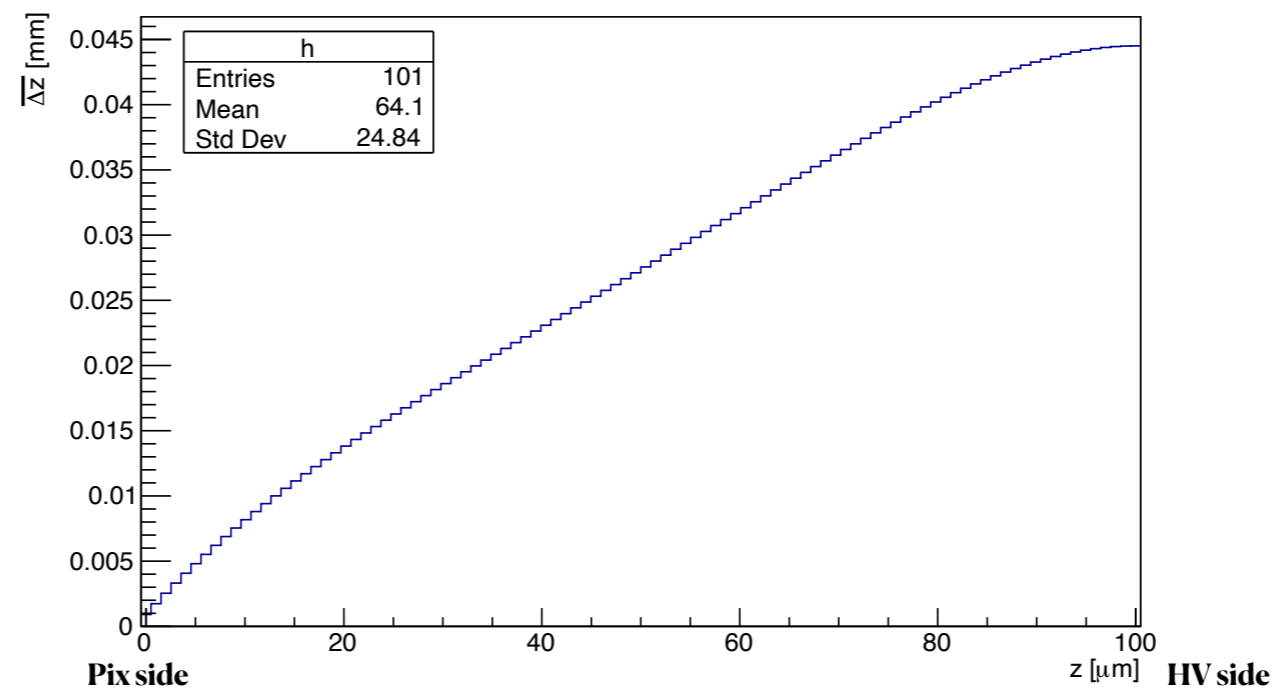
Charge collection efficiency map



Tan Lorentz Angle Map



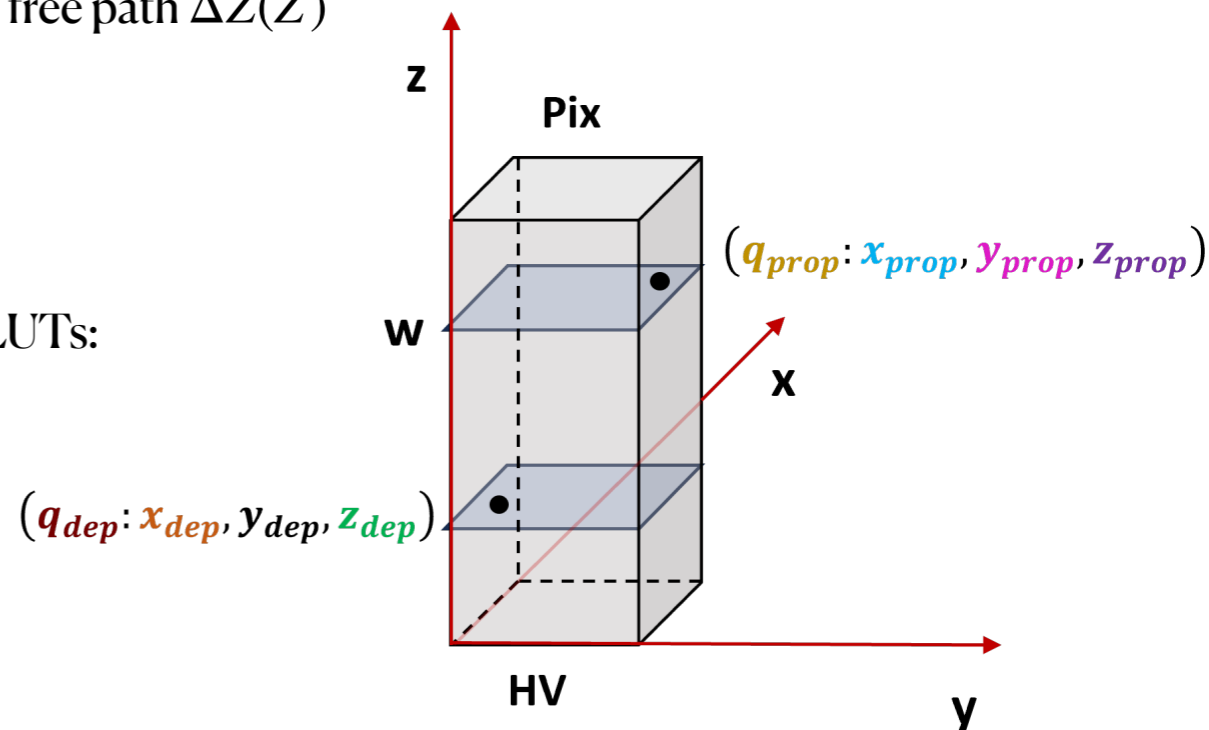
$\Delta z$  Map



- Fluence =  $4 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$
- Voltage = 600V
- Thickness = 100  $\mu\text{m}$
- Pitch = 50  $\mu\text{m} \times 50 \mu\text{m}$

# Closure test

- Using AP2, we've estimated :
  - ✦ CCE (Z), average Lorentz angle deflection as a function Z , average free path  $\Delta Z(Z)$
- Closure test to validate our approach :
  - ✦ Simulate charge deposition
  - ✦ Determine final position and fraction of induced charge using our LUTs:
    - ✦  $q_{prop} = CCE(z_{dep}) * q_{dep}(z_{dep})$
    - ✦  $z_{prop} = z_{dep} + \Delta z(z_{dep})$
    - ✦  $x_{prop} = x_{dep} + \tan(\theta_L)(z_{dep}) * \Delta z(z_{dep})$
  - ✦ Continue with transfer and digitisation steps
  - ✦ Compare the results at 3rd bullet with the ones obtained using the full chain that was used to produce the lookup table
- Developed a new module in Allpix-squared : LUTPropagator
- Performed closure tests with: point charge deposition, line charge deposition, **120 GeV Pions** using LUTs generated with the “scan” model of charge deposition
  - ✦ RD50 Dec'23 : [slides](#)
  - ✦ Allpix-Squared user workshop May23 : [slides](#)

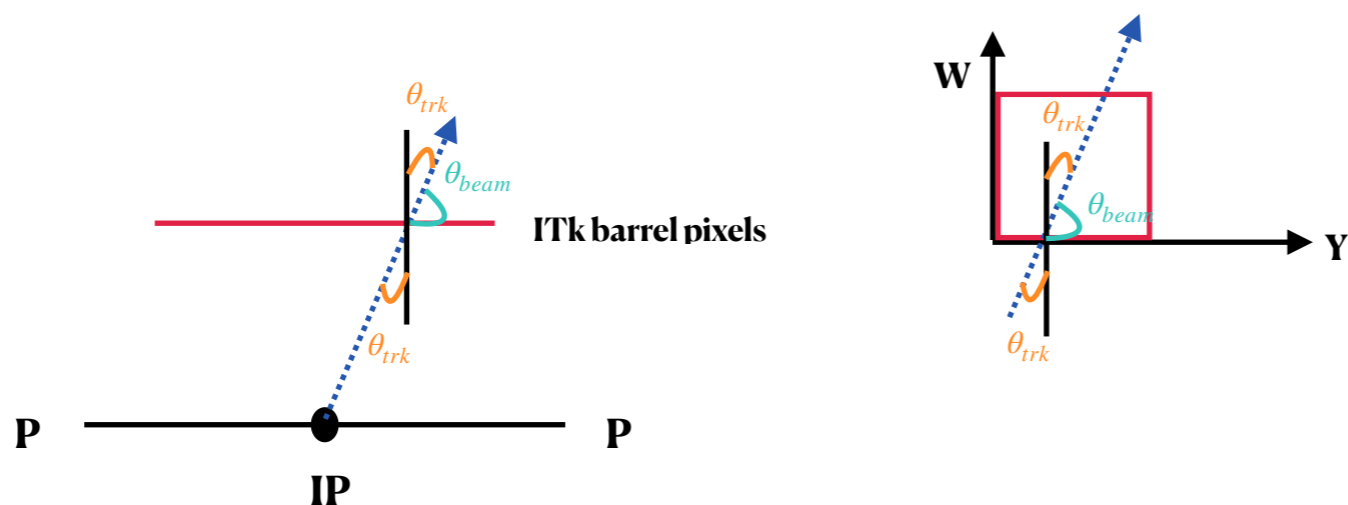




# Realistic simulation studies of ITk barrel pixels

## Investigating Pt and $\eta$ dependencies

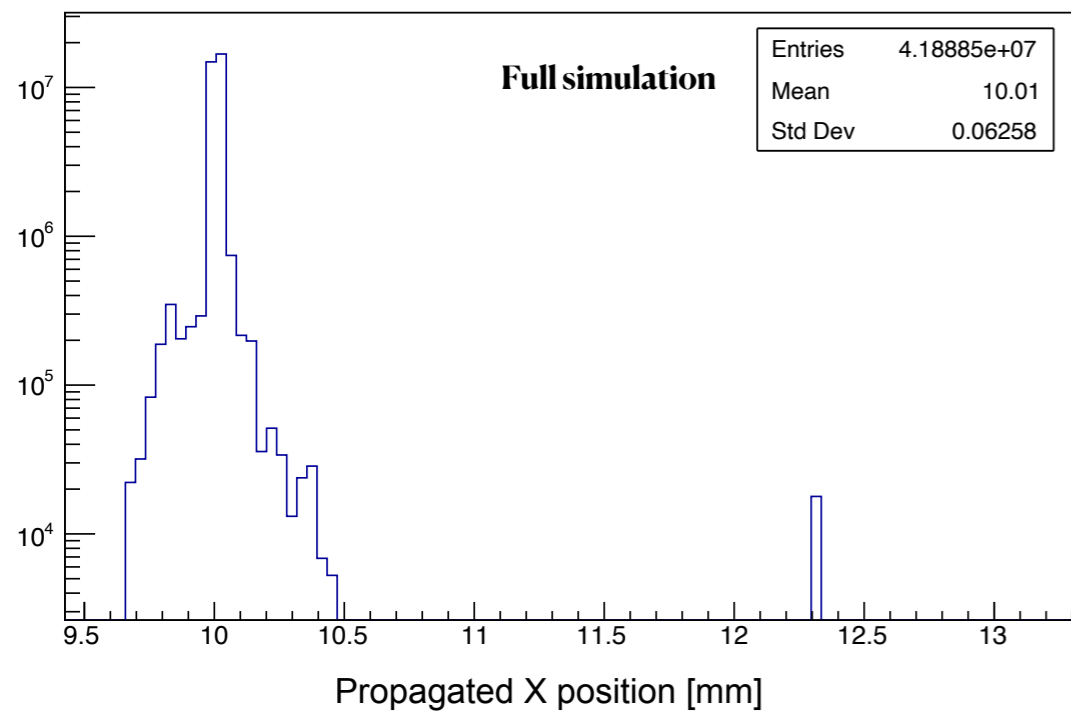
- Barrel layer ITk pixel modules tilted in the phi (**-0.25 rad**) to compensate for Lorentz angle deflection
- Studies with a **100um** thick planar pixel sensors (**50  $\mu\text{m}$  x 50  $\mu\text{m}$** ) at a fluence of **4x10<sup>15</sup> neq/cm<sup>2</sup>** and **600V**
  - ✦ Pions ( $\pi^+$ ) with **Pt = 100 GeV, 10 GeV and 1 GeV** at  $\eta = 0, 1$  and **1.4** ( $\theta_{trk} = 0$  rad, 0.866 rad and 1.088 rad respectively)
    - ✦ Each event has a single pion passing through the detector ; 1000 events simulated



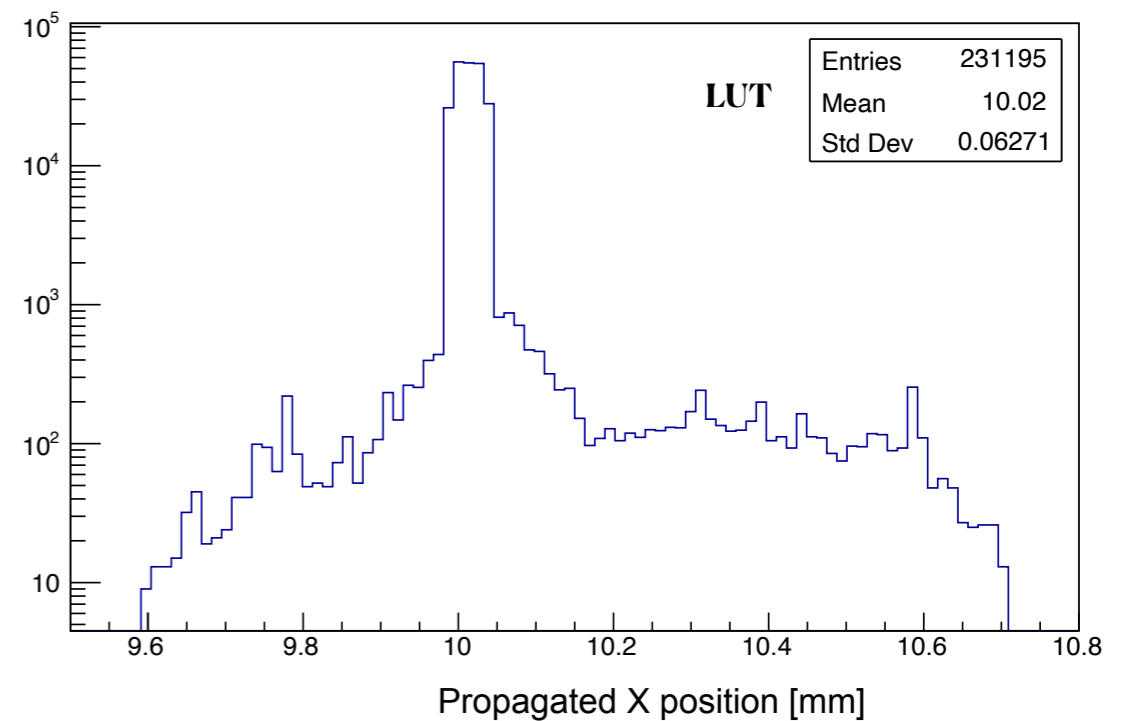
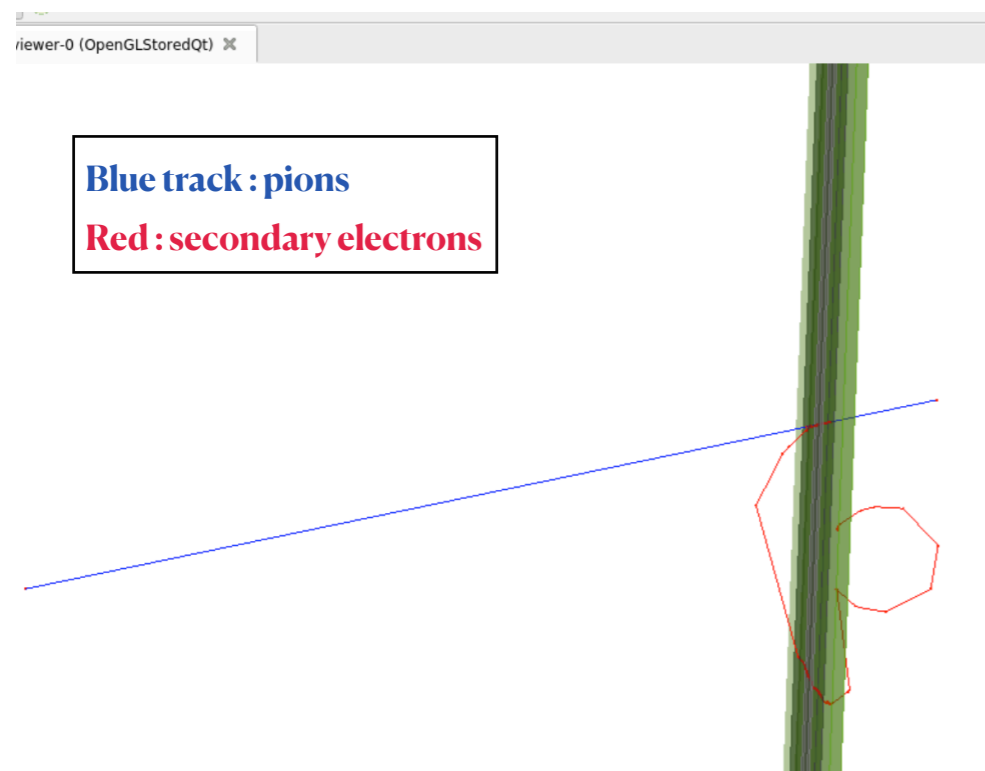
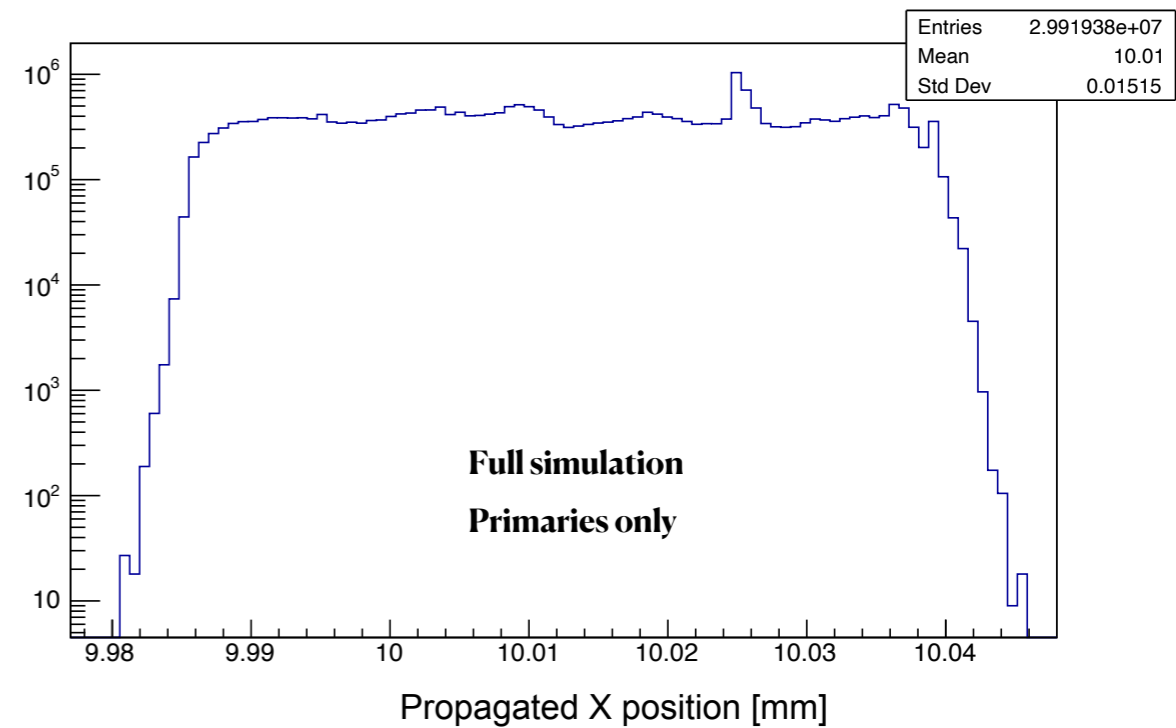
- Comparison of Allpix-Squared full simulation (FS) with LUTPropagator based simulations (LUT)
  - ✦ LUTPropagator module : Scale the charges using CCE LUT , propagate the carriers using **tan(LA)** and  **$\Delta Z$**  LUTs
- Comparison variables : **propagated X position**, cluster size x, cluster size y, cluster charge

# Propagated X Position

Pt = 100GeV, Eta = 1.4 ( $\theta_{trk} = 1.088$  rad), -0.25 rad phi



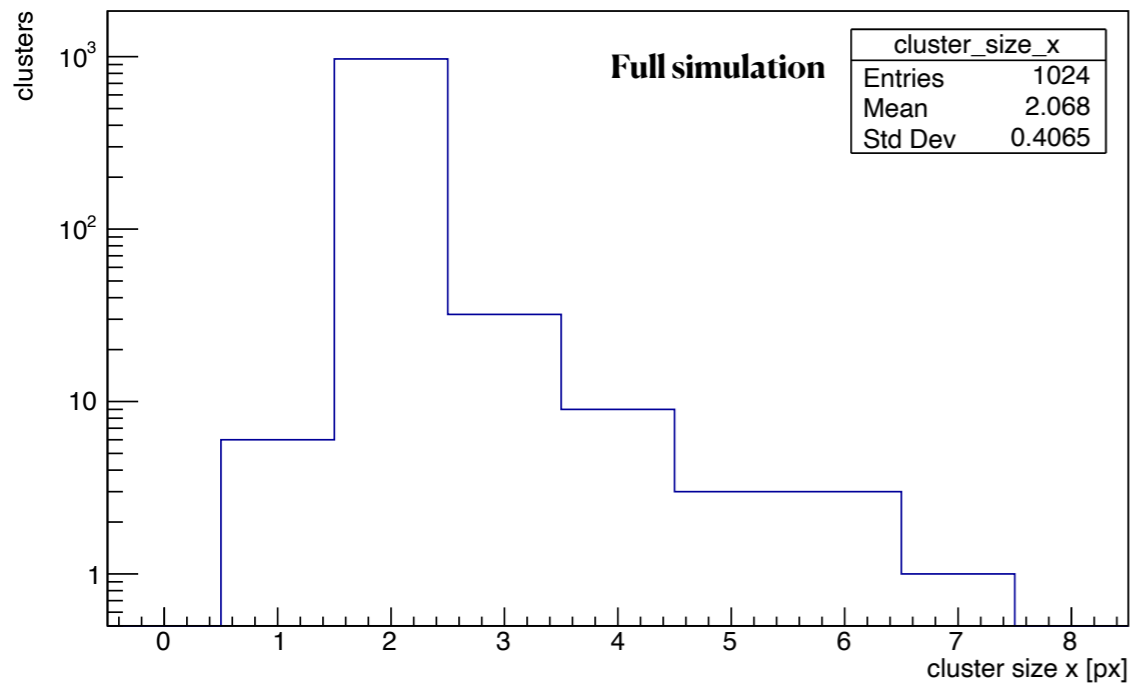
Filtering  
secondaries  
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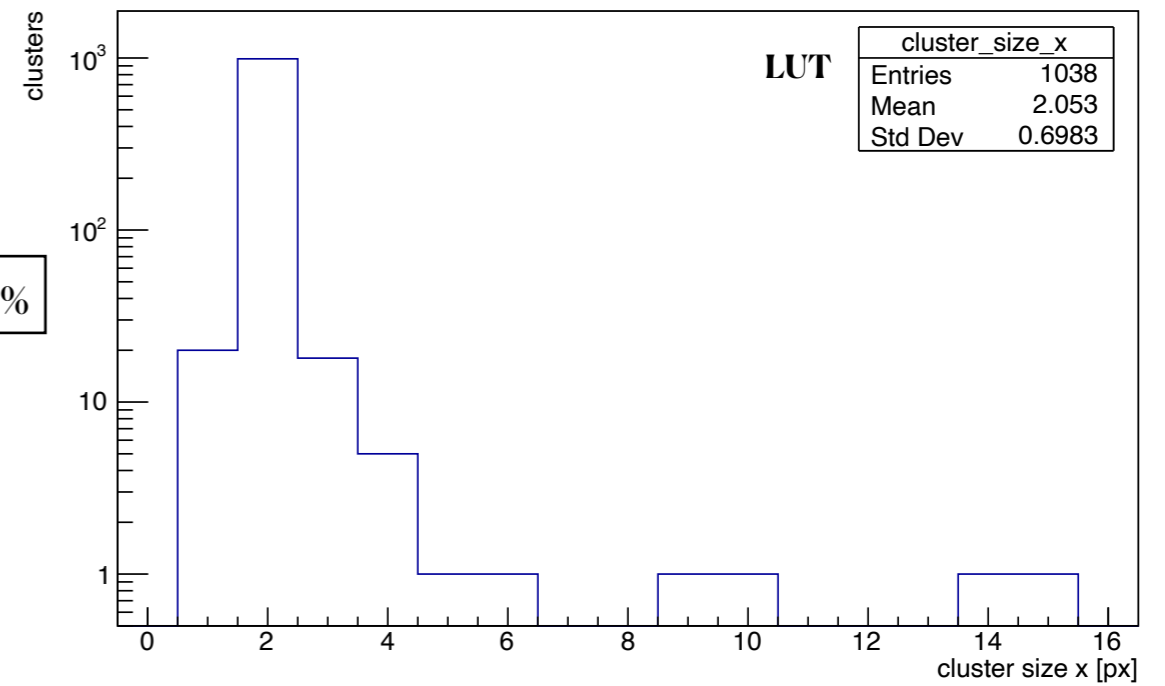
# Cluster size - X,Y

Pt = 100GeV, Eta = 1.4 ( $\theta_{trk} = 1.088$  rad), -0.25 rad phi

Cluster size in X (detector1)

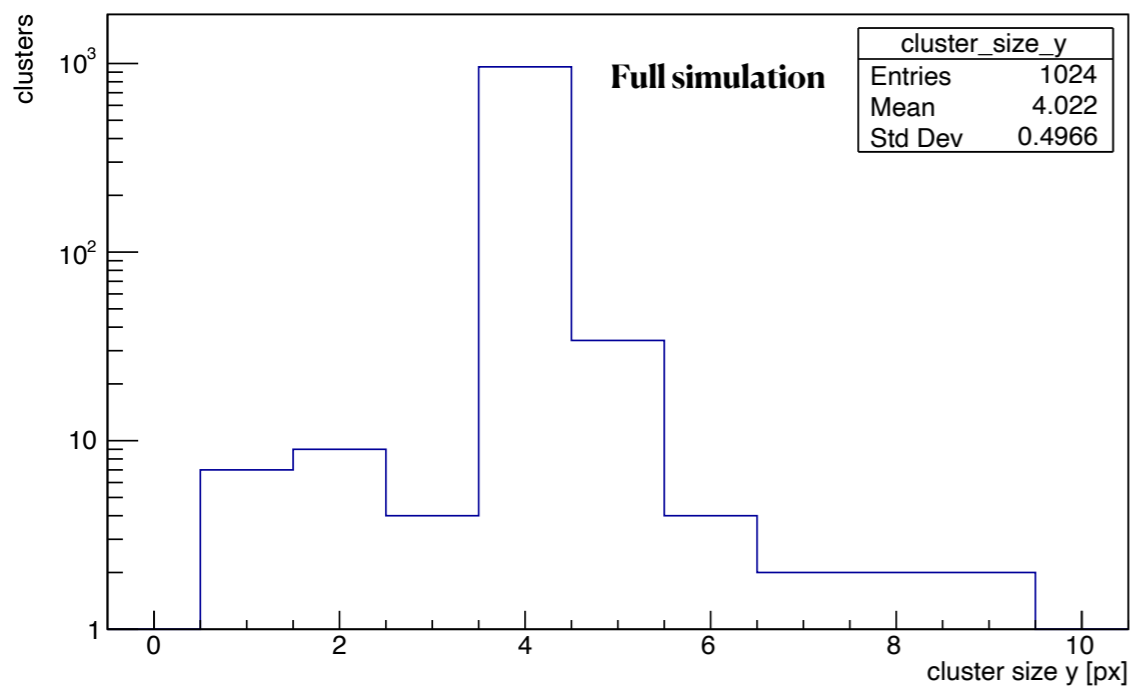


Cluster size in X (detector1)

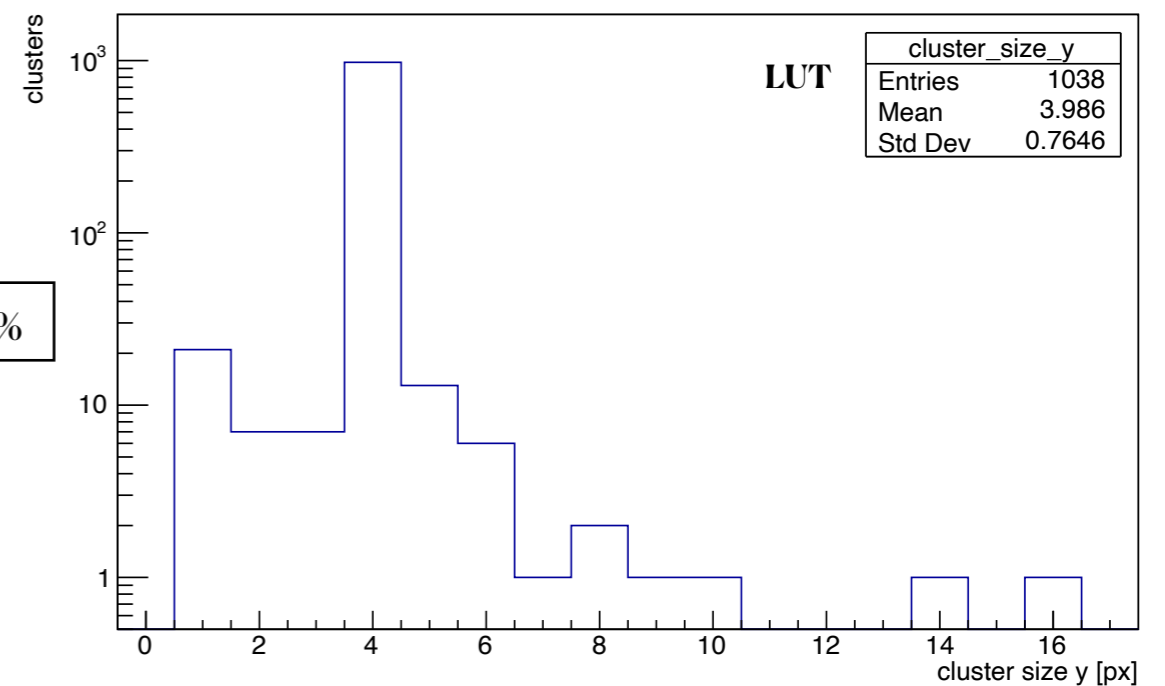


Rel err mean: 0.72%

Cluster size in Y (detector1)



Cluster size in Y (detector1)

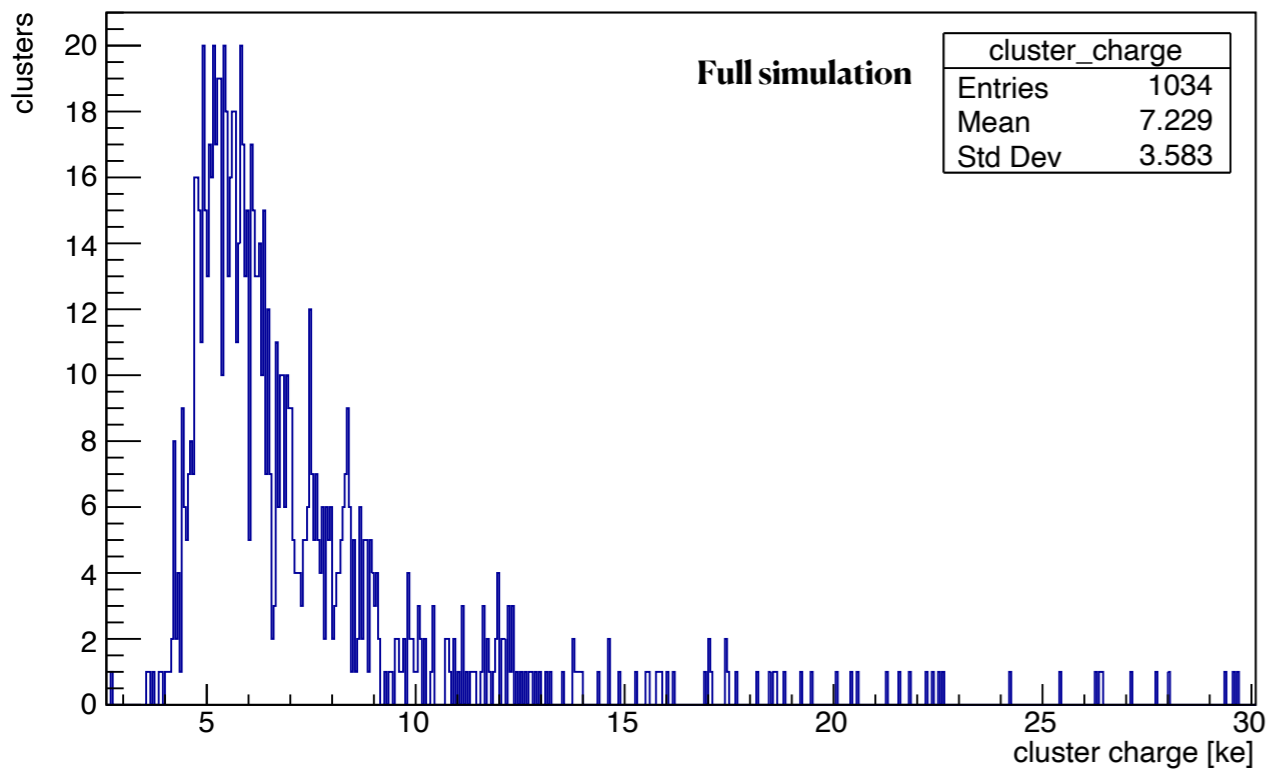


Rel err mean: 0.89%

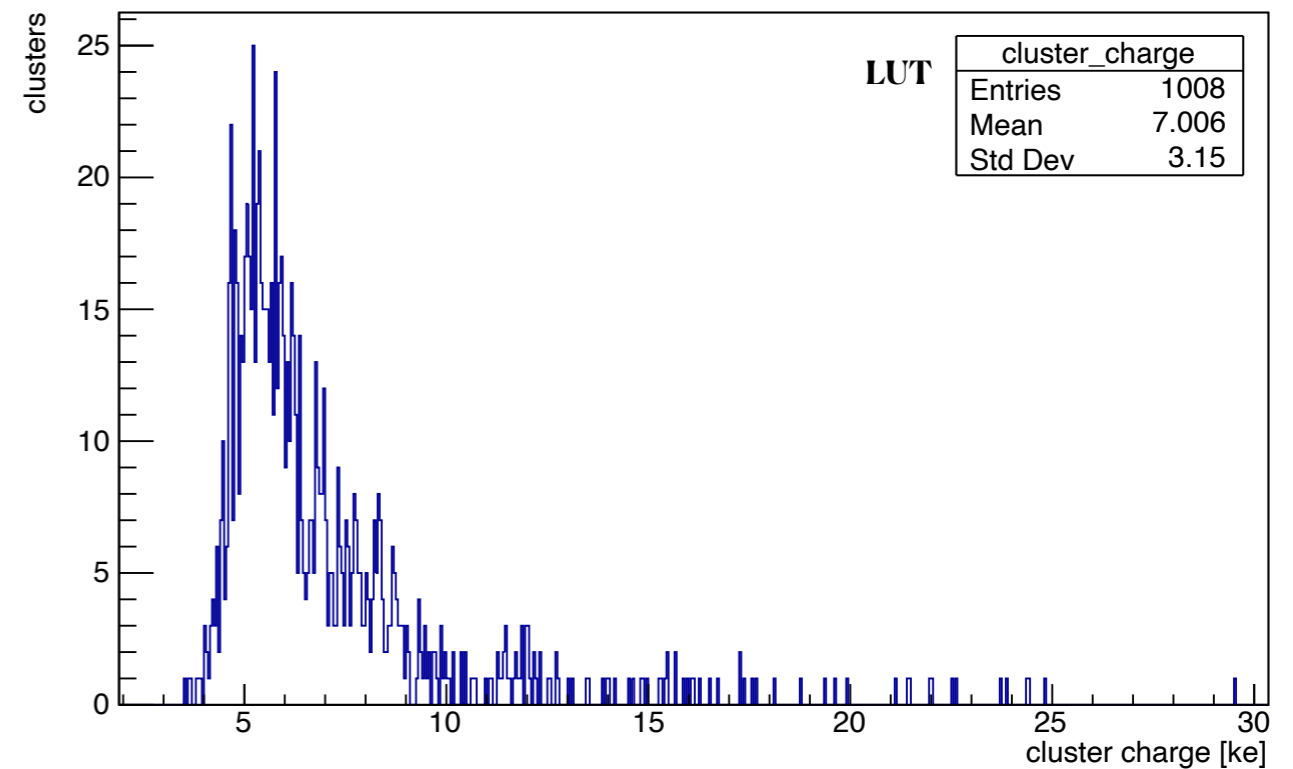
# Cluster charge

Pt = 100GeV, Eta = 1.4 ( $\theta_{trk} = 1.088$  rad), -0.25 rad phi

Cluster charge (detector1)



Cluster charge (detector1)



Rel err mean: 3.1%

- Results for Pt = 100GeV : backup slide #18 -29
- Results for Pt = 10 GeV : backup slides #30 - 41
- Results for Pt = 1GeV : backup slides #42 -53

# Results of Pt = 100 GeV

## Understanding trends

Eta	Propagated X Position (mm)			Cluster Size Y(pix)			Cluster Size X(pix)			Cluster Charge (ke)		
	FS	LUT	Diff/pitch	FS	LUT	Rel err	FS	LUT	Rel err	FS	LUT	Rel err
Normal incidence	10	10	0	1.075	1.033	3.9%	1.079	1.042	3.4%	7.334	7.252	1.1%
1 (theta_trk = 0.866Rad)	10.01	10.01	0	3.011	3.013	0.07%	1.243	1.424	14.5%	10.39	10.68	2.8%
1.4 (theta_trk = 1.088 Rad)	10.0133	10.0207	14.8 %	4.022	3.986	0.89%	2.068	2.053	0.72%	14.29	14.76	3.3%

- Excellent agreement btw FS and LUT for PropagatedXPosition for eta = 0, 1 ; 15% difference observed at eta = 1.4
- Excellent agreement btw FS and LUT for cluster size y at different eta values
- Transverse cluster size (X) increases with higher eta values in both FS and LUT
  - ✦ Similar trend observed in ATLAS pixel data
  - ✦ Transverse cluster size  $\propto$  Longitudinal cluster size
- Excellent closure between FS and LUT for cluster charge at different eta values
  - ✦ Increasing eta -> particles incident at shallower angles, longer path length traversed in silicon, larger deposited charge , larger cluster charge

# Cluster size $X$ at $P_t = 100$ GeV

## Investigating the trend

Eta	Cluster size $X$ (pix)		
	FS	LUT	Rel err
0	1.079	1.042	3.4%
0.4	1.09	1.047	3.9%
0.8	1.117	1.073	3.9%
1	1.243	1.424	14.5%
1.2	2.042	2.018	1.2%
1.4	2.068	2.053	0.72%

- Observed a discrepancy in the mean cluster size  $X$  between FS and LUT at eta = 1
- Conducted a study by sampling finer eta values around 1
- Excellent closure between FS and LUT seen for the new data points

# Results of Pt = 10 GeV

## Understanding trends

Eta	Propagated X Position (mm)			Cluster Size Y(pix)			Cluster Size X(pix)			Cluster Charge (ke)		
	FS	LUT	Diff/pitch	FS	LUT	Rel err	FS	LUT	Rel err	FS	LUT	Rel err
Normal incidence	10.0020	10.0063	8.6%	1.082	1.04	3.9%	1.097	1.055	3.8%	7.229	7.006	3.1%
1 (theta_trk = 0.866Rad)	10.0089	10.0155	4.6%	3.023	2.988	1.2%	1.217	1.422	16.8%	10.37	10.95	5.6%
1.4 (theta_trk = 1.088 Rad)	10.0131	10.0154	4.6 %	4.015	3.989	0.65%	2.07	2.046	1.2%	14.29	15.05	5.3%

- Good agreement btw FS and LUT for PropagatedXPosition, relative difference < 10%
- Excellent agreement btw FS and LUT for cluster size y at different eta values
- Transverse cluster size (X) increases with higher eta values in both FS and LUT
  - ✦ Similar trend observed in ATLAS pixel data
  - ✦ Transverse cluster size  $\propto$  Longitudinal cluster size
- Good closure between FS and LUT for cluster charge at different eta values
  - ✦ Increasing eta -> particles incident at shallower angles, longer path length traversed in silicon, larger deposited charge , larger cluster charge

# Results of Pt = 1 GeV

## Understanding trends

Eta	Propagated X Position (mm)			Cluster Size Y(pix)			Cluster Size X(pix)			Cluster Charge (ke)		
	FS	LUT	Diff/pitch	FS	LUT	Rel err	FS	LUT	Rel err	FS	LUT	Rel err
Normal incidence	10	10	0 %	1.1	1.032	6.2%	1.099	1.041	5.3%	6.957	6.741	3.1%
1 (theta_trk = 0.866Rad)	10.01	10.01	0 %	3.027	3.001	0.86%	1.186	1.404	18.38%	10.25	10.54	2.8%
1.4 (theta_trk = 1.088 Rad)	10.0131	10.0152	4.2 %	4.027	4.019	0.20%	2.058	2.047	0.53%	13.99	14.62	4.5%

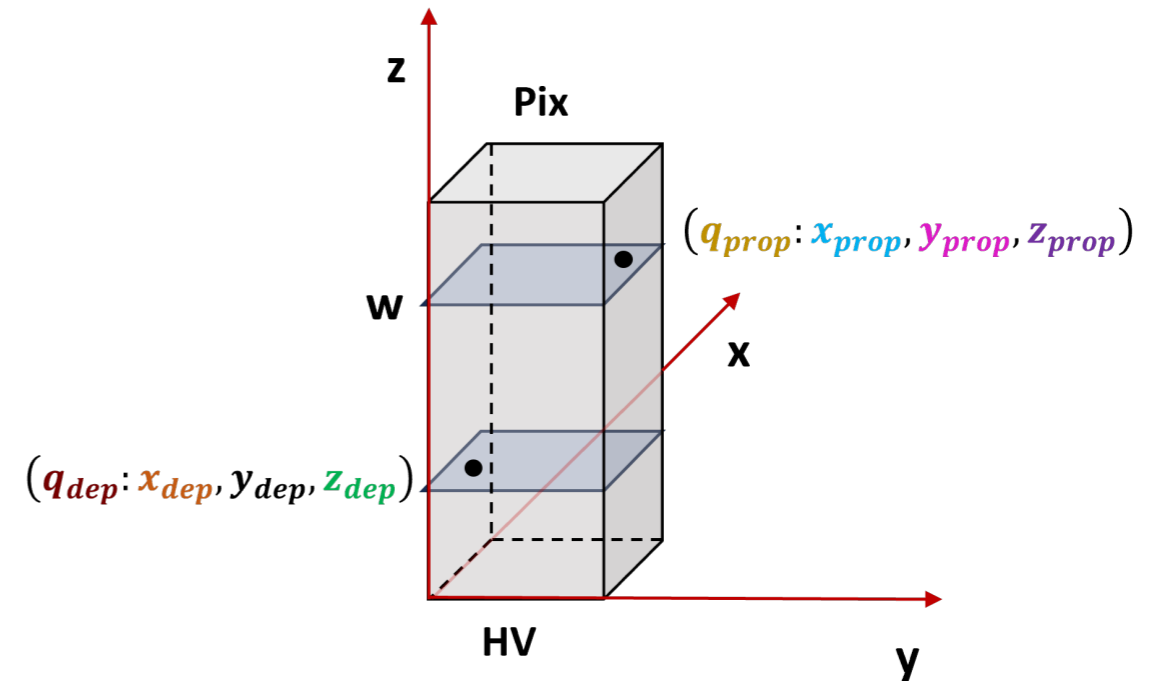
- Excellent agreement btw FS and LUT for PropagatedXPosition, relative difference < 5%
- Excellent agreement btw FS and LUT for cluster size y at different eta values
- Transverse cluster size (X) increases with higher eta values in both FS and LUT
  - ✦ Similar trend observed in ATLAS pixel data
  - ✦ Transverse cluster size  $\propto$  Longitudinal cluster size
- Good closure between FS and LUT for cluster charge at different eta values
  - ✦ Increasing eta -> particles incident at shallower angles, longer path length traversed in silicon, larger deposited charge, larger cluster charge



# ITk Pixel Radiation Damage Digitiser Speed Test

## First tests in Athena

- Studies by Tomas Dado - Thanks!!
- Reminder - charge scaling and propagation :
  - ✦  $q_{prop} = CCE(z_{dep}) * q_{dep}(z_{dep})$
  - ✦  $z_{prop} = z_{dep} + \Delta z(z_{dep})$
  - ✦  $x_{prop} = x_{dep} + \tan(\theta_L)(z_{dep}) * \Delta z(z_{dep})$
- Performed first tests to determine the relative speed of the radiation damage digitiser for the planar ITk pixels using dummy LUTs (unirradiated detector)
  - ✦ No impact anticipated upon switching to LUTs for irradiated devices
- Initial tests indicates that the radiation damage digitiser is as fast as standard digitiser
  - ✦ Expectation: algorithm is the same, only additive and multiplicative corrections are applied



# Summary

## What next??

- Silicon detectors at hadron colliders are exposed to unprecedented levels of radiation damage
- Signal loss is the most important effect for cluster position determination
- Simulation of these effects in ATLAS MC for HL-LHC -> pixel reweighting
- Allpix-Squared together with TCAD simulations to make correction to take into account signal reduction and cluster shape changes
- Produced CCE vs  $Z$ ,  $\tan(\theta_L)$  vs  $Z$  and,  $\Delta Z$  vs  $Z$  LUTs from Allpix-squared
- Validated the approach using closure tests: point charge depositions, line charge deposition, 120GeV Pions, Pions with  $P_t = 100\text{GeV}$ , 10 GeV and 1GeV at  $\eta = 0, 1, \text{ and } 1.4$
- Similar efforts in progress for 3D and strip detectors
- Next steps :
  - ✦ Repeat the studies at different fluences and operating voltages ( $1\text{-}3 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ , 300V - 500V)
  - ✦ Perform studies using planar sensors with pixel pitch of  $25 \mu\text{m} \times 100 \mu\text{m}$ , serving as further validation for the proposed technique
  - ✦ Understand the small discrepancy between FS and CT seen in cluster size x observable for  $\eta = 1$
  - ✦ Anticipating the 2024 TB campaign for ITkPixV2 modules to validate our approach with the TB data

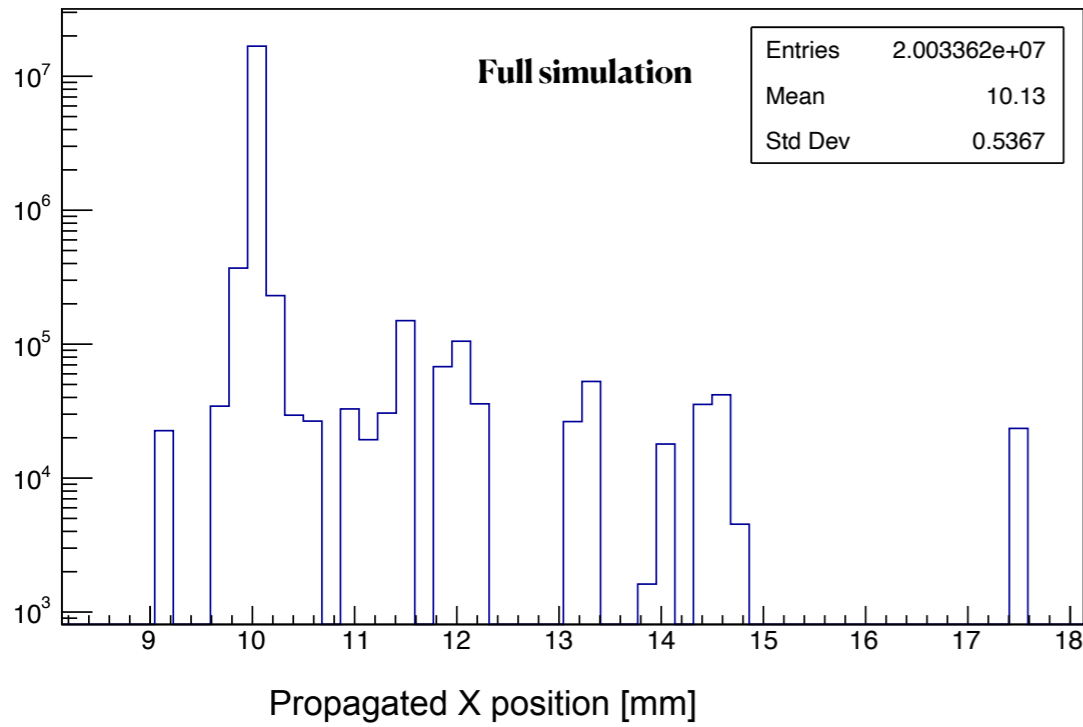
**Thank you so much for your attention !! :)**

# Backup

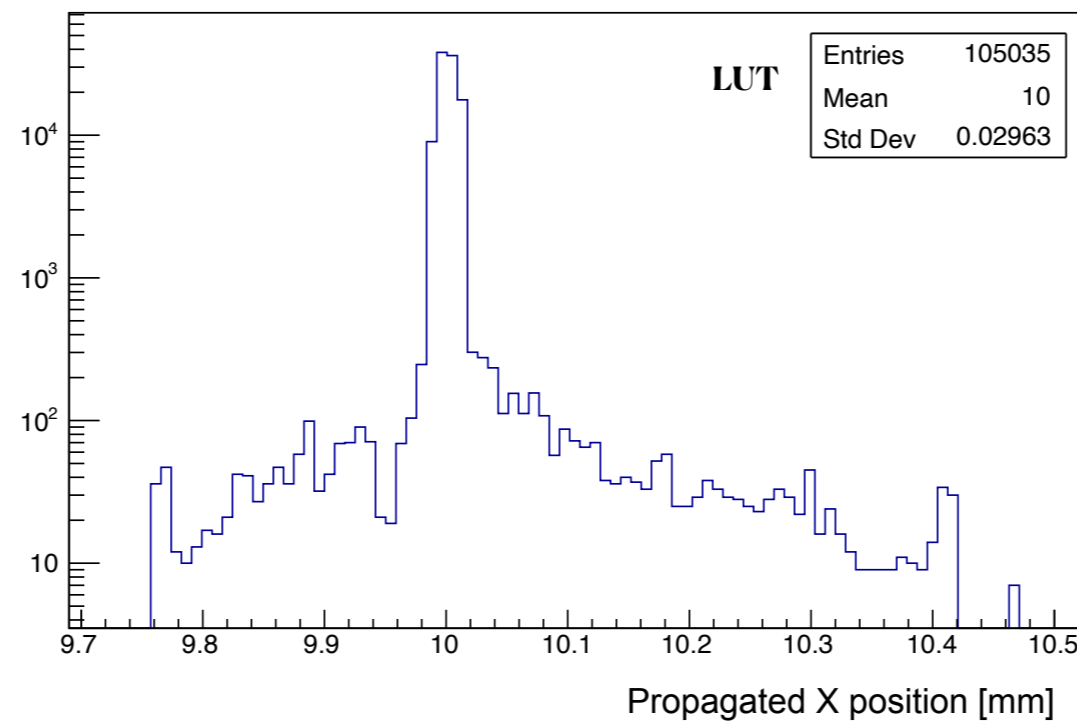
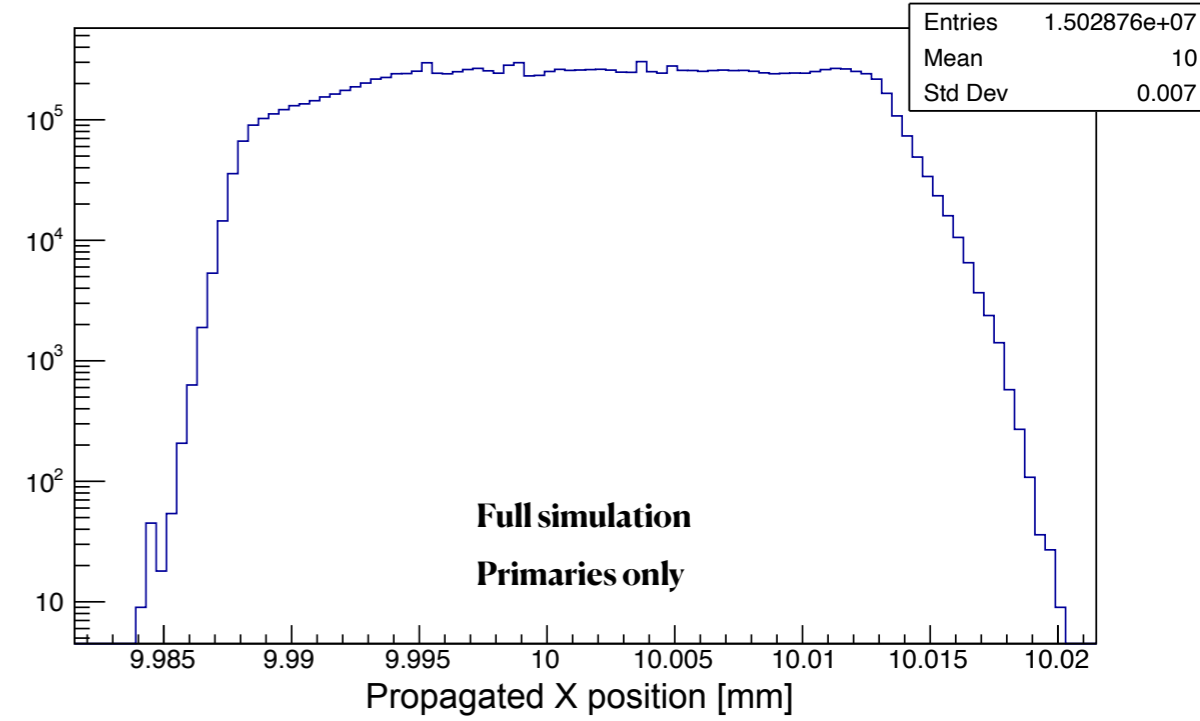
**$P_t = 100 \text{ GeV}, \eta = 0$**

# Propagated X Position

Pt = 100GeV, Eta = 0 ( $\theta_{trk} = 0$  rad), -0.25 rad phi



Filtering  
secondaries

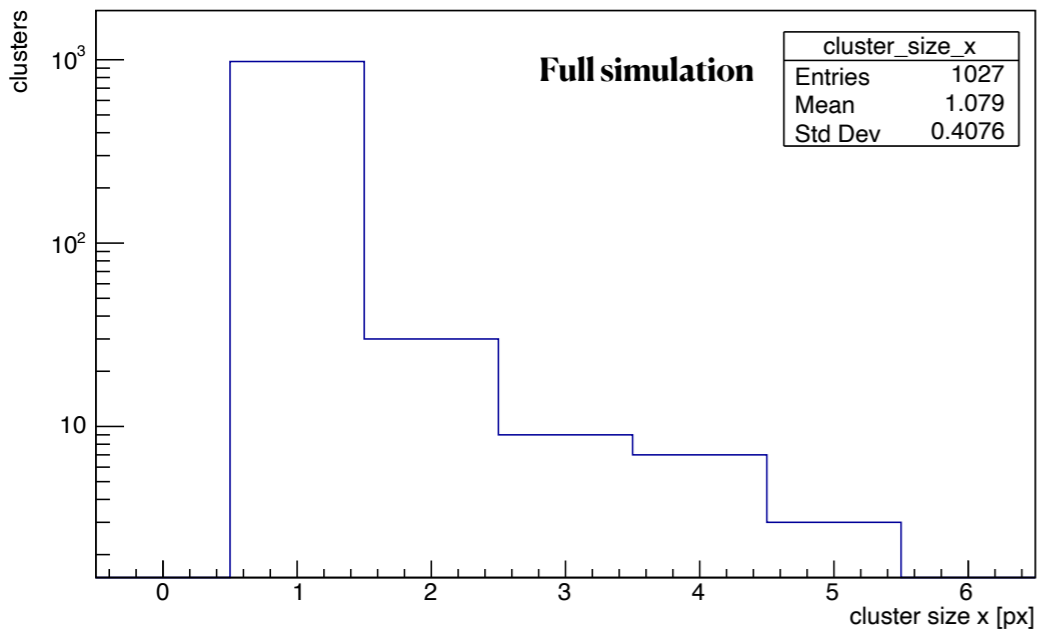


Diff = 0um

# Cluster size X & Y

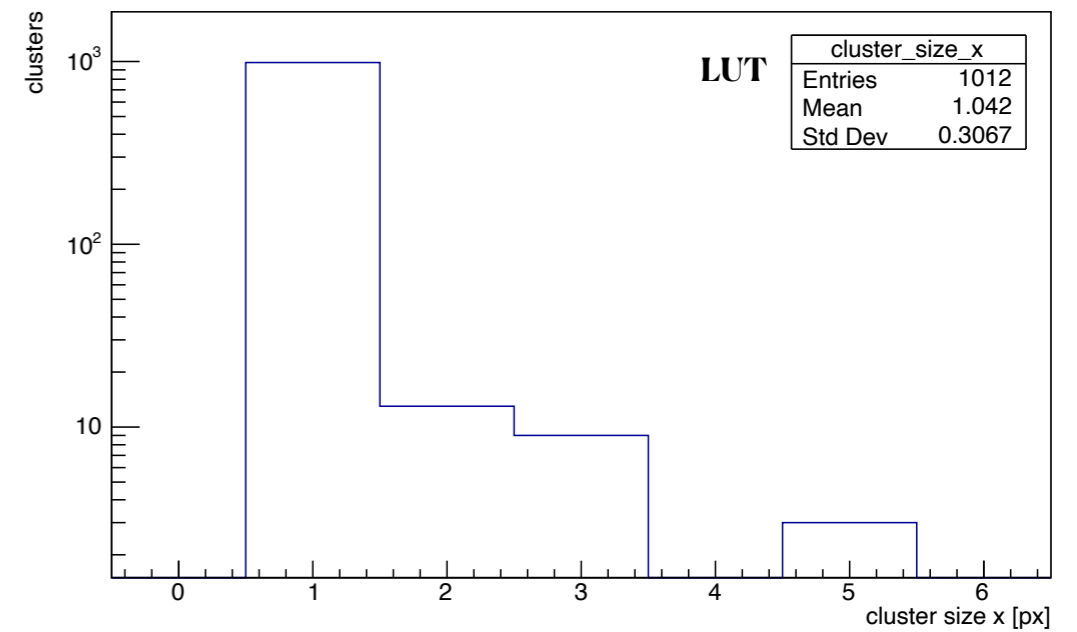
Pt = 100GeV, Eta = 0 ( $\theta_{trk} = 0$  rad), -0.25 rad phi

Cluster size in X (detector1)

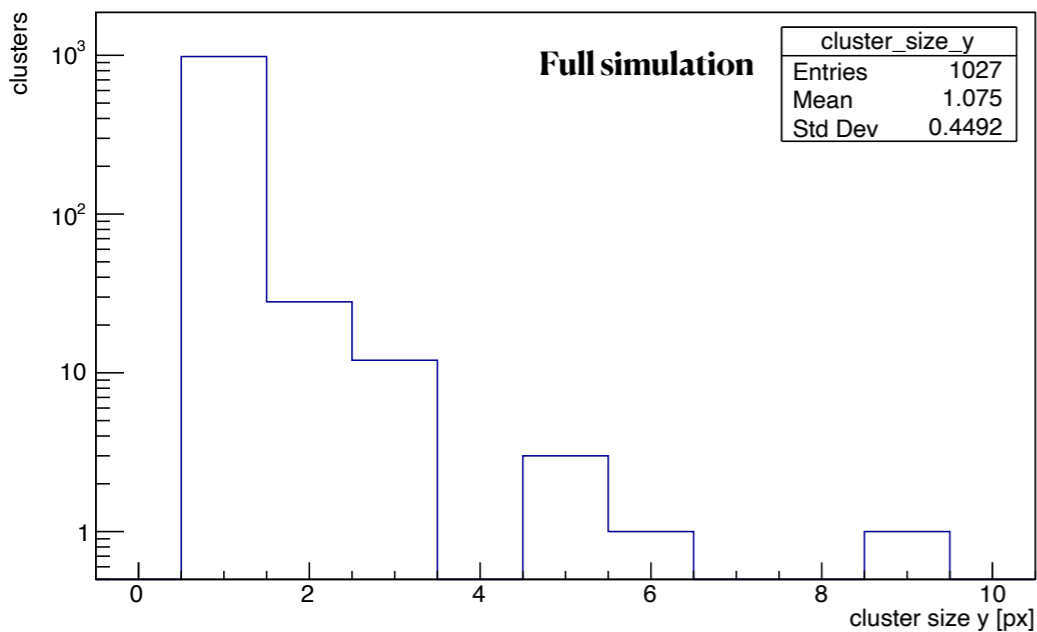


Rel err mean: 3.4%

Cluster size in X (detector1)

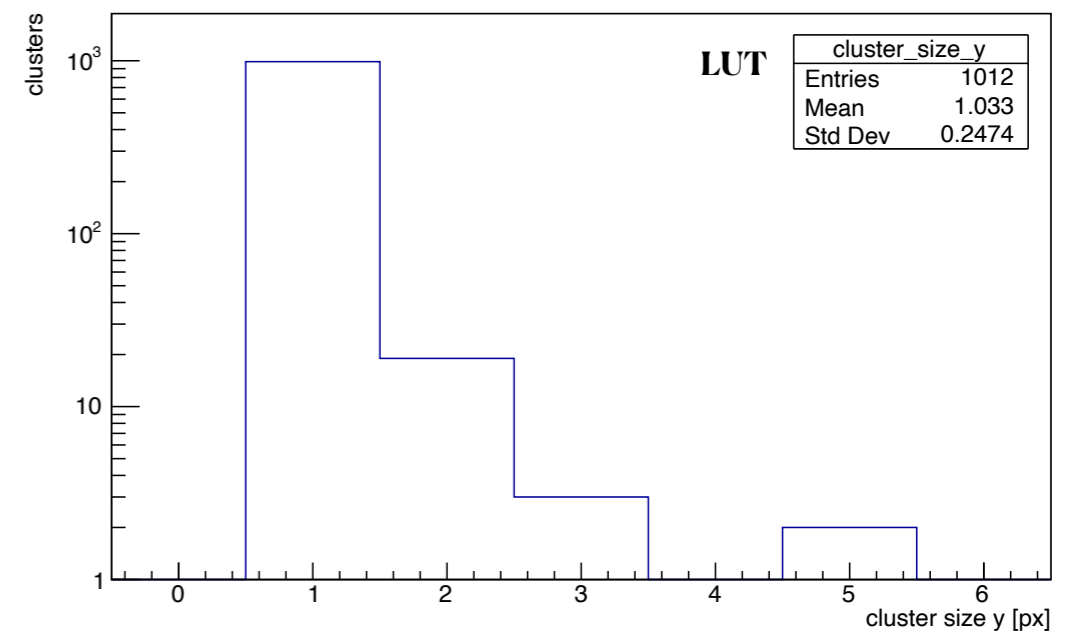


Cluster size in Y (detector1)



Rel err mean: 3.9%

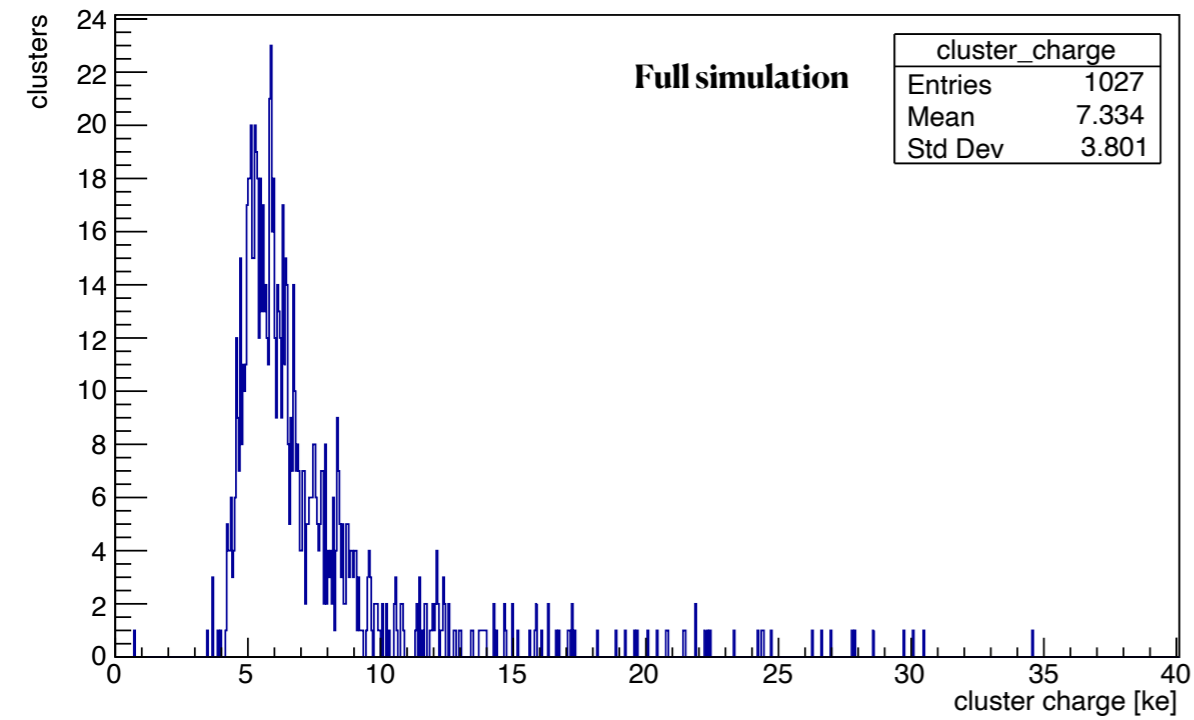
Cluster size in Y (detector1)



# Cluster charge

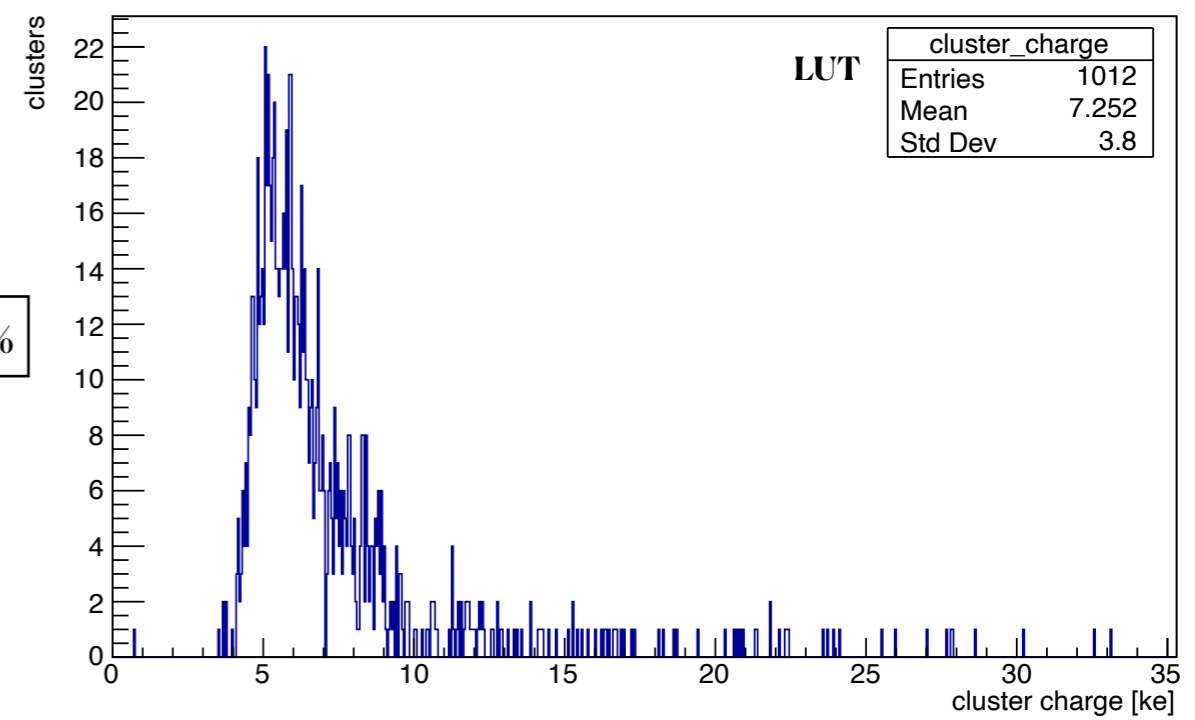
Pt = 100GeV, Eta = 0 ( $\theta_{trk} = 0$  rad), -0.25 rad phi

Cluster charge (detector1)



Rel err mean: 1.1%

Cluster charge (detector1)

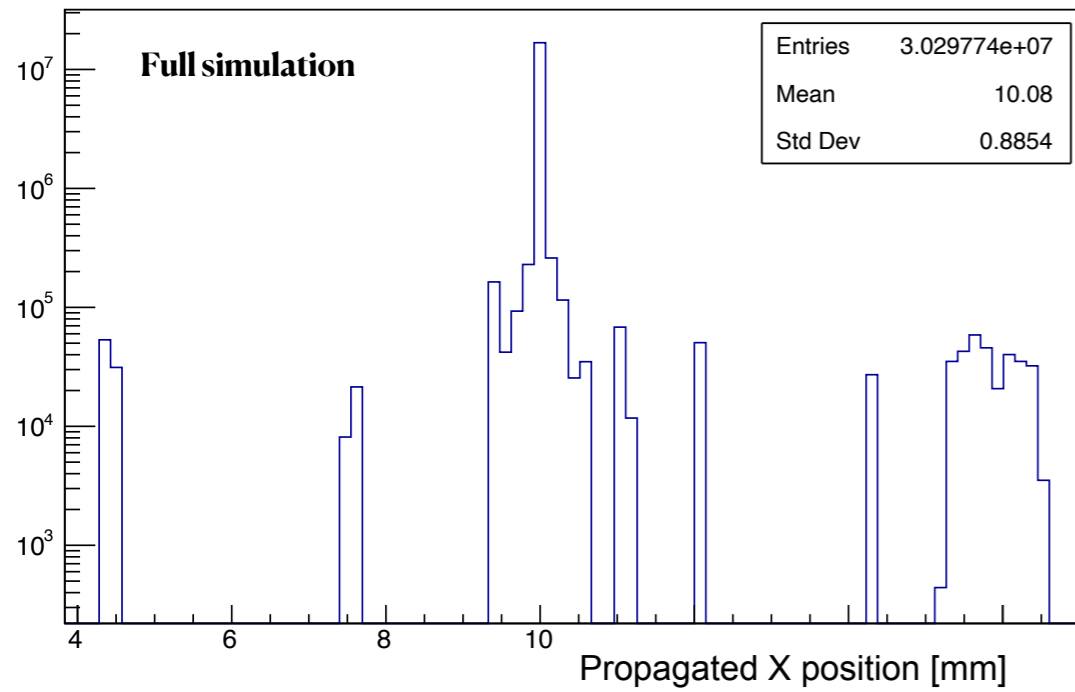


**$P_t = 100 \text{ GeV}, \eta = 1$**

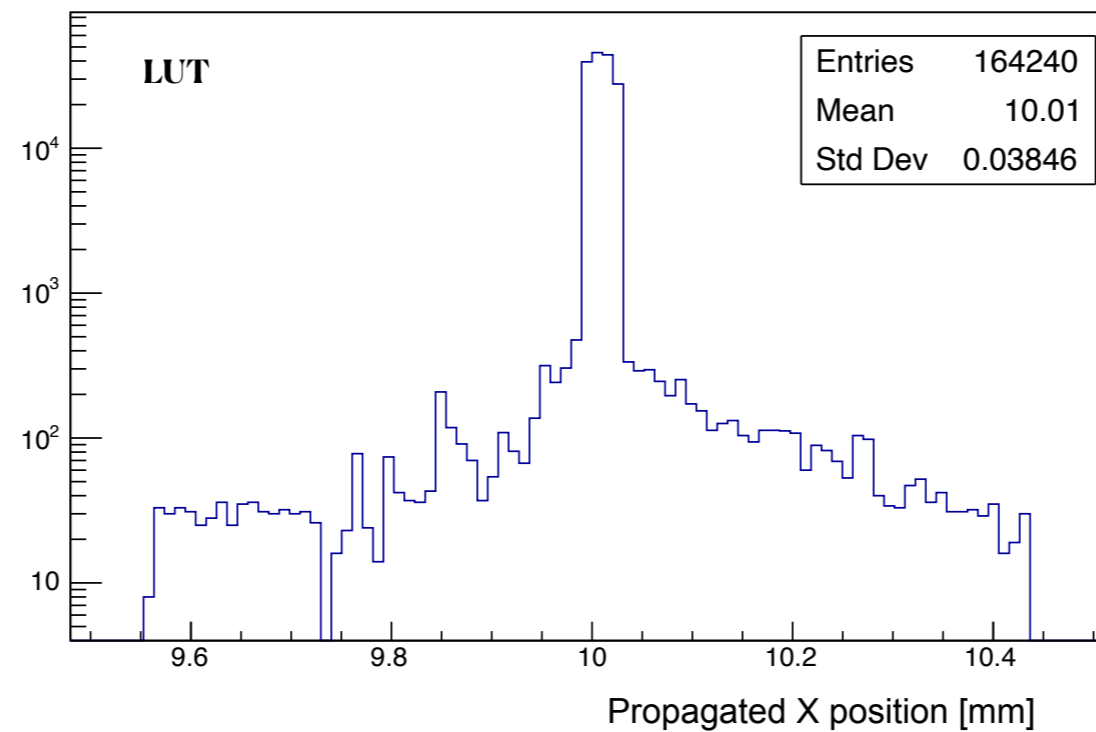
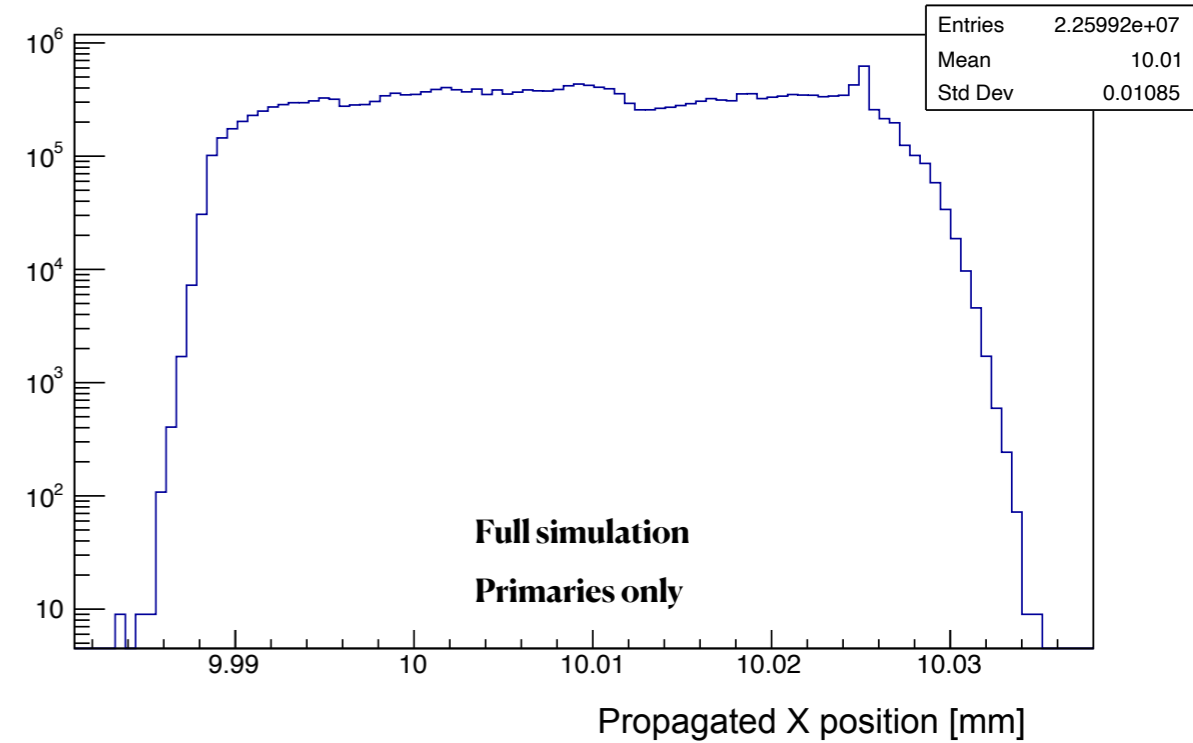


# Propagated X Position

Pt = 100GeV, Eta = 1 ( $\theta_{trk} = 0.866$  rad), -0.25 rad phi



Filtering  
secondaries



Diff = 0um

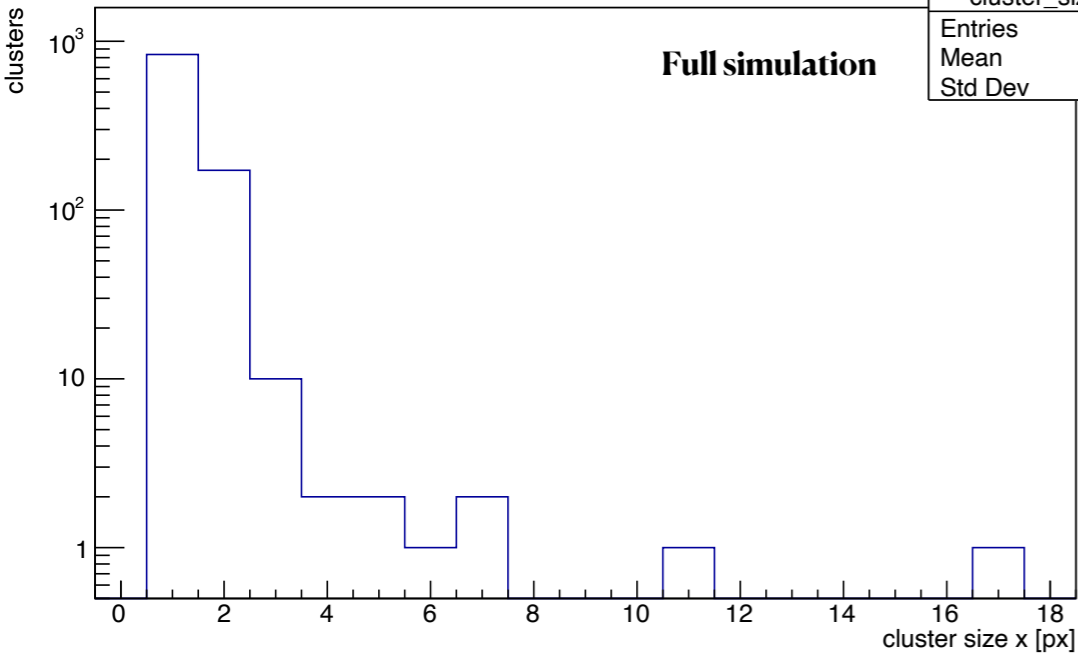
# Cluster size X & Y

Pt = 100GeV, Eta = 1 ( $\theta_{trk} = 0.866$  rad), -0.25 rad phi

Cluster size in X (detector1)

Full simulation

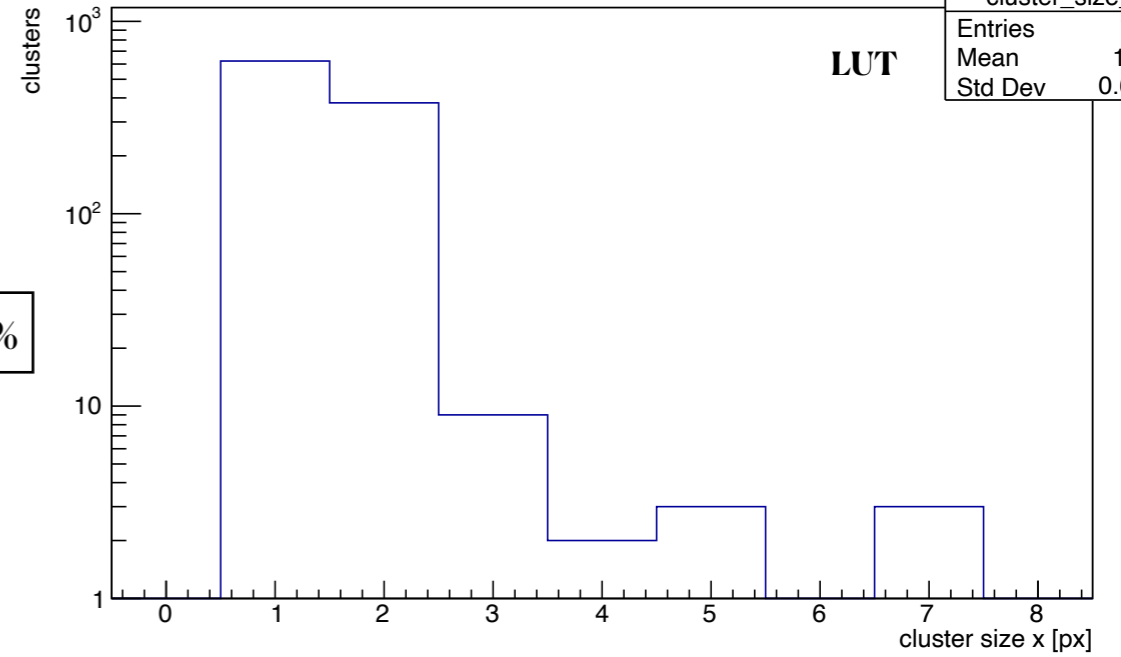
cluster_size_x	
Entries	1026
Mean	1.243
Std Dev	0.7987



Cluster size in X (detector1)

LUT

cluster_size_x	
Entries	1016
Mean	1.424
Std Dev	0.6307

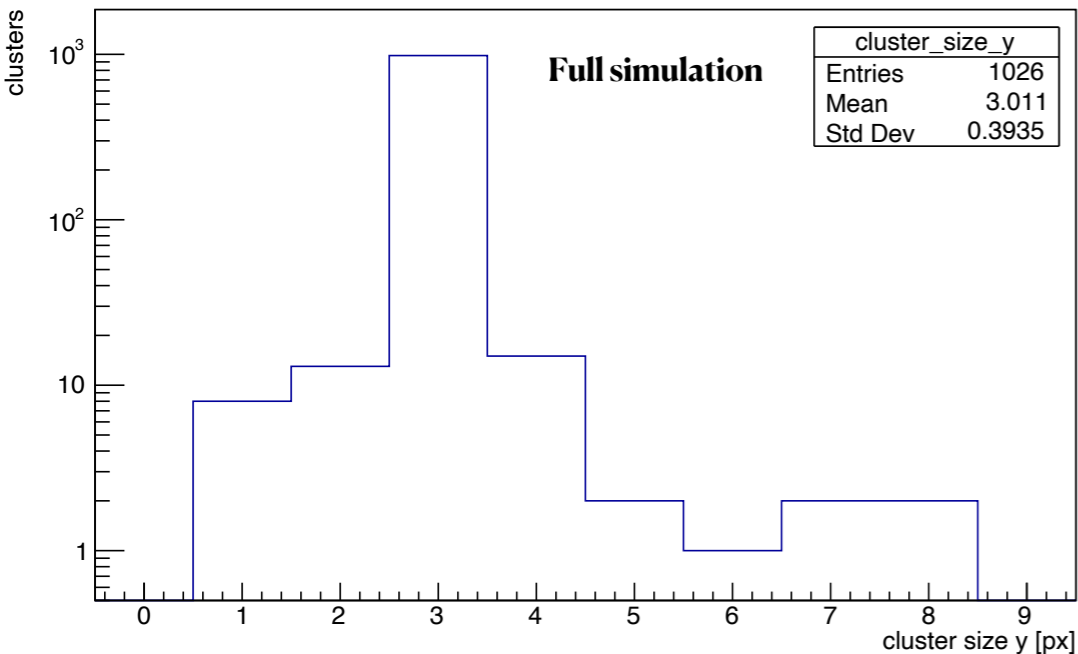


Rel err mean: 14.5%

Cluster size in Y (detector1)

Full simulation

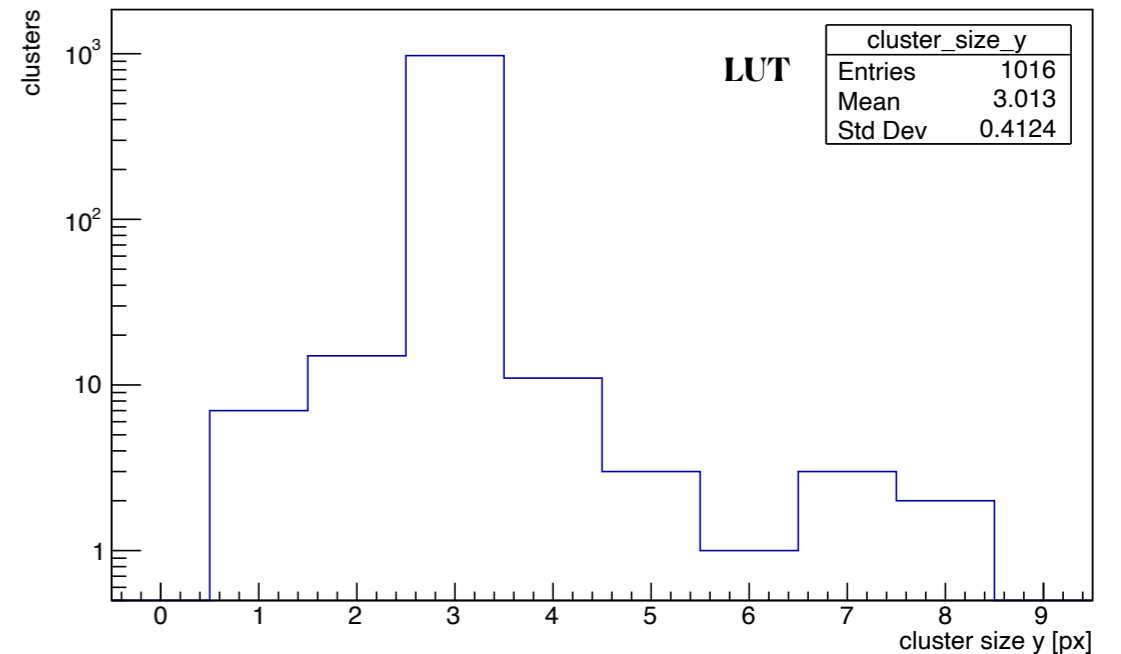
cluster_size_y	
Entries	1026
Mean	3.011
Std Dev	0.3935



Cluster size in Y (detector1)

LUT

cluster_size_y	
Entries	1016
Mean	3.013
Std Dev	0.4124

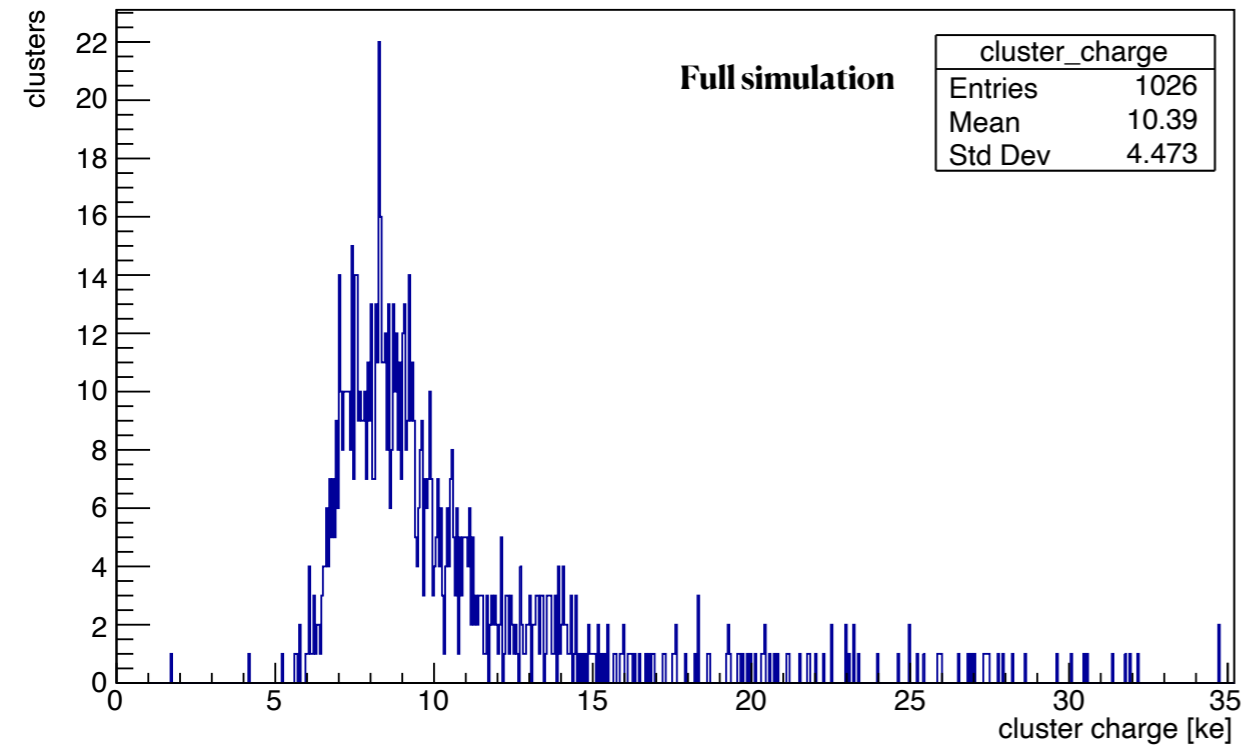


Rel err mean: 0.07%

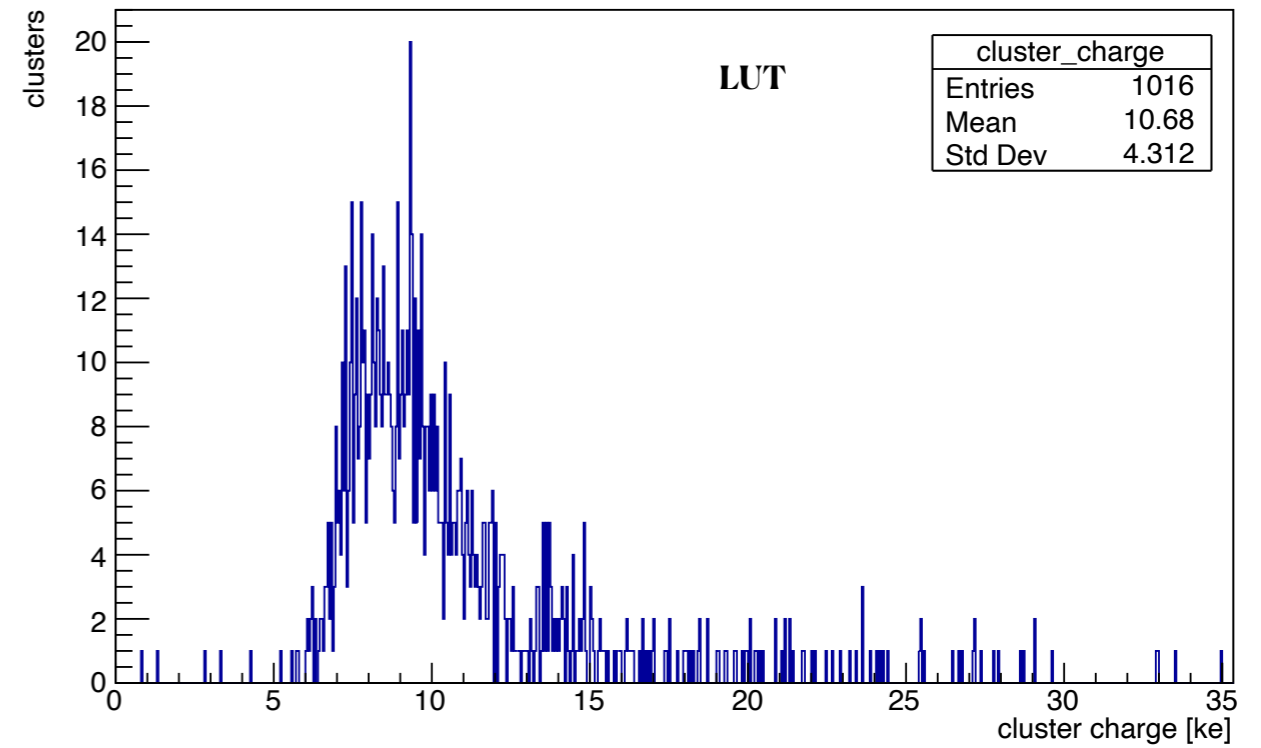
# Cluster charge

Pt = 100GeV, Eta = 1 ( $\theta_{trk} = 0.866$  rad), -0.25 rad phi

Cluster charge (detector1)



Cluster charge (detector1)

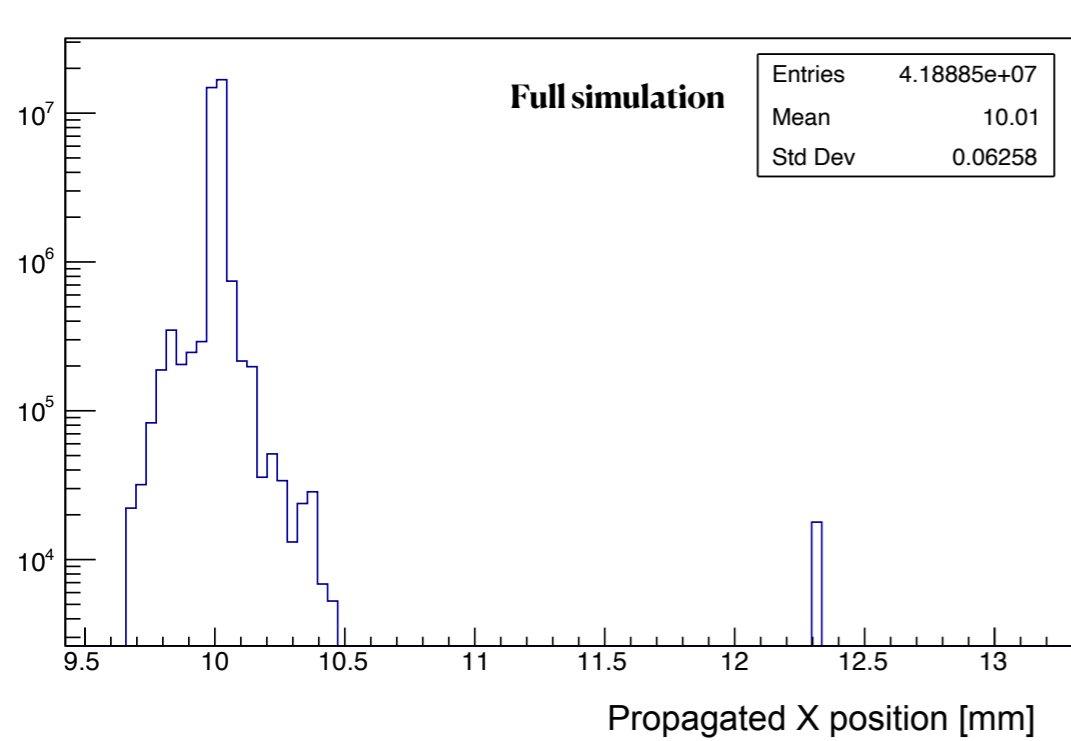


Rel err mean: 2.8%

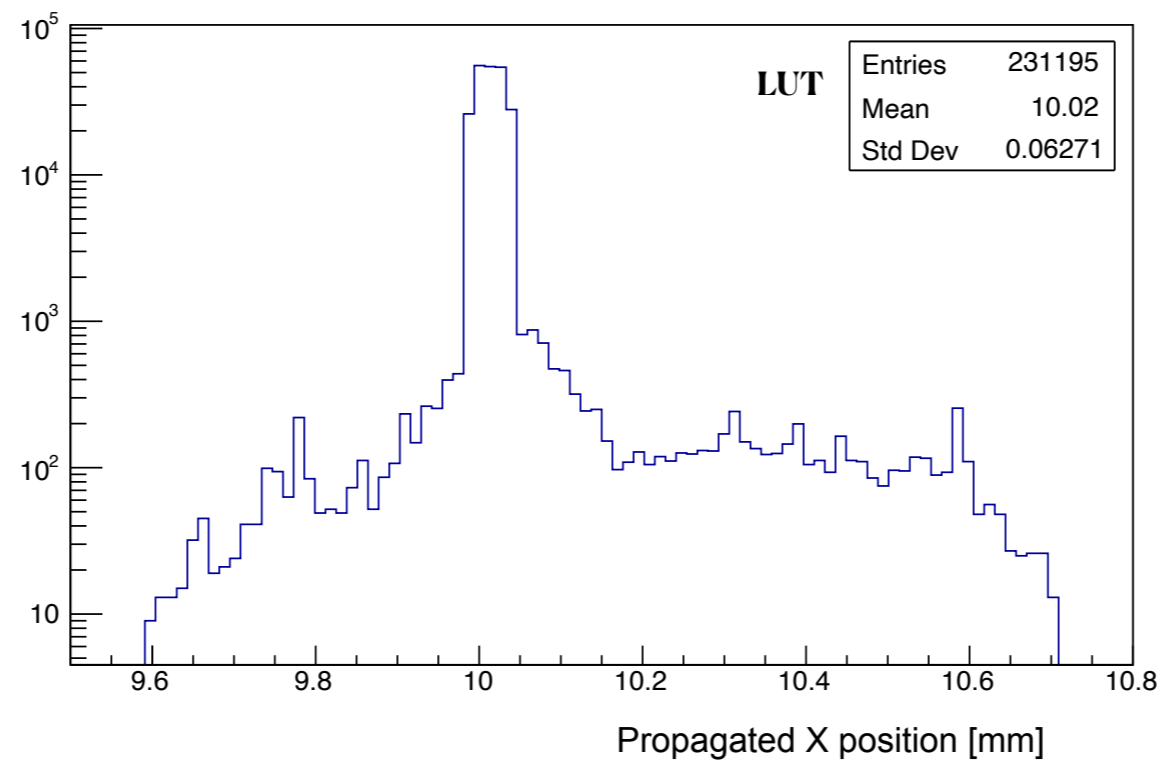
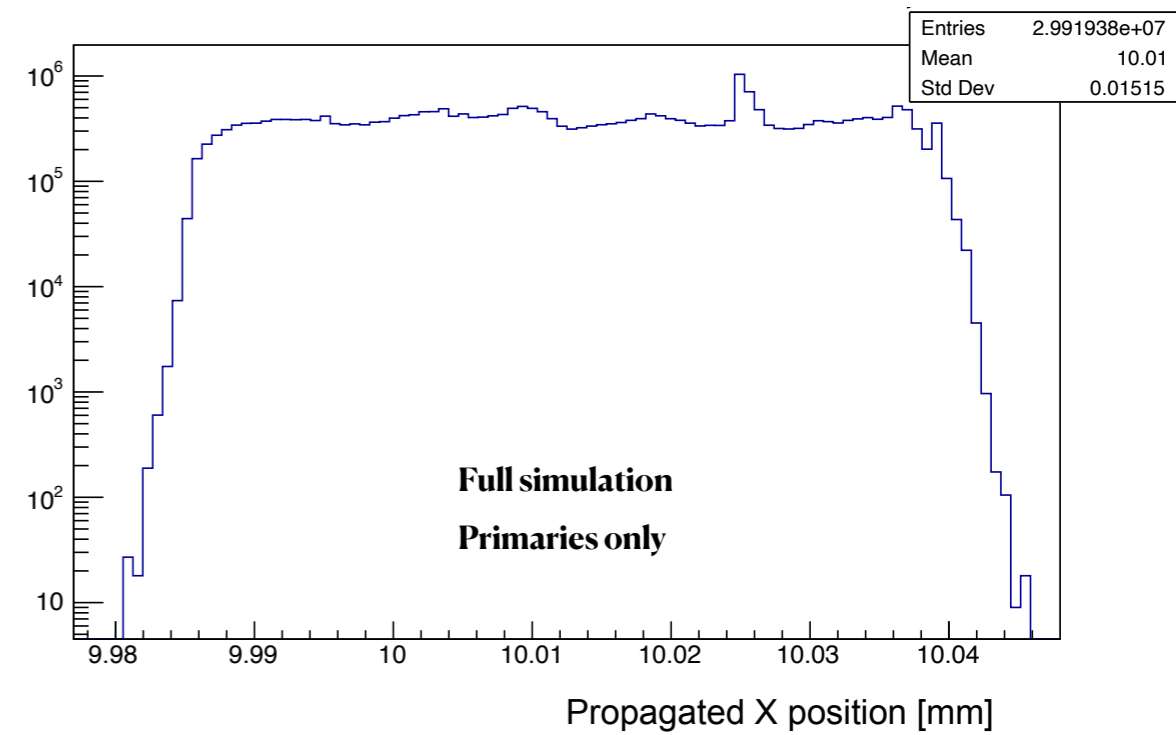
**$P_t = 100 \text{ GeV}, \eta = 1.4$**

# Propagated X Position

Pt = 100GeV, Eta = 1.4 ( $\theta_{trk} = 1.088$  rad), -0.25 rad phi



Filtering  
secondaries

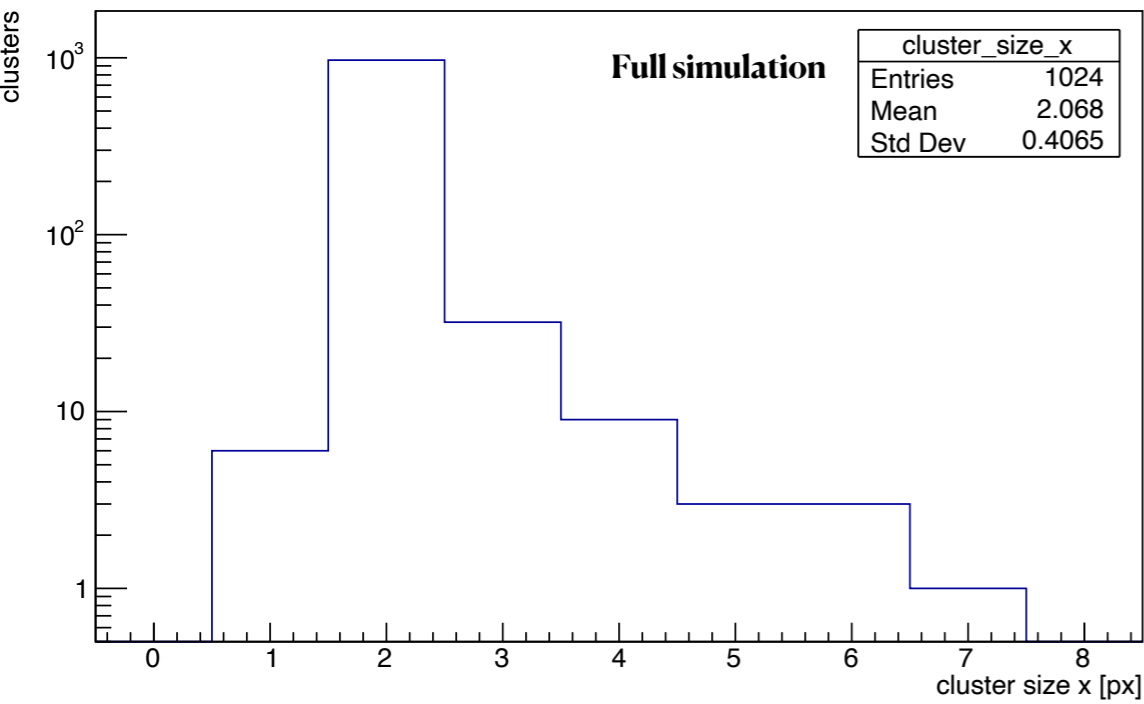


Diff = 10um  
diff/pitch = 0.2

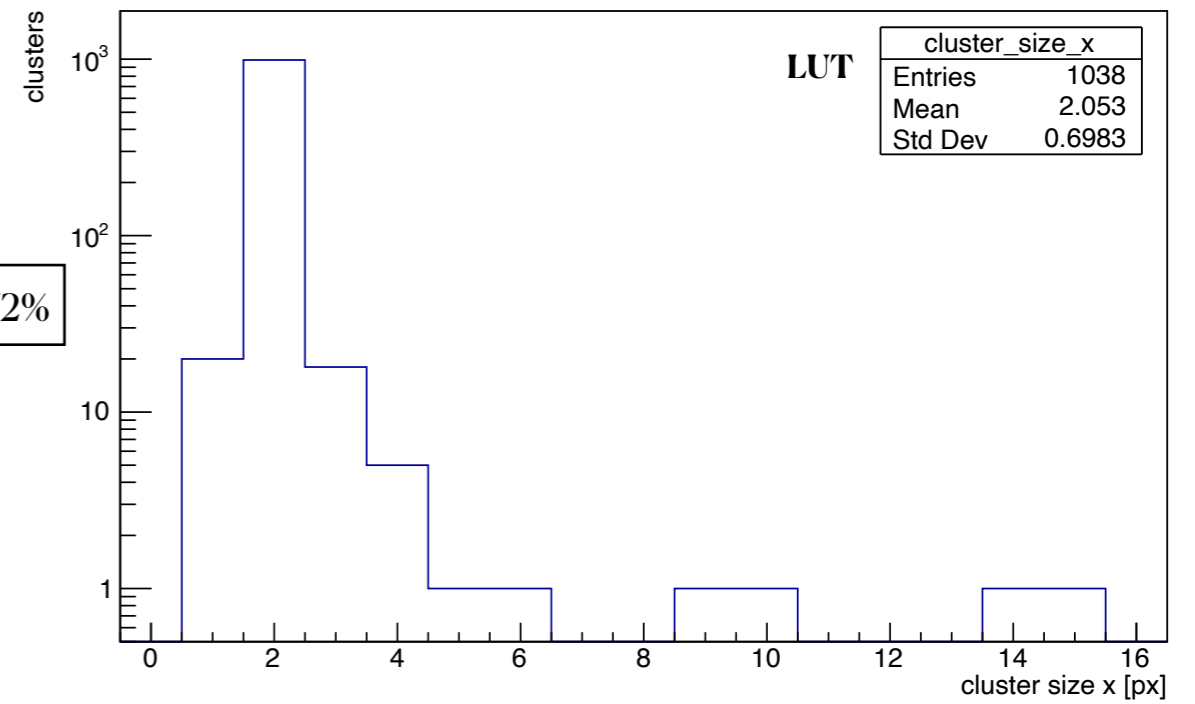
# Cluster size X & Y

Pt = 100GeV, Eta = 1.4 ( $\theta_{trk} = 1.088$  rad), -0.25 rad phi

Cluster size in X (detector1)

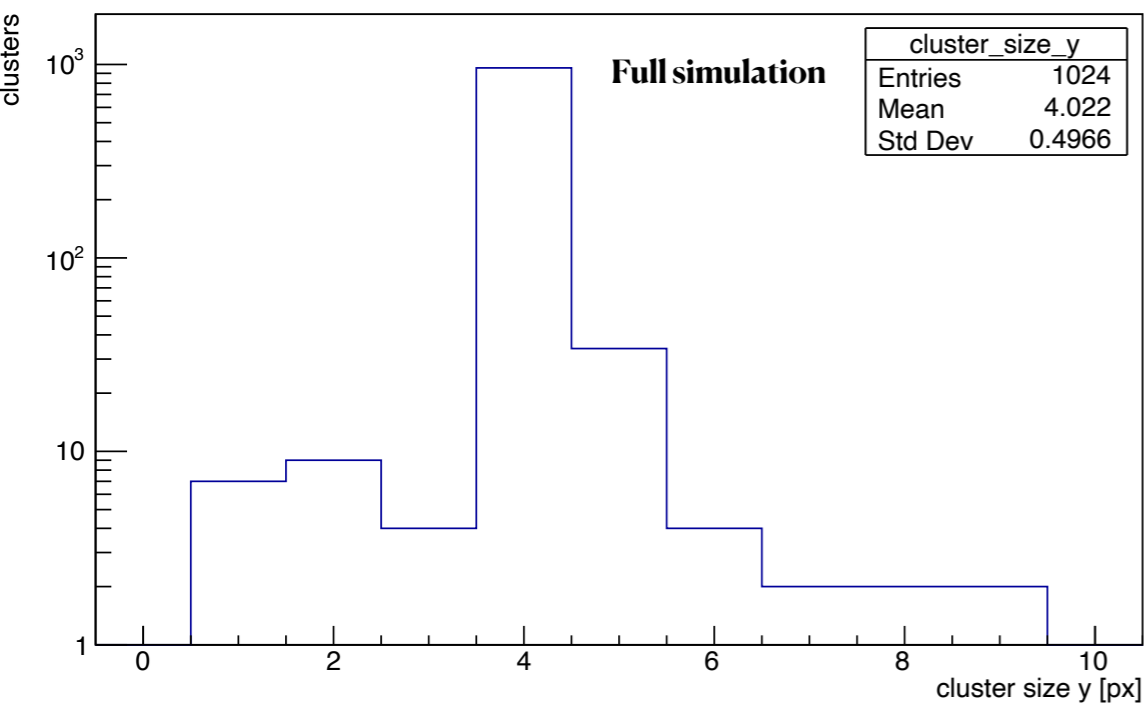


Cluster size in X (detector1)

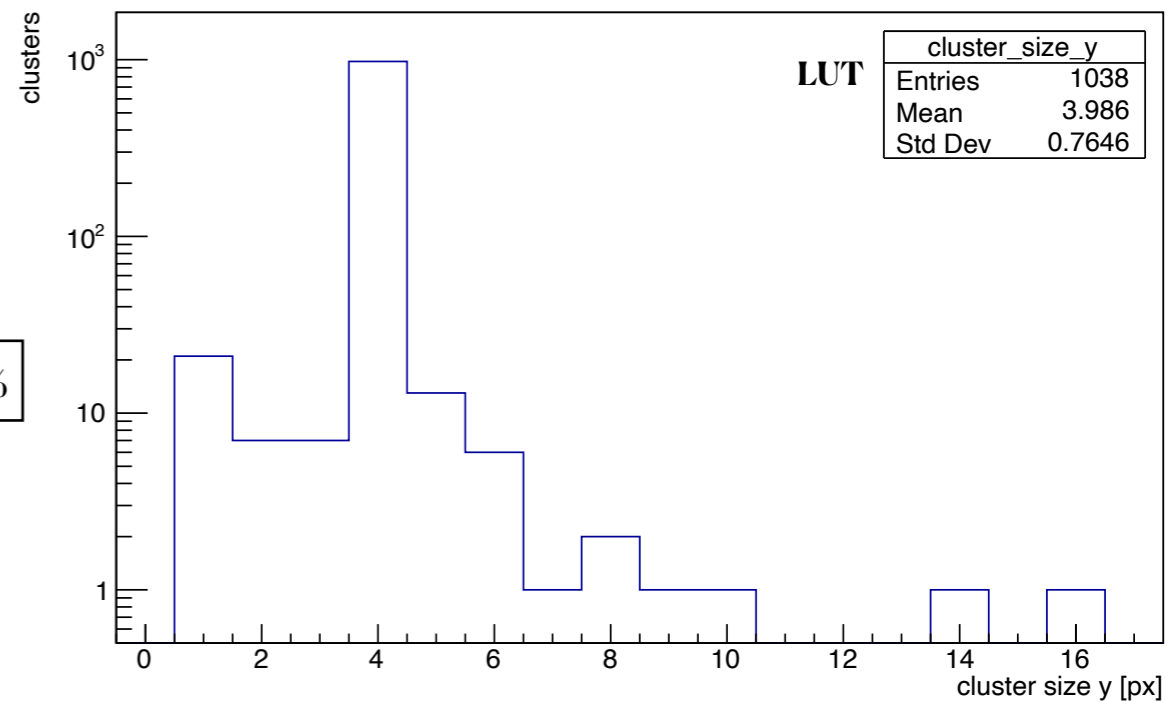


Rel err mean: 0.72%

Cluster size in Y (detector1)



Cluster size in Y (detector1)

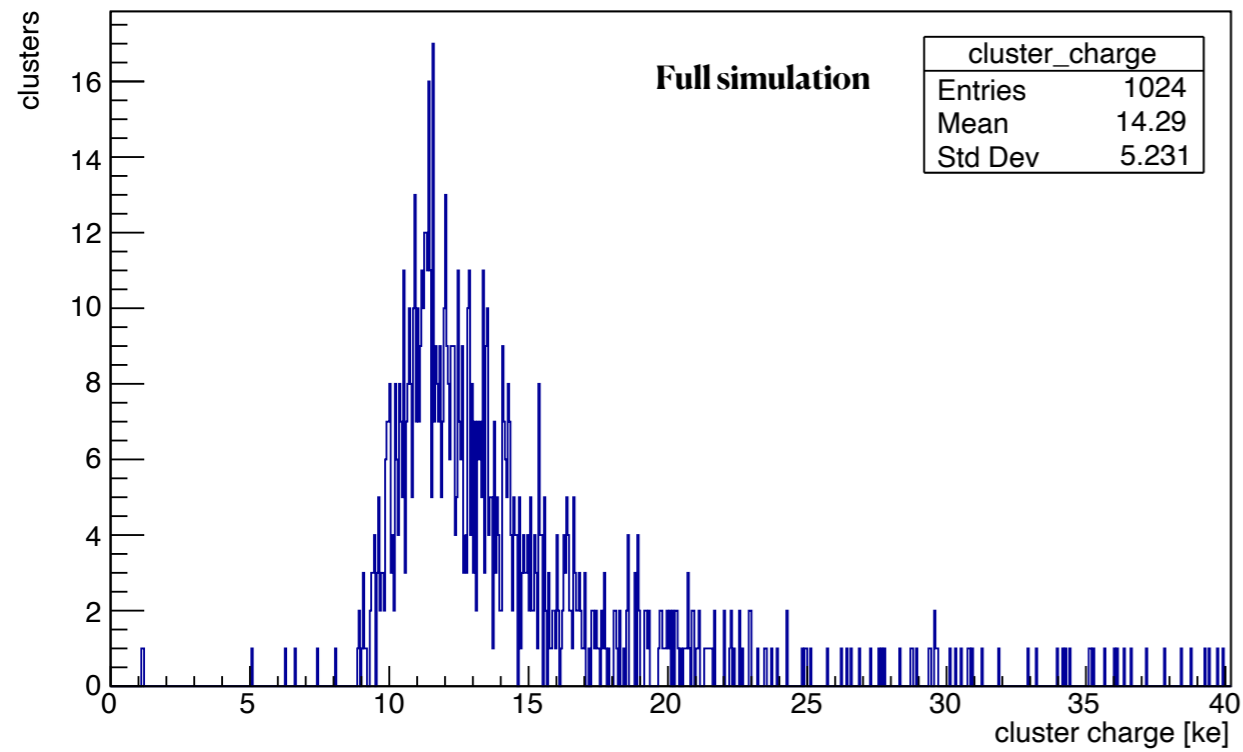


Rel err mean: 0.89%

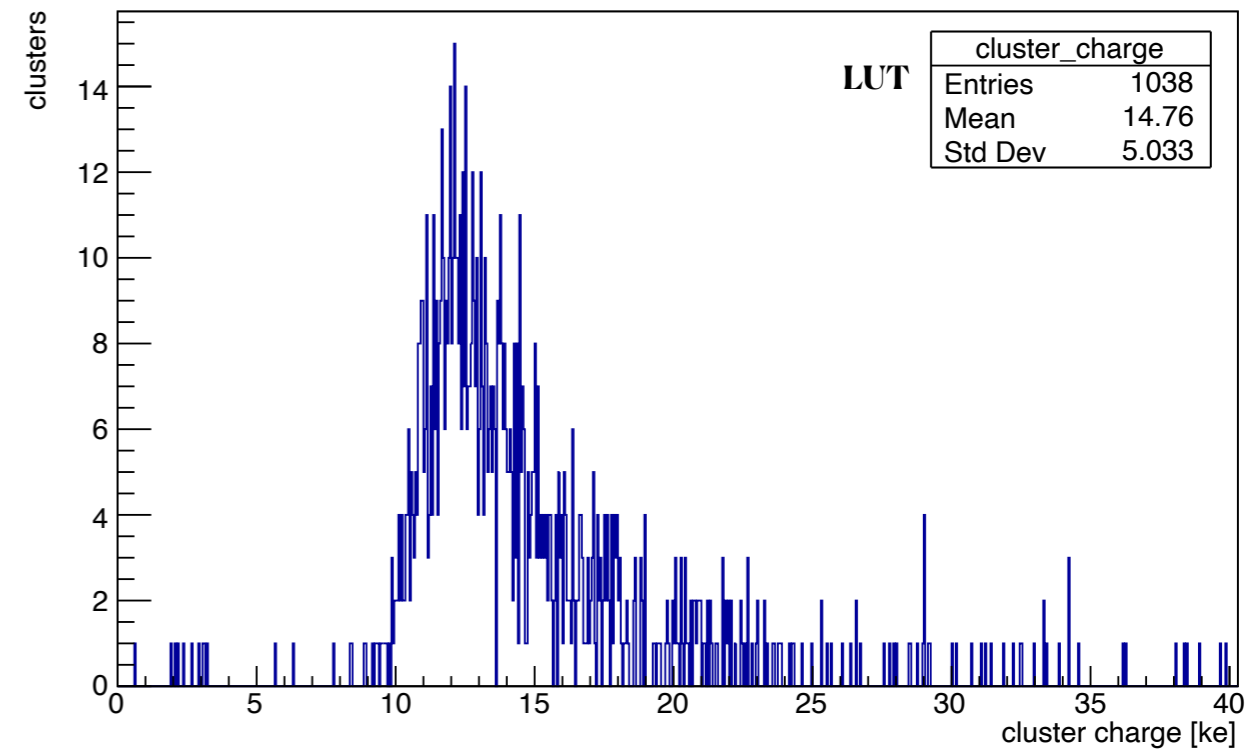
# Cluster charge

Pt = 100GeV, Eta = 1.4 ( $\theta_{trk} = 1.088$  rad), -0.25 rad phi

Cluster charge (detector1)



Cluster charge (detector1)



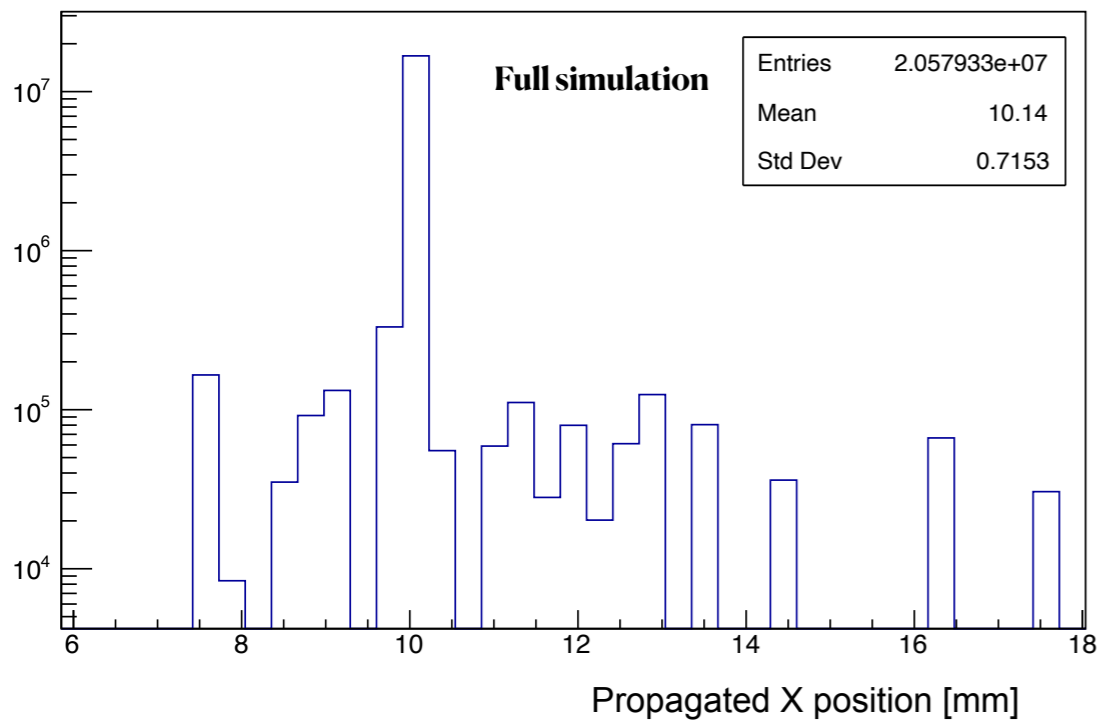
Rel err mean: 3.3%

**$P_t = 10 \text{ GeV}, \eta = 0$**

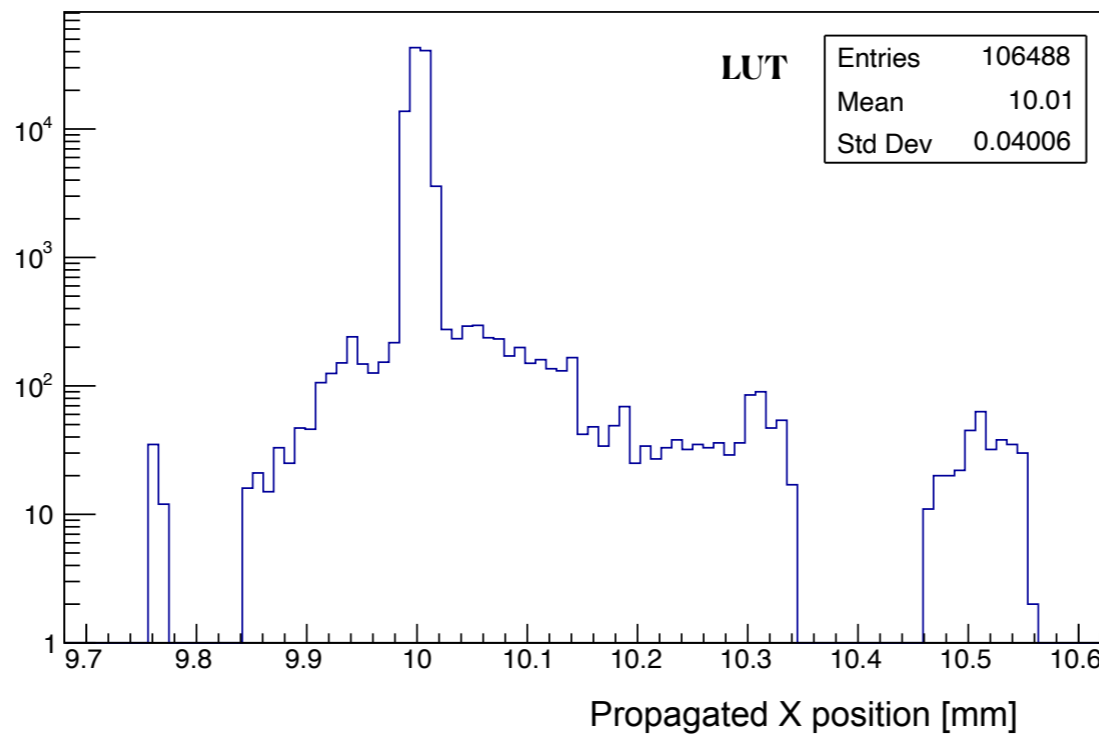
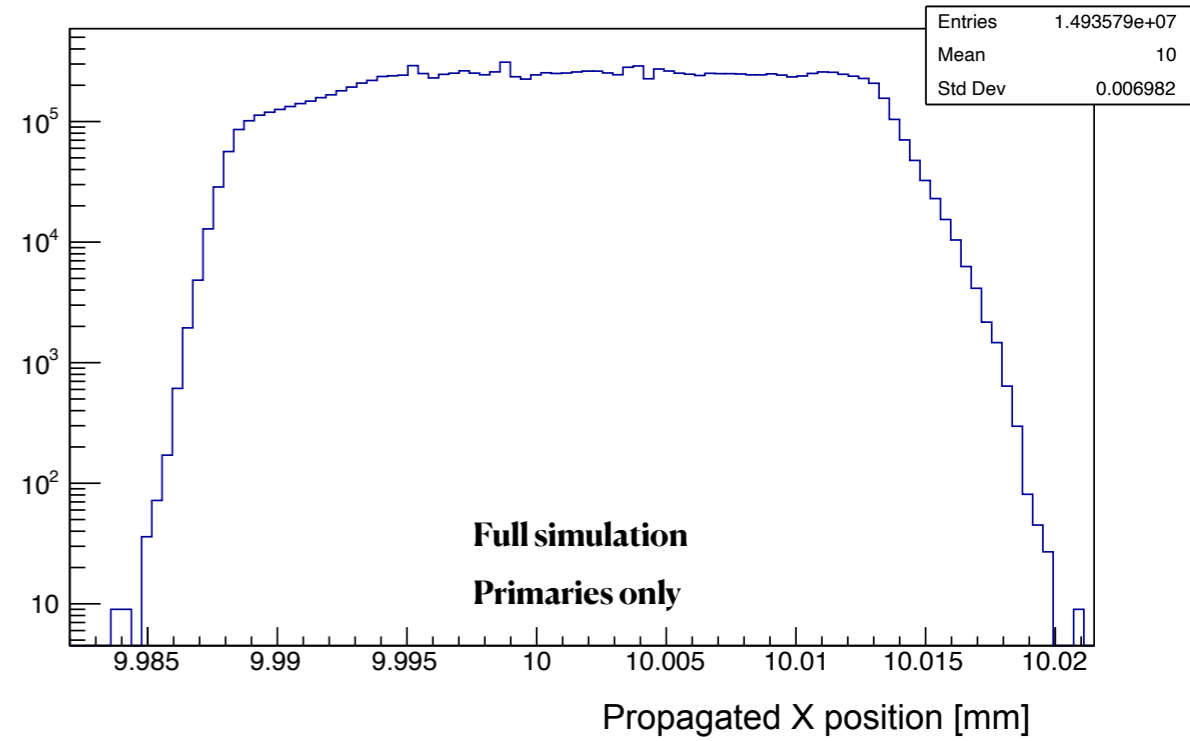


# Propagated X Position

Pt = 10GeV, Eta = 0 ( $\theta_{trk} = 0$  rad), -0.25 rad phi



Filtering  
secondaries

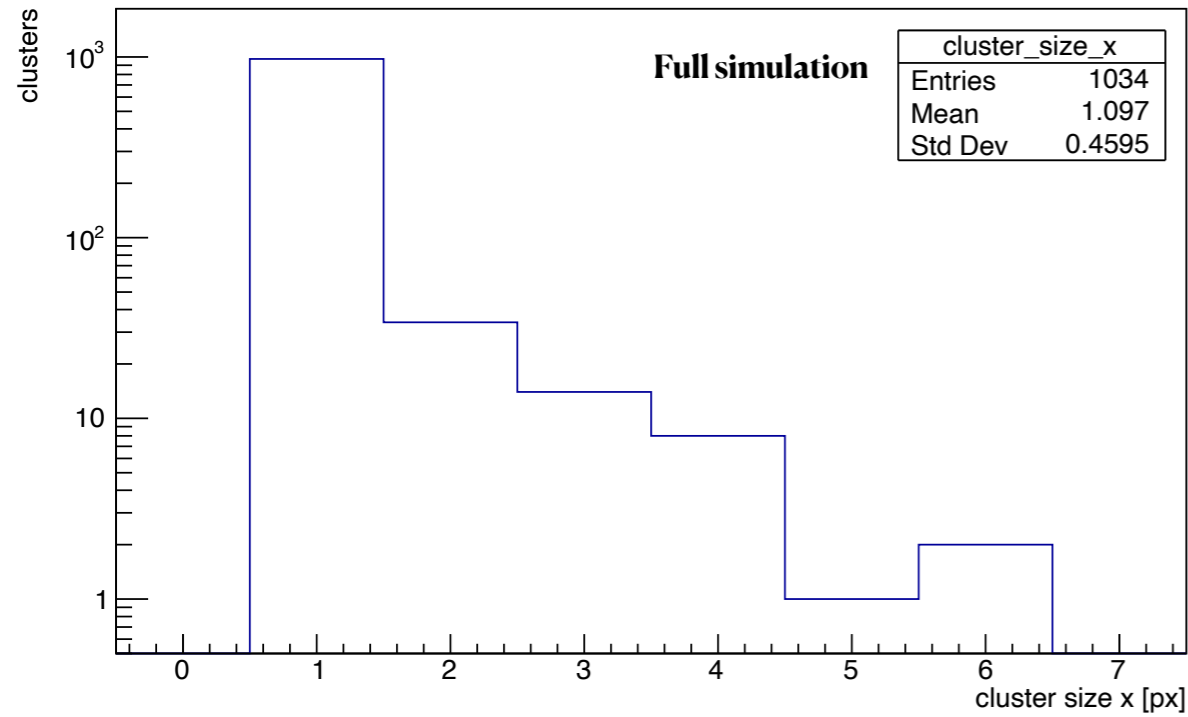


Diff = 1 $\mu$ m  
Diff/pitch = 0.2

# Cluster size X & Y

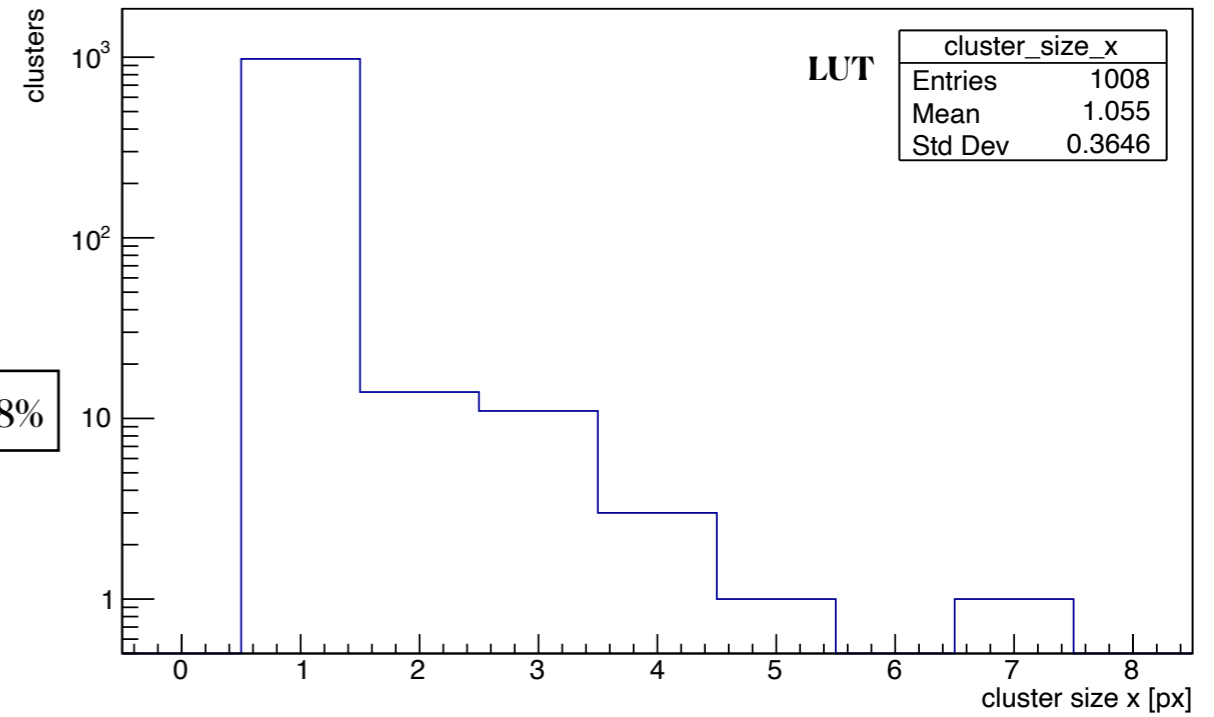
Pt = 10GeV, Eta = 0 ( $\theta_{trk} = 0$  rad), -0.25 rad phi

Cluster size in X (detector1)

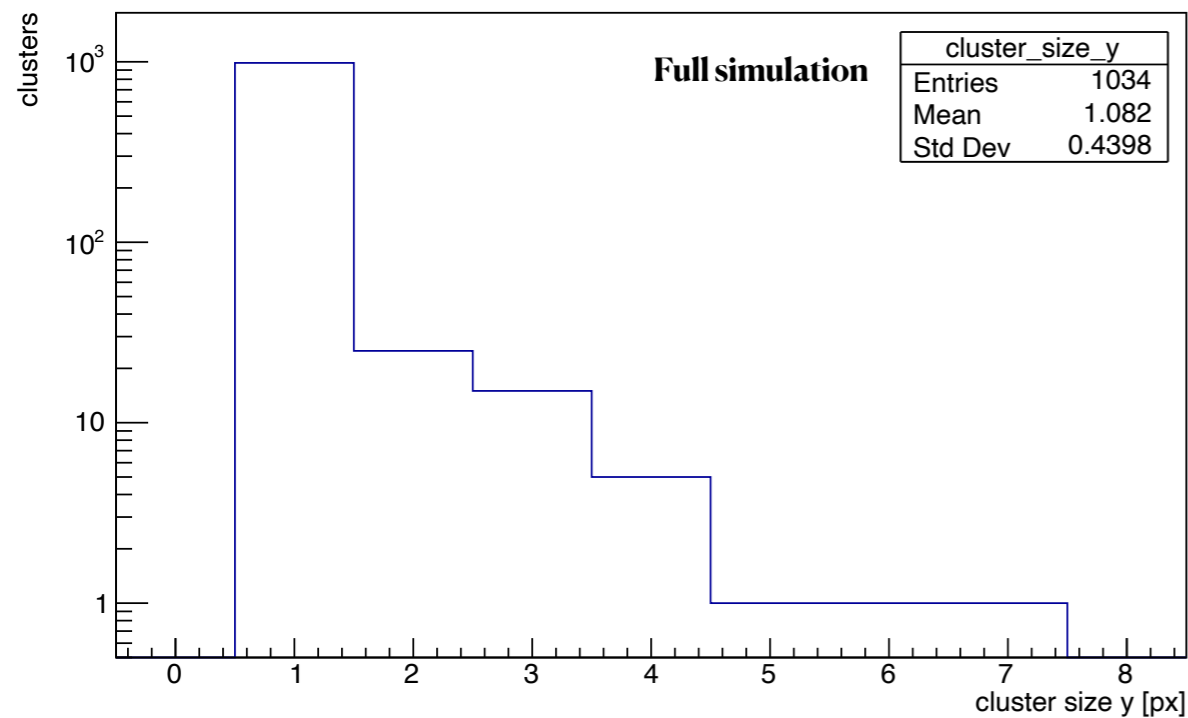


Rel err mean: 3.8%

Cluster size in X (detector1)

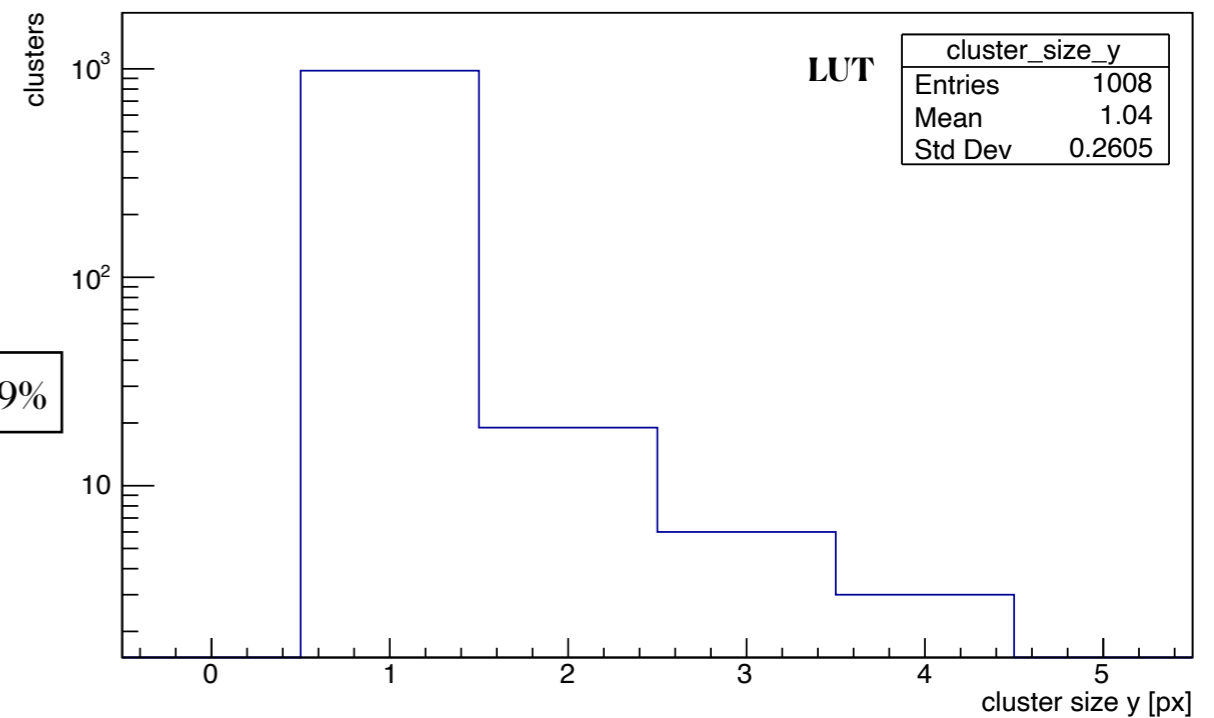


Cluster size in Y (detector1)



Rel err mean: 3.9%

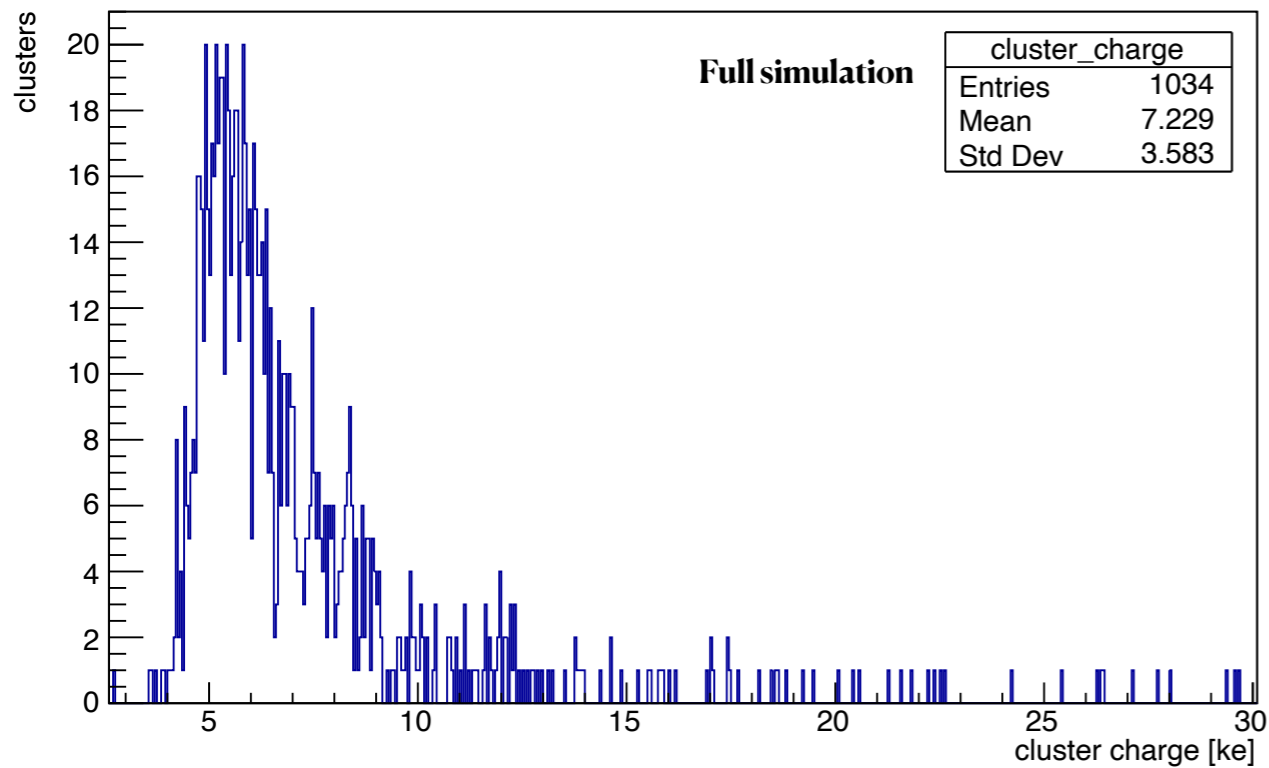
Cluster size in Y (detector1)



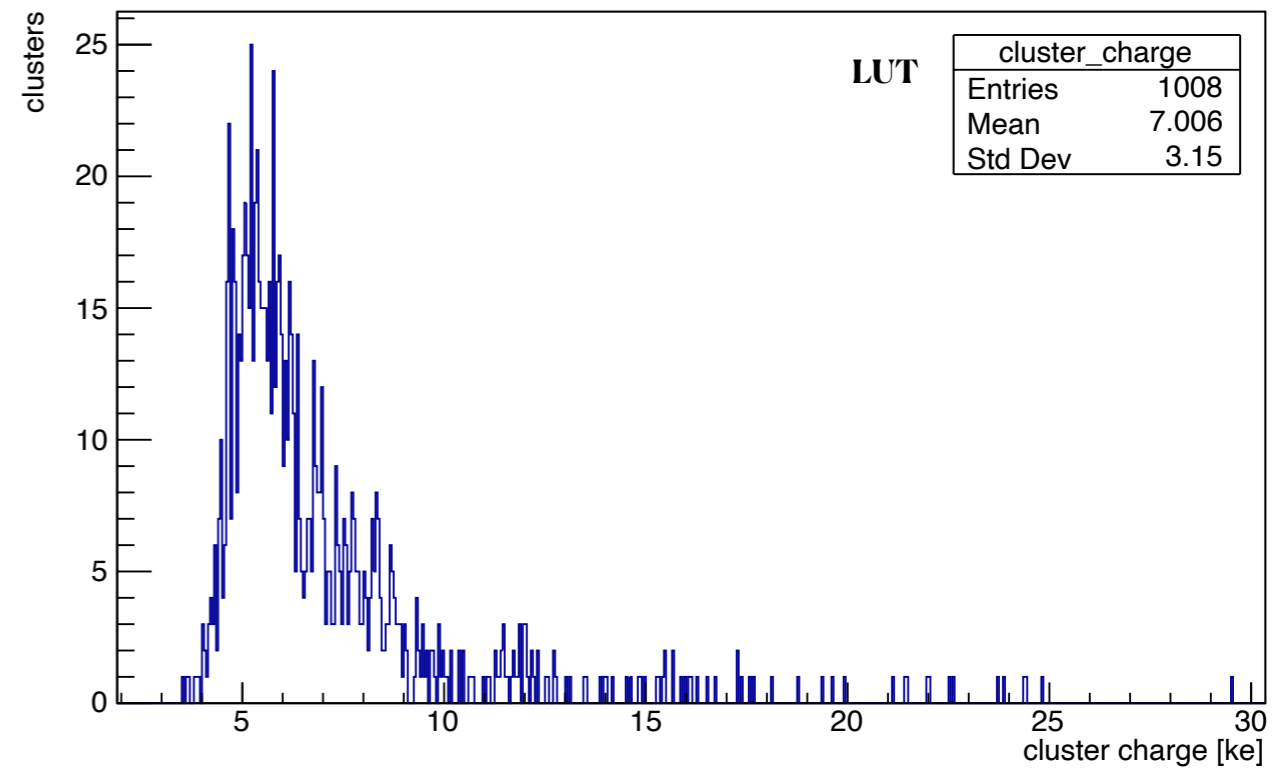
# Cluster charge

Pt = 10GeV, Eta = 0 ( $\theta_{trk} = 0$  rad), -0.25 rad phi

Cluster charge (detector1)



Cluster charge (detector1)

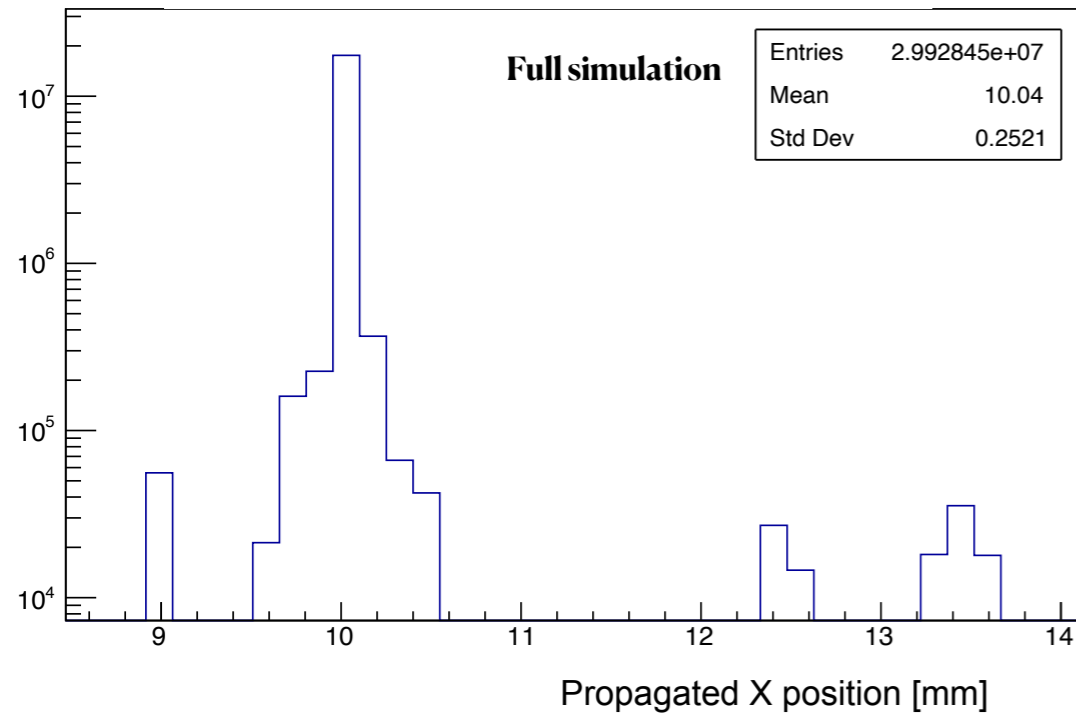


Rel err mean: 3.1%

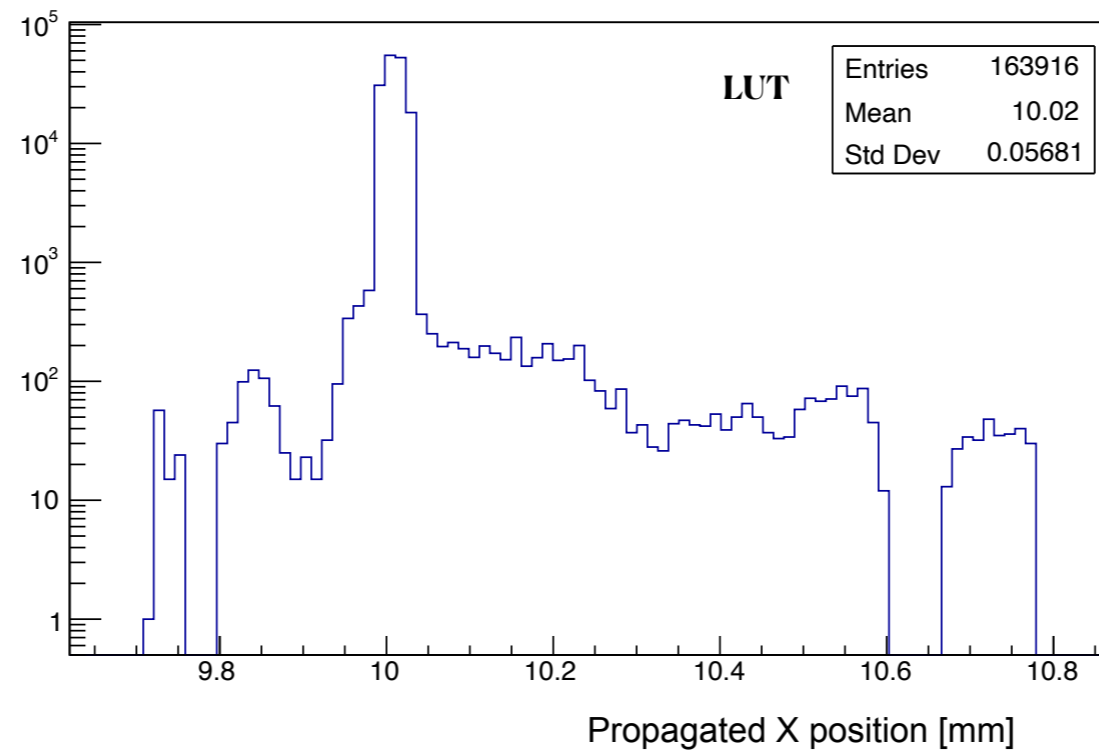
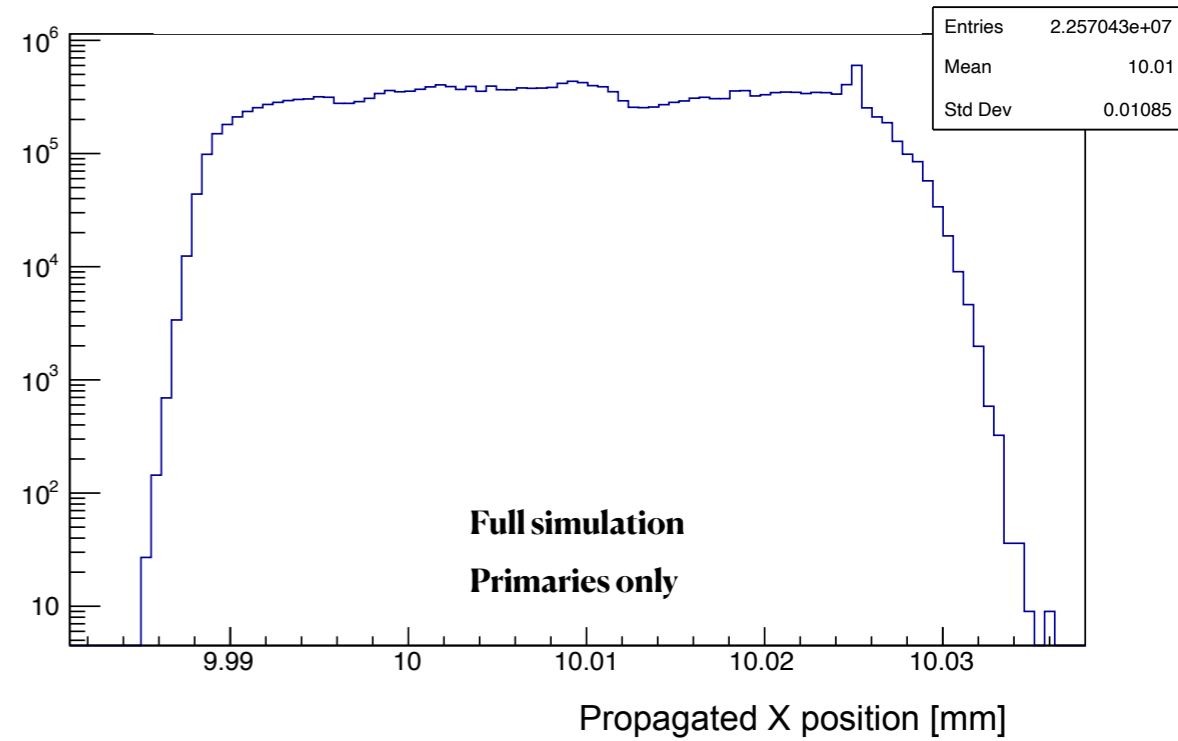
**$P_t = 10 \text{ GeV}, \eta = 1$**

# Propagated X Position

Pt = 10GeV, Eta = 1 ( $\theta_{trk} = 0.866$  rad), -0.25 rad phi



Filtering  
secondaries

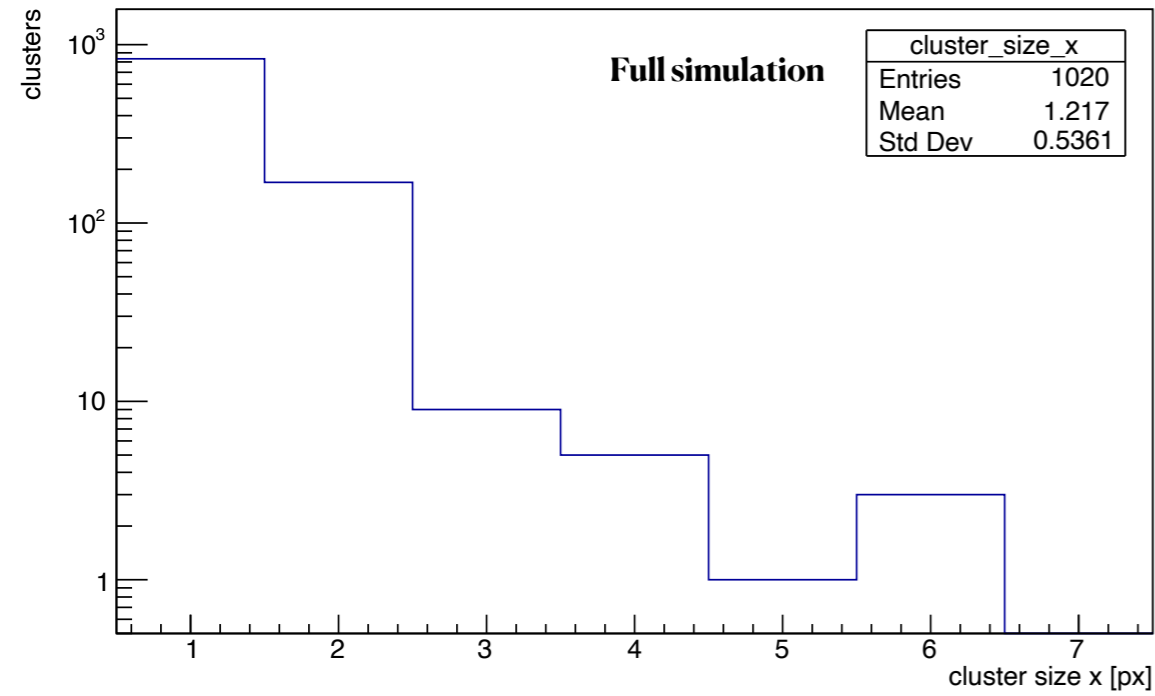


Diff = 10um  
Normalised diff = 0.2

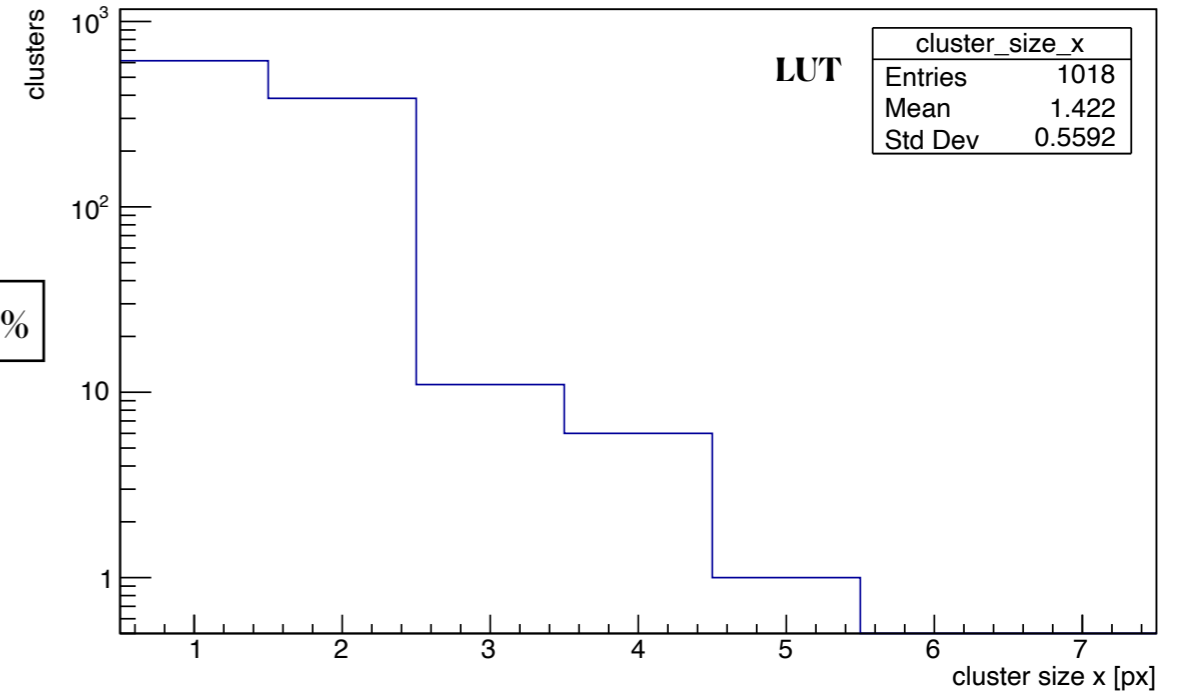
# Cluster size X & Y

Pt = 10GeV, Eta = 1 ( $\theta_{trk} = 0.866$  rad), -0.25 rad phi

Cluster size in X (detector1)

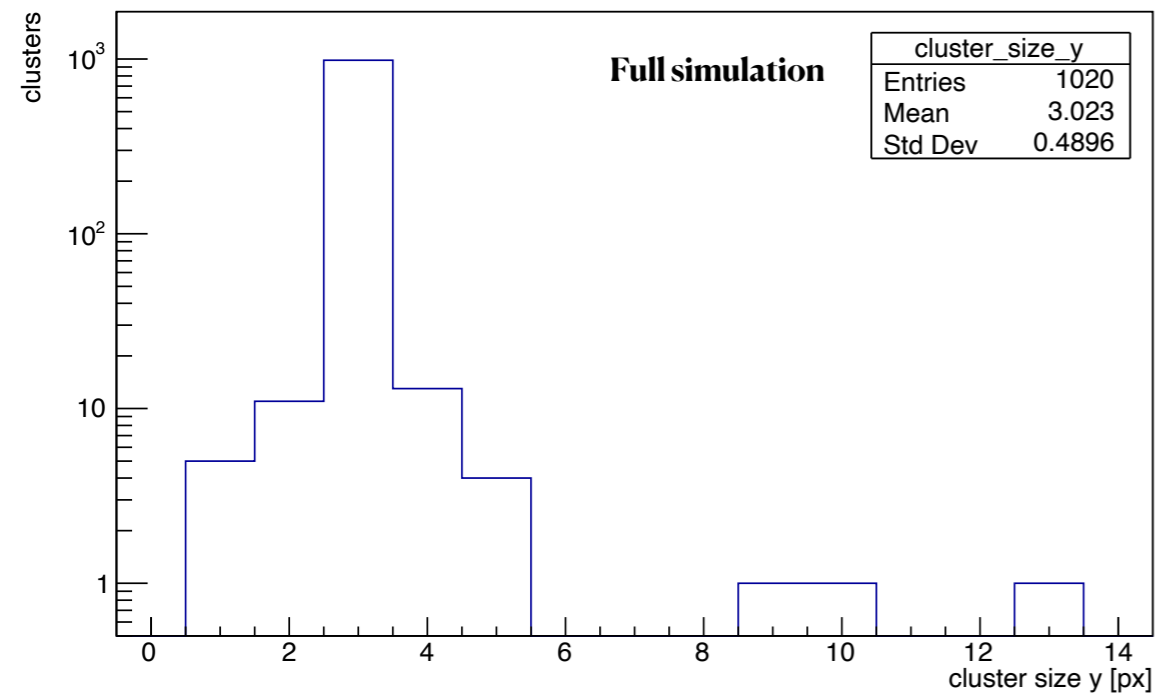


Cluster size in X (detector1)

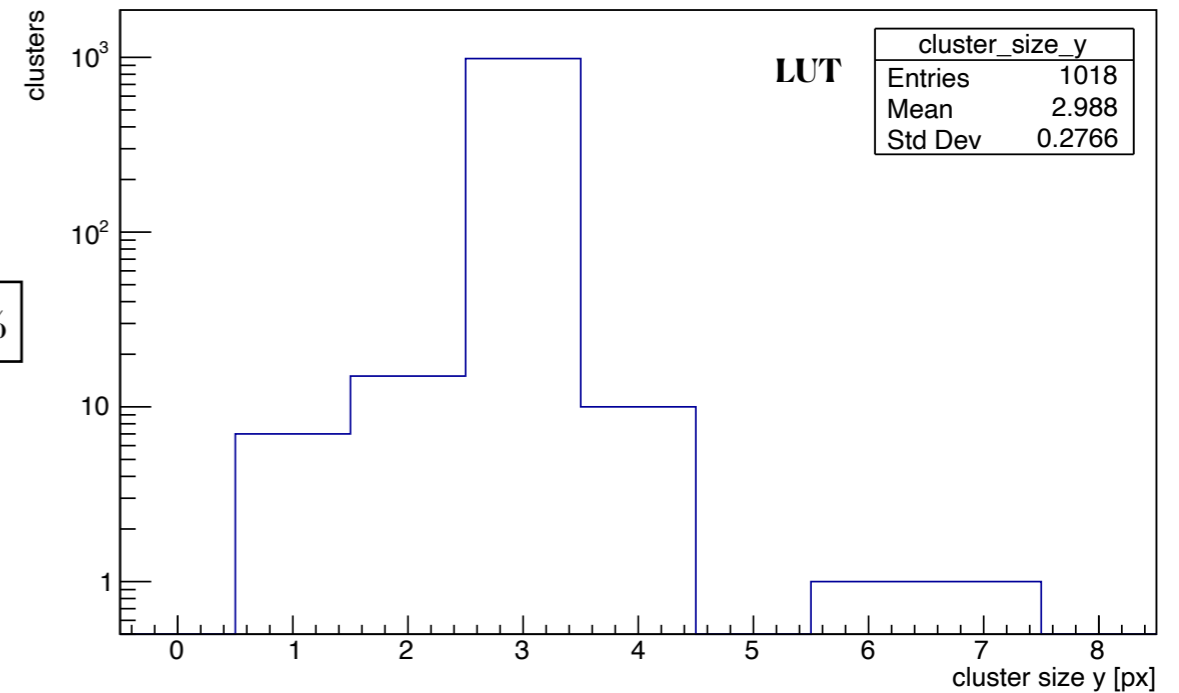


Rel err mean: 16.8 %

Cluster size in Y (detector1)



Cluster size in Y (detector1)

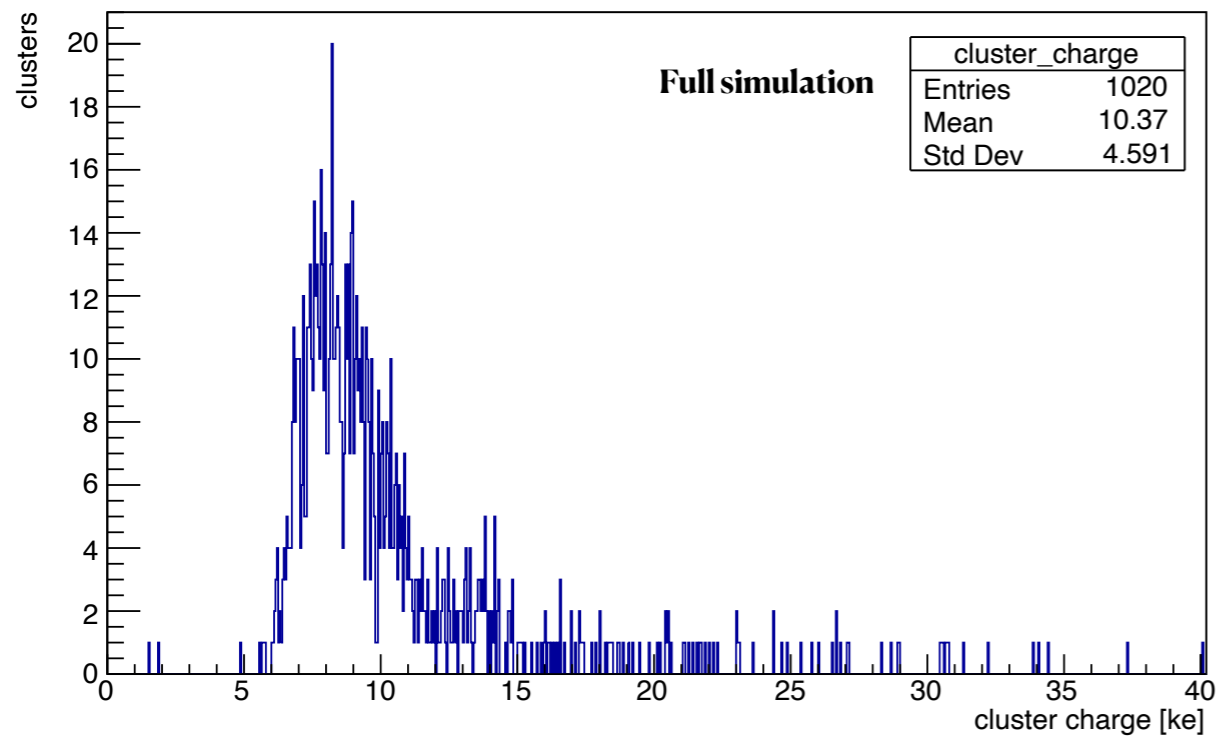


Rel err mean: 1.2 %

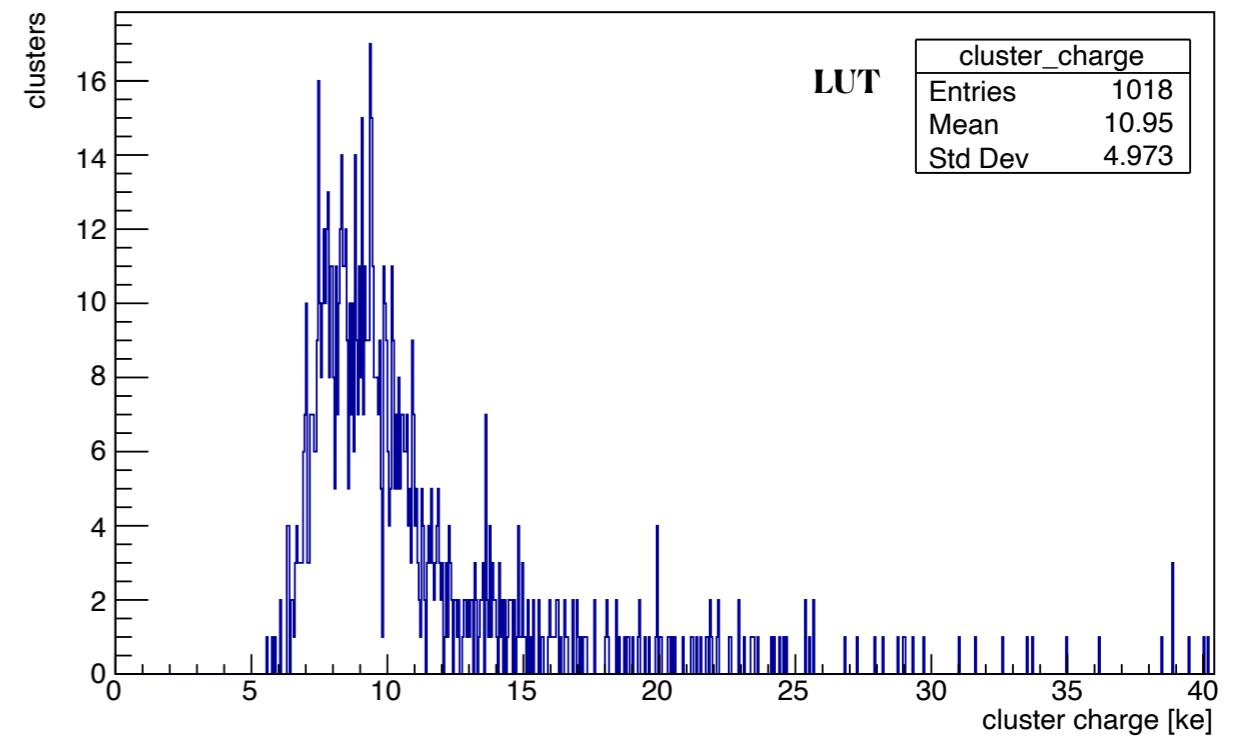
# Cluster charge

Pt = 10GeV, Eta = 1 ( $\theta_{trk} = 0.866$  rad), -0.25 rad phi

Cluster charge (detector1)



Cluster charge (detector1)



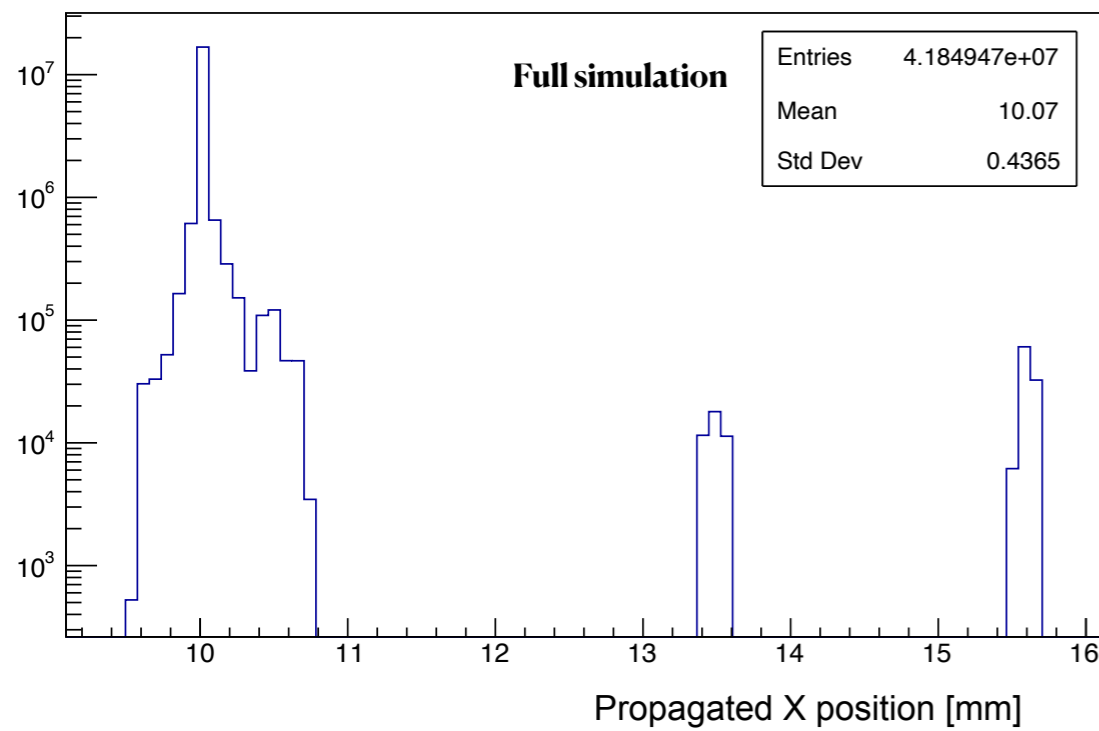
Rel err mean: 5.6%

**$P_t = 10 \text{ GeV}, \eta = 1.4$**

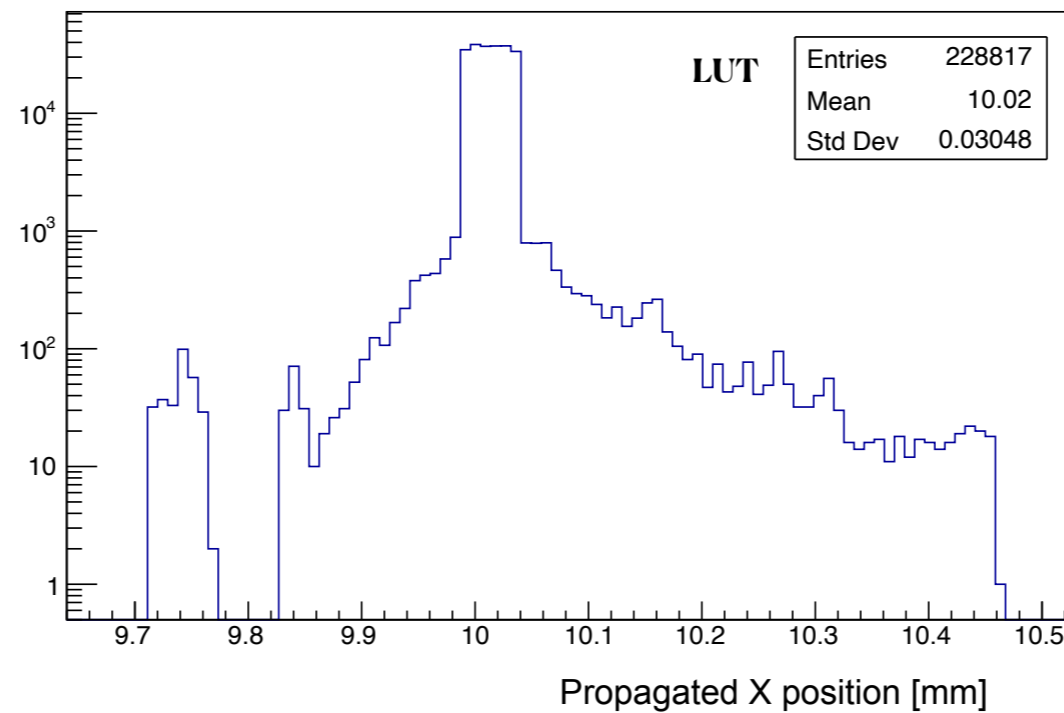
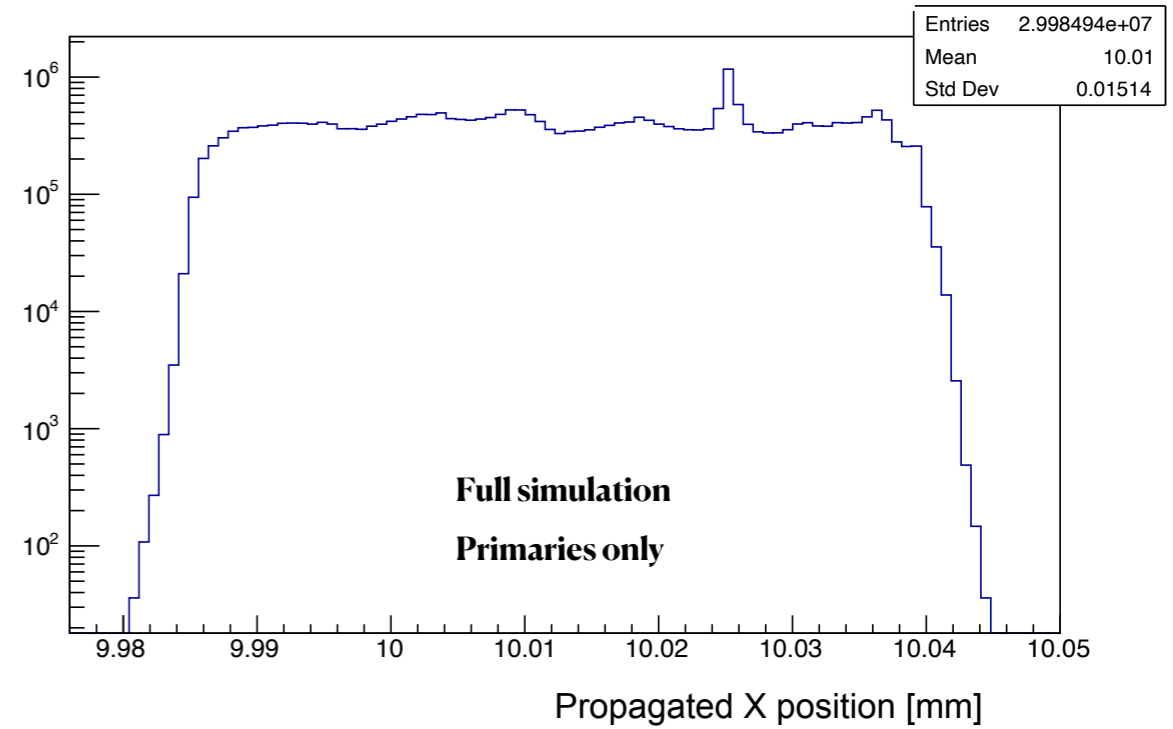


# Propagated X Position

Pt = 10GeV, Eta = 1.4 ( $\theta_{trk} = 1.088$  rad), -0.25 rad phi



Filtering  
secondaries  
→

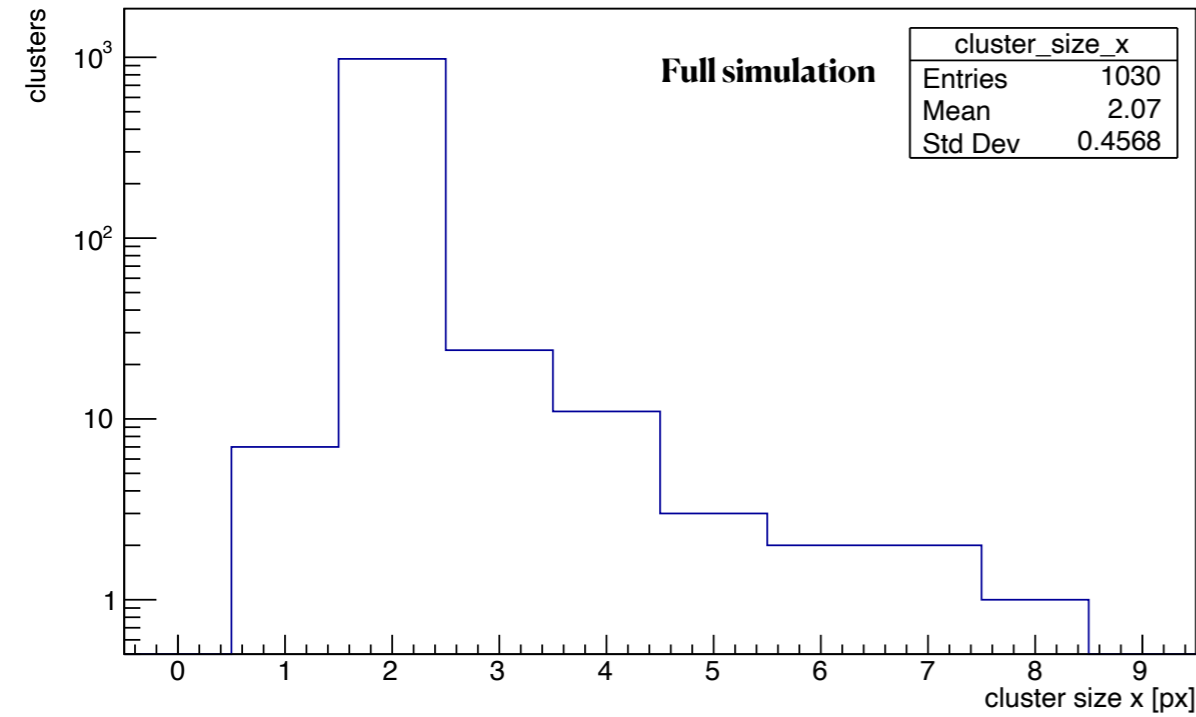


Diff = 10um  
Diff/pitch = 0.2

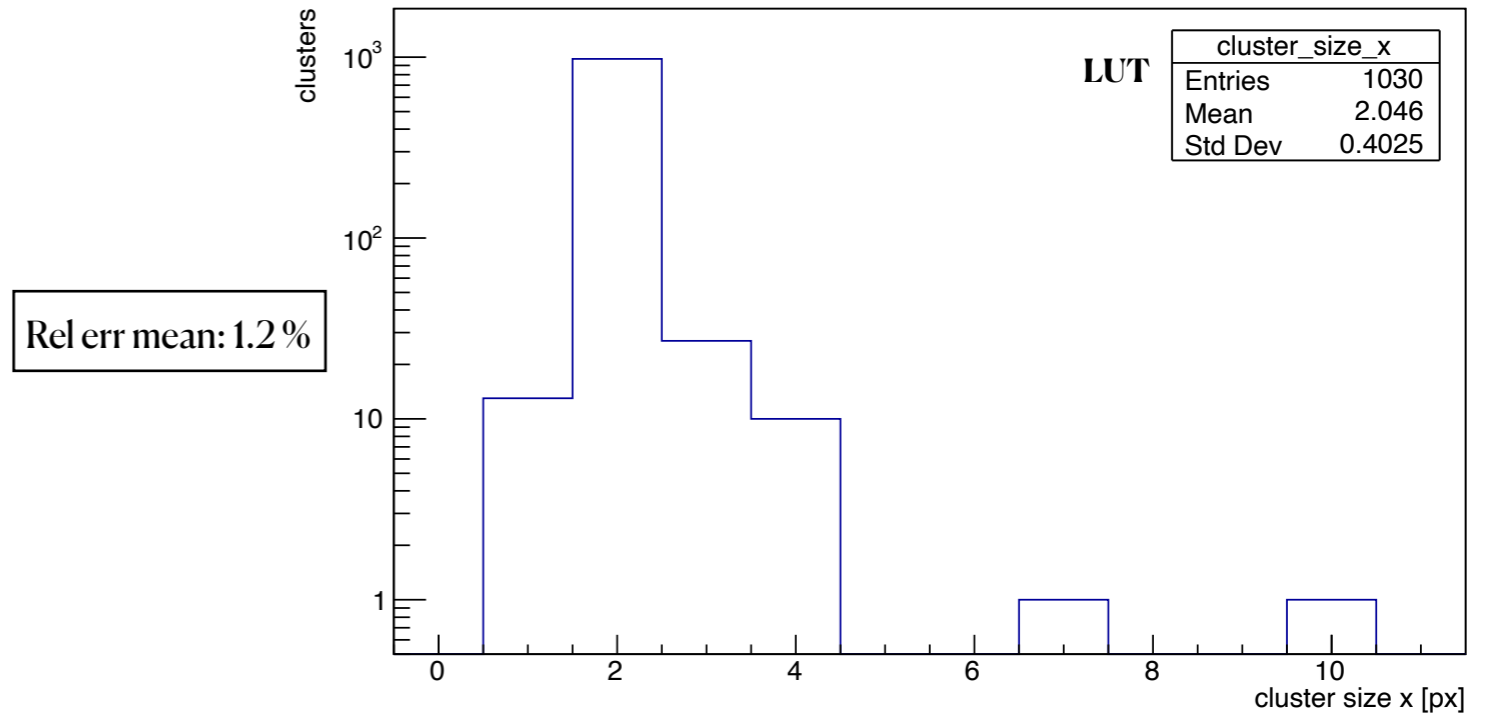
# Cluster size X & Y

Pt = 10GeV, Eta = 1.4 ( $\theta_{trk} = 1.088$  rad), -0.25 rad phi

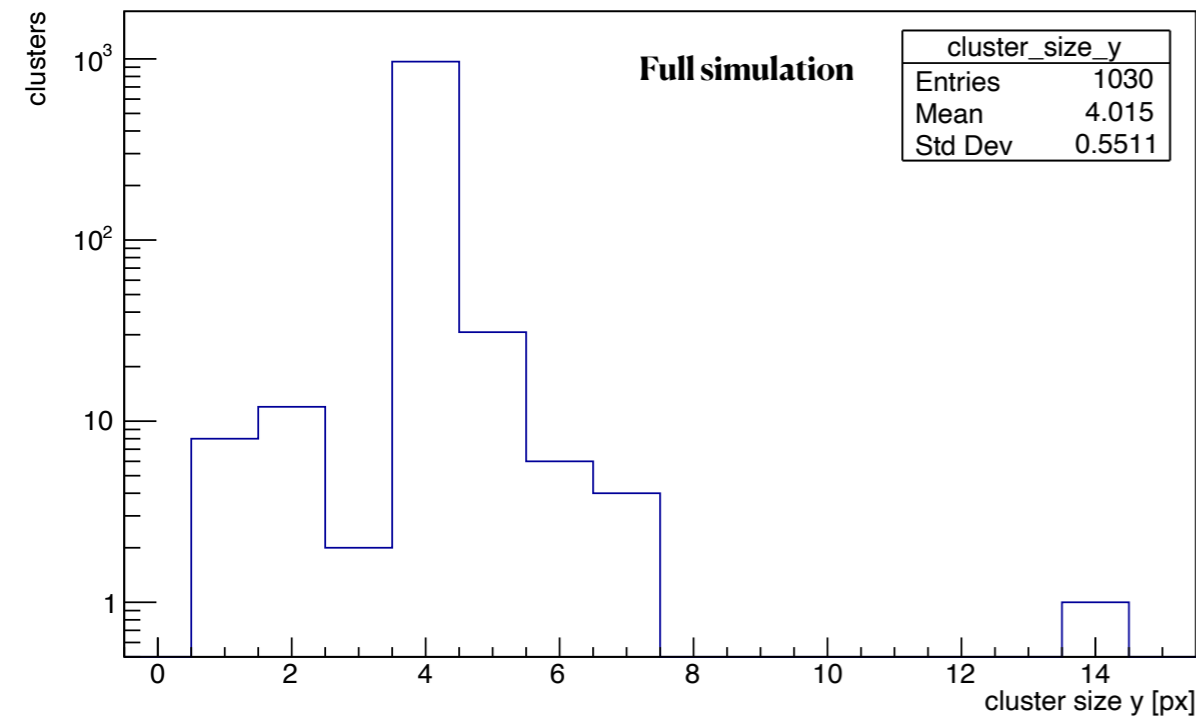
Cluster size in X (detector1)



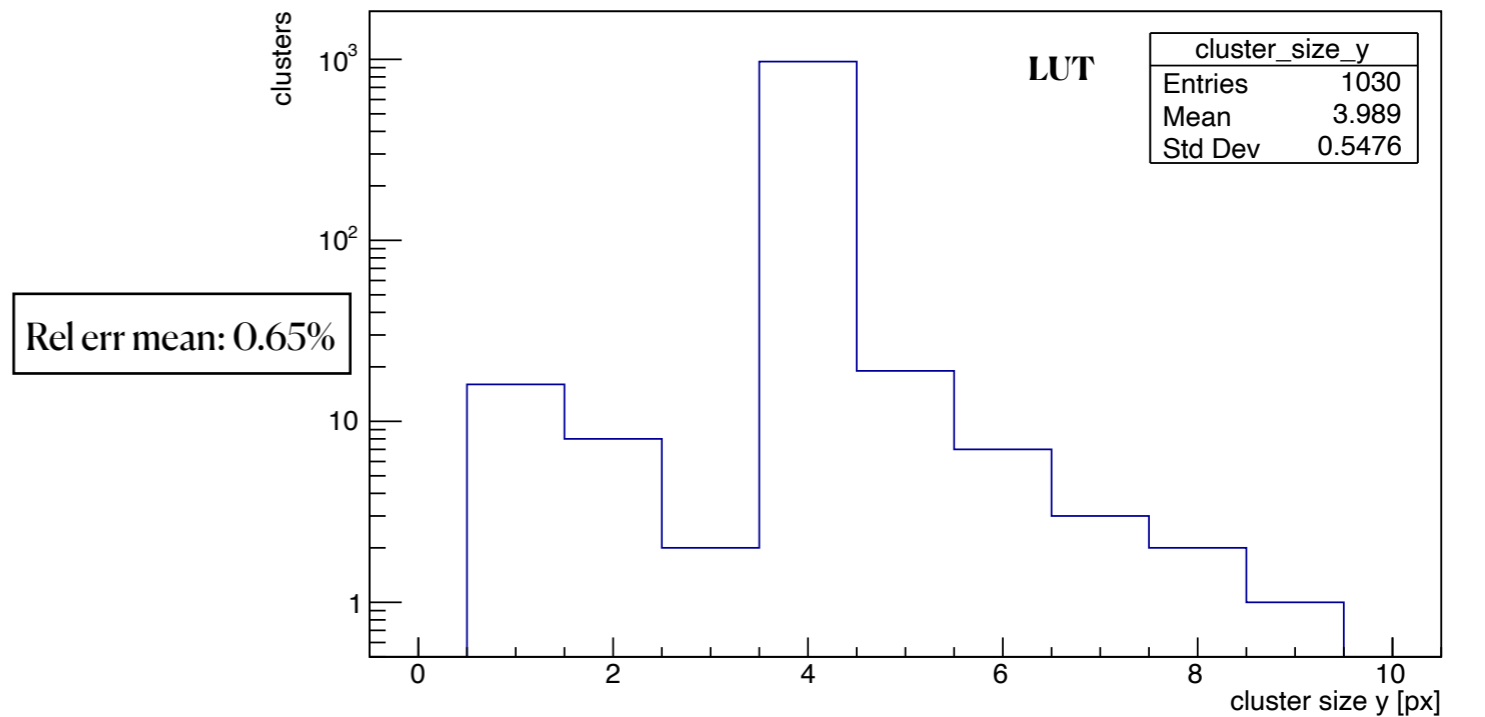
Cluster size in X (detector1)



Cluster size in Y (detector1)



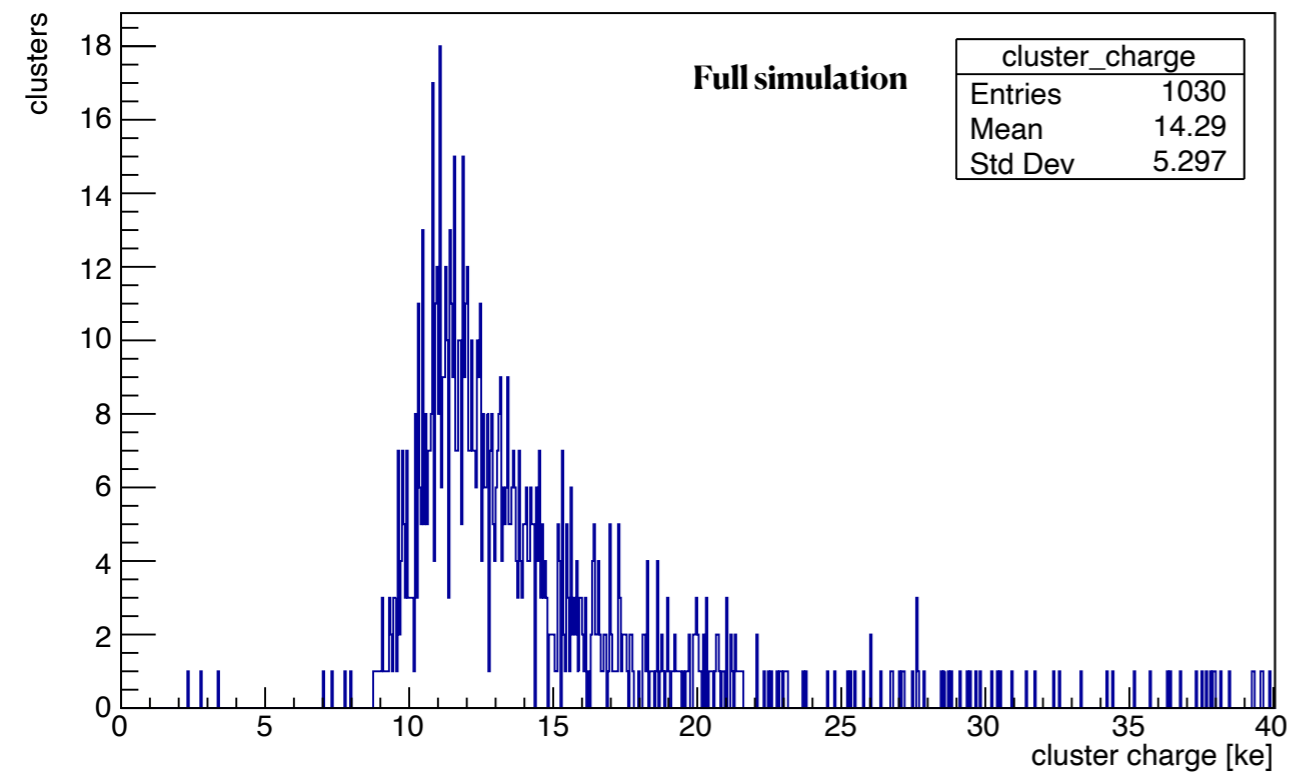
Cluster size in Y (detector1)



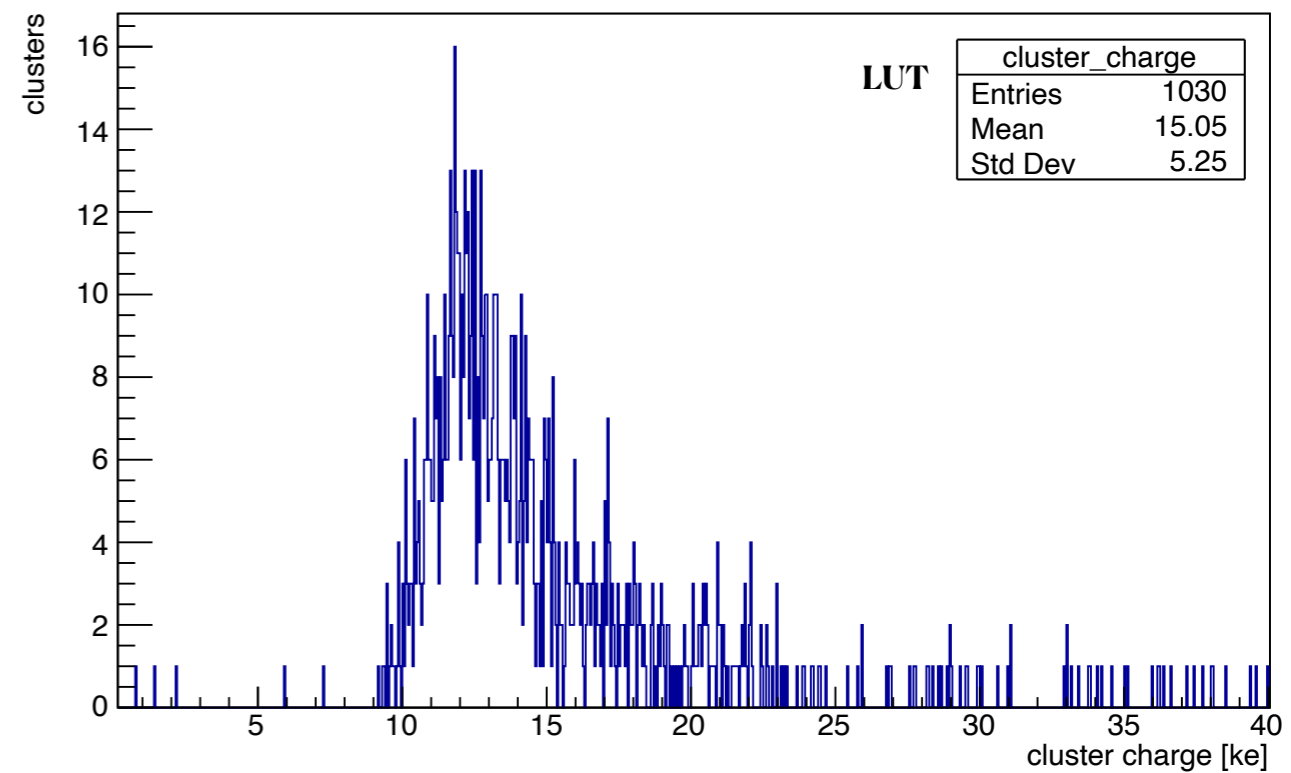
# Cluster charge

Pt = 10 GeV, Eta = 1.4 ( $\theta_{trk} = 1.088$  rad), -0.25 rad phi

Cluster charge (detector1)



Cluster charge (detector1)

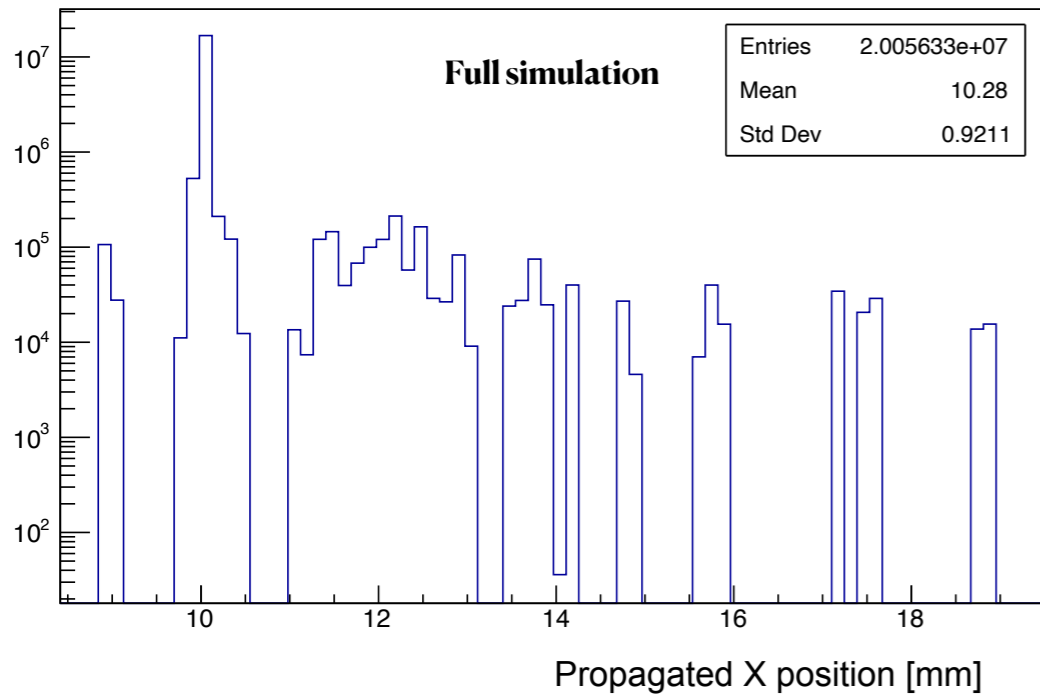


Rel err mean: 5.32%

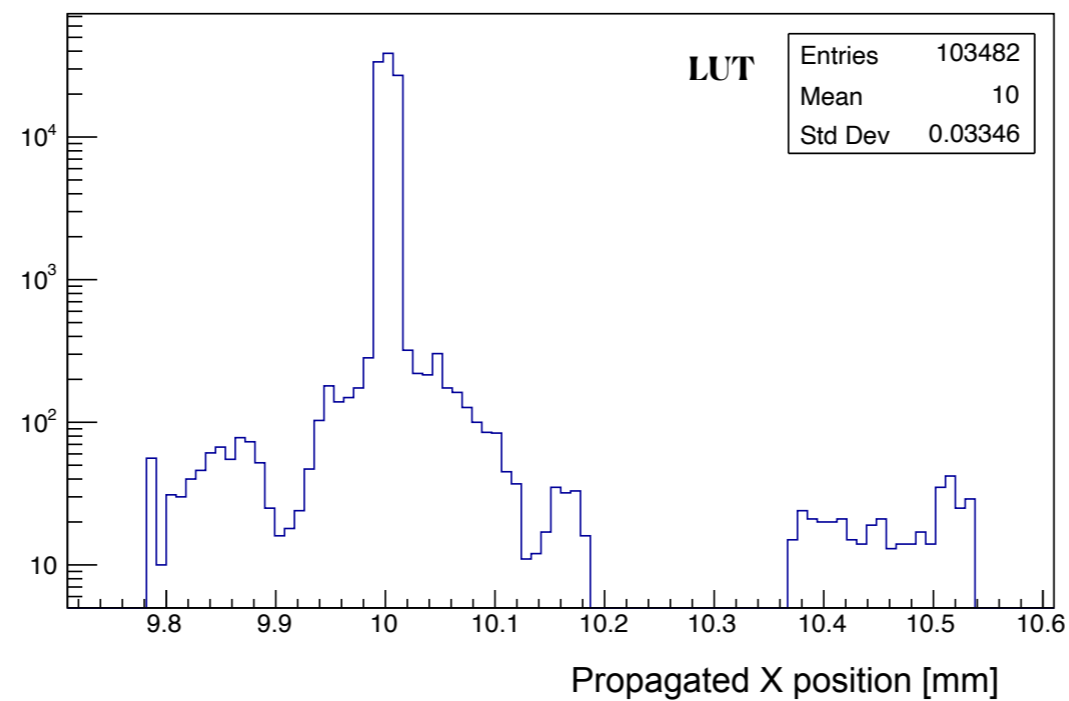
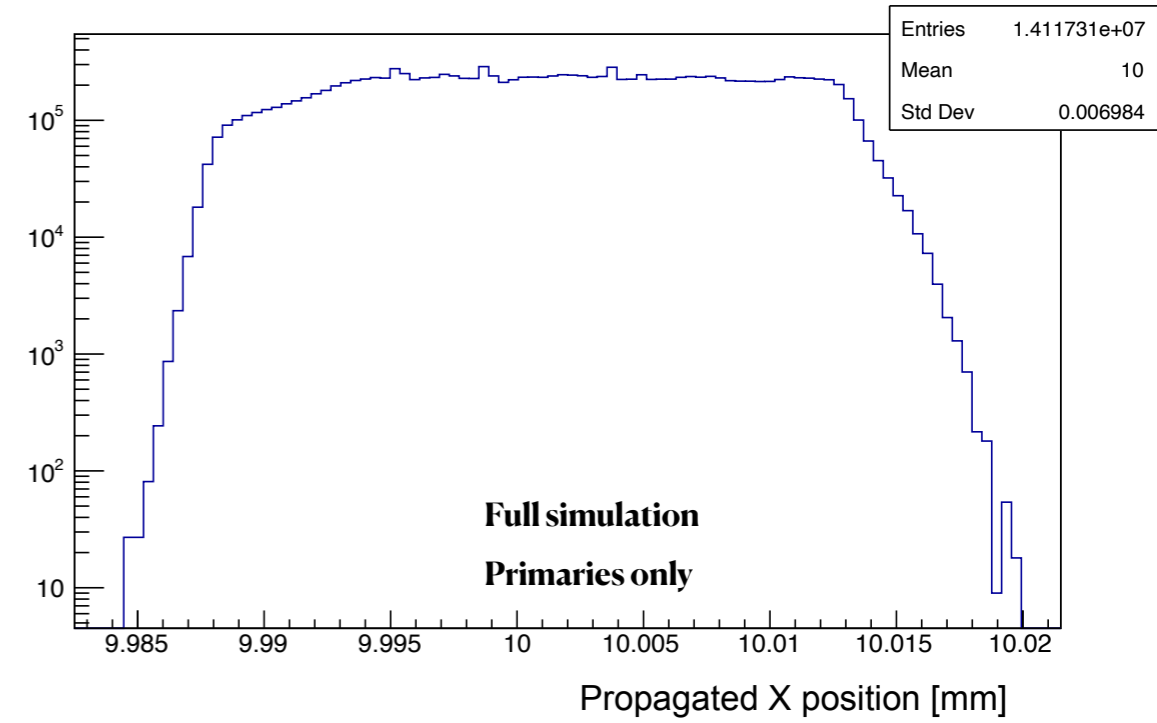
**$P_t = 1 \text{ GeV}, \eta = 0$**

# Propagated X Position

Pt = 1GeV, Eta = 0 ( $\theta_{trk} = 0$  rad), -0.25 rad phi



Filtering  
secondaries

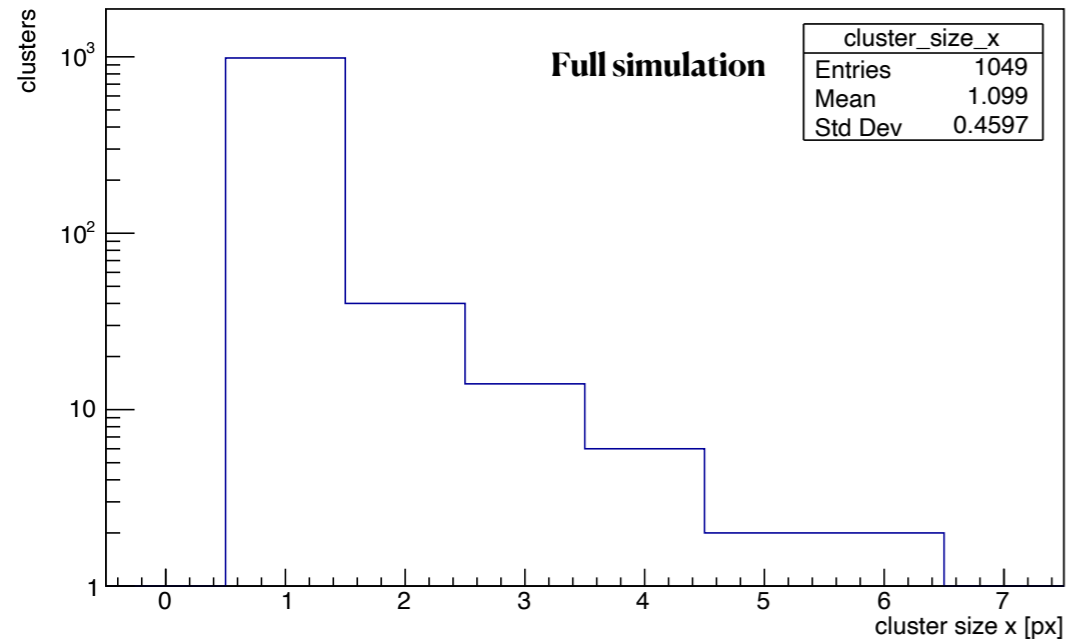


Diff = 0um

# Cluster size X & Y

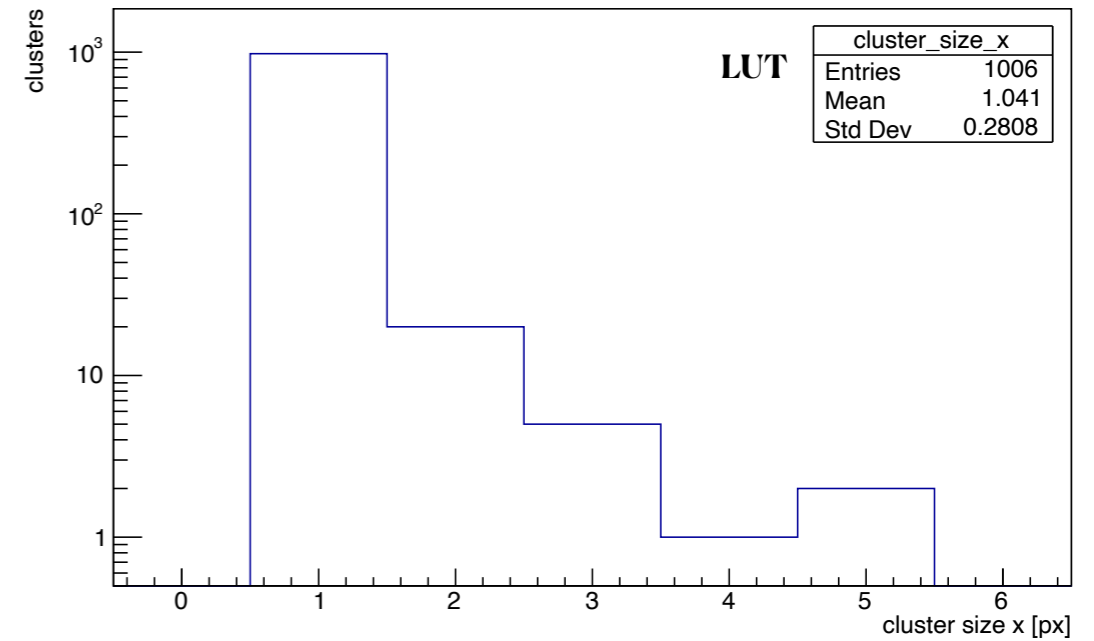
Pt = 1GeV, Eta = 0 ( $\theta_{trk} = 0$  rad), -0.25 rad phi

Cluster size in X (detector1)

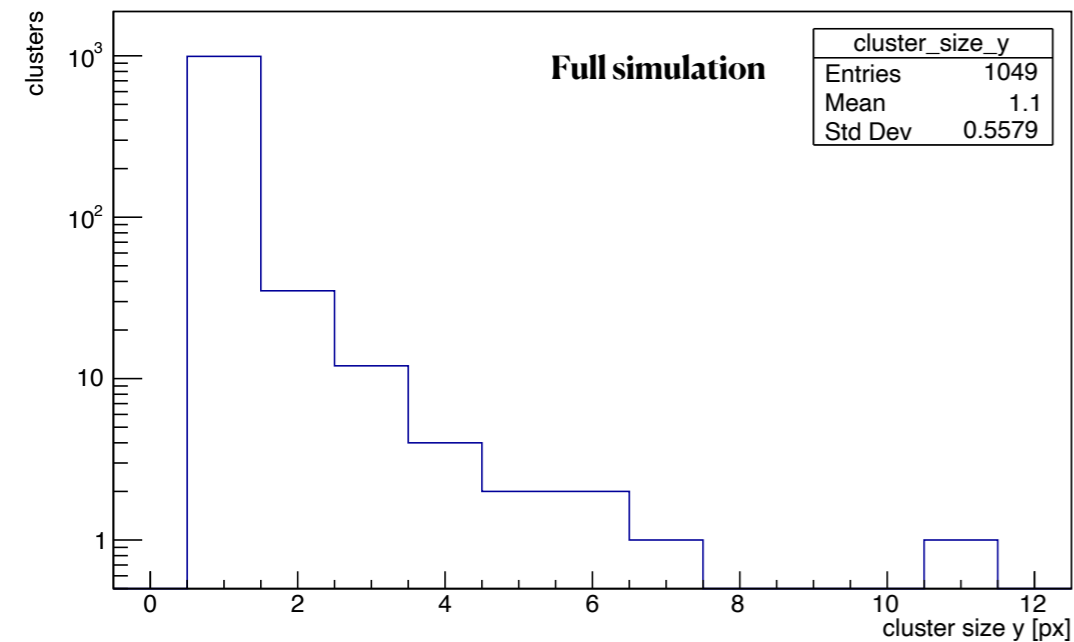


Rel err mean: 5.3%

Cluster size in X (detector1)

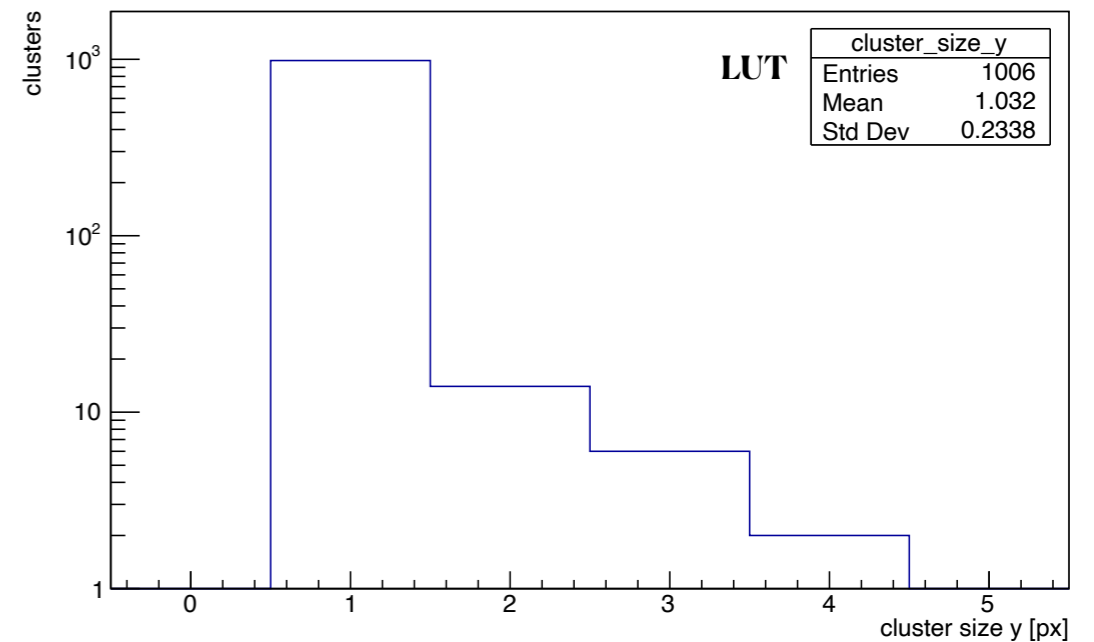


Cluster size in Y (detector1)



Rel err mean: 6.2%

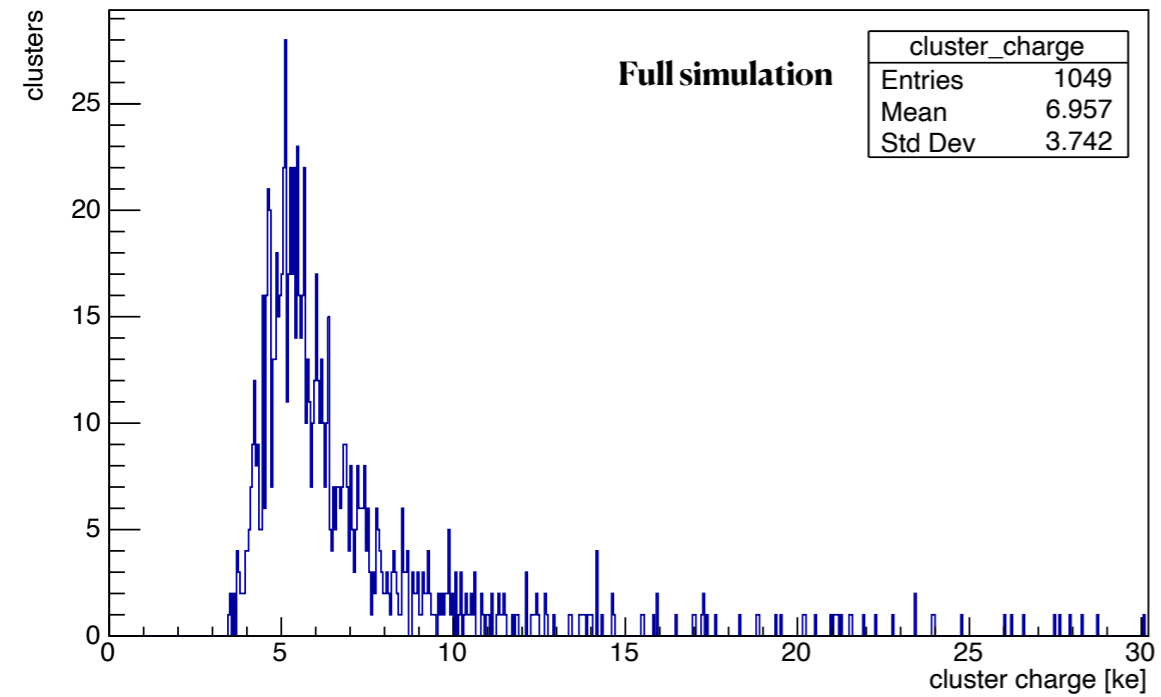
Cluster size in Y (detector1)



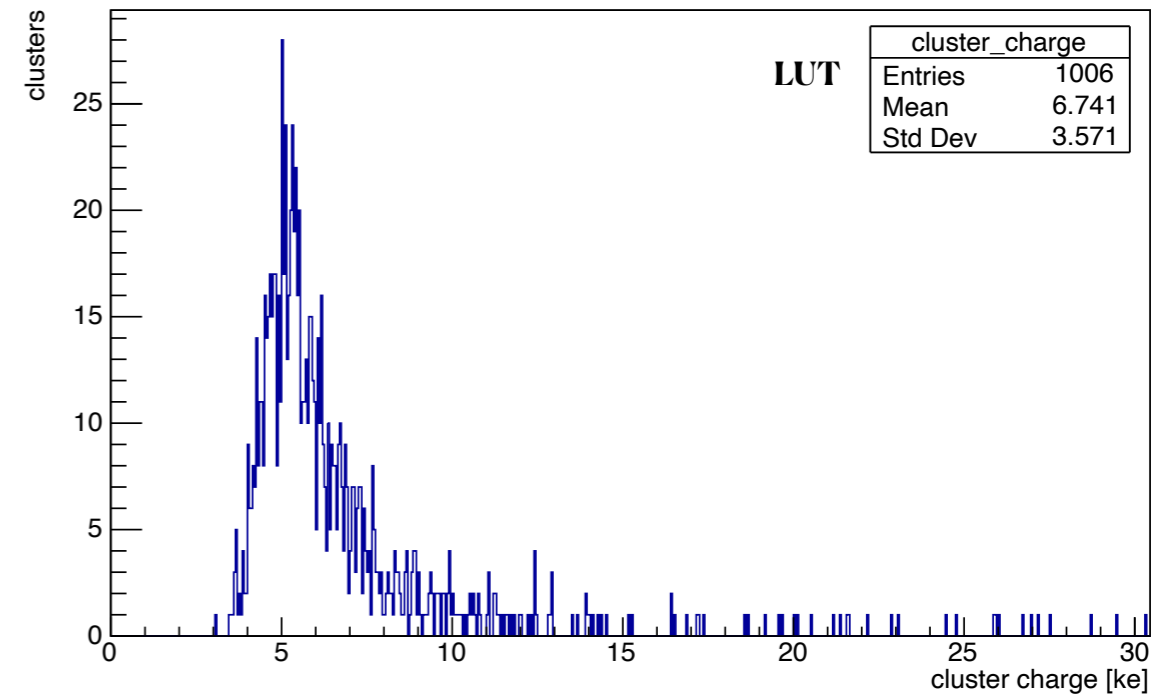
# Cluster charge

Pt = 1GeV, Eta = 0 ( $\theta_{trk} = 0$  rad), -0.25 rad phi

Cluster charge (detector1)



Cluster charge (detector1)



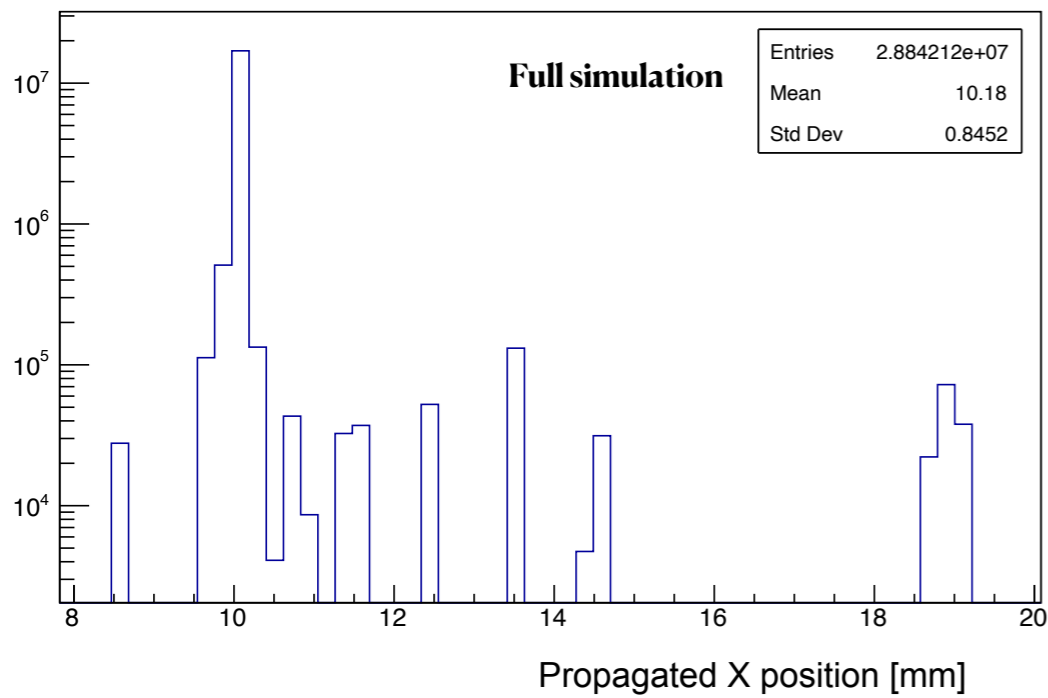
Rel err mean: 3.1%

**$P_t = 1 \text{ GeV}, \eta = 1$**

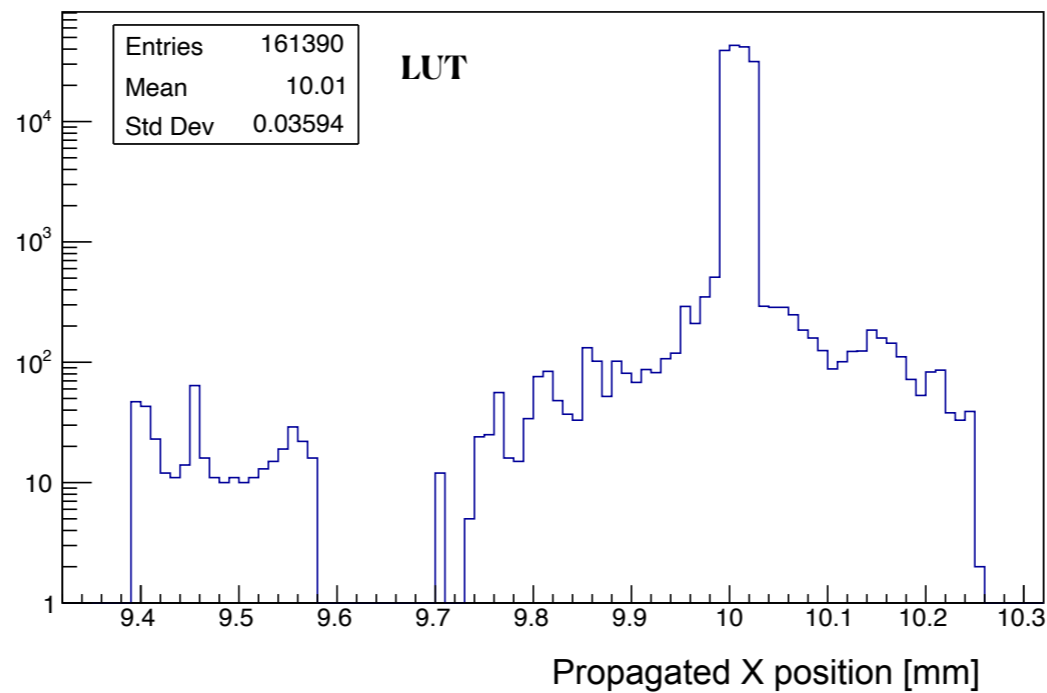
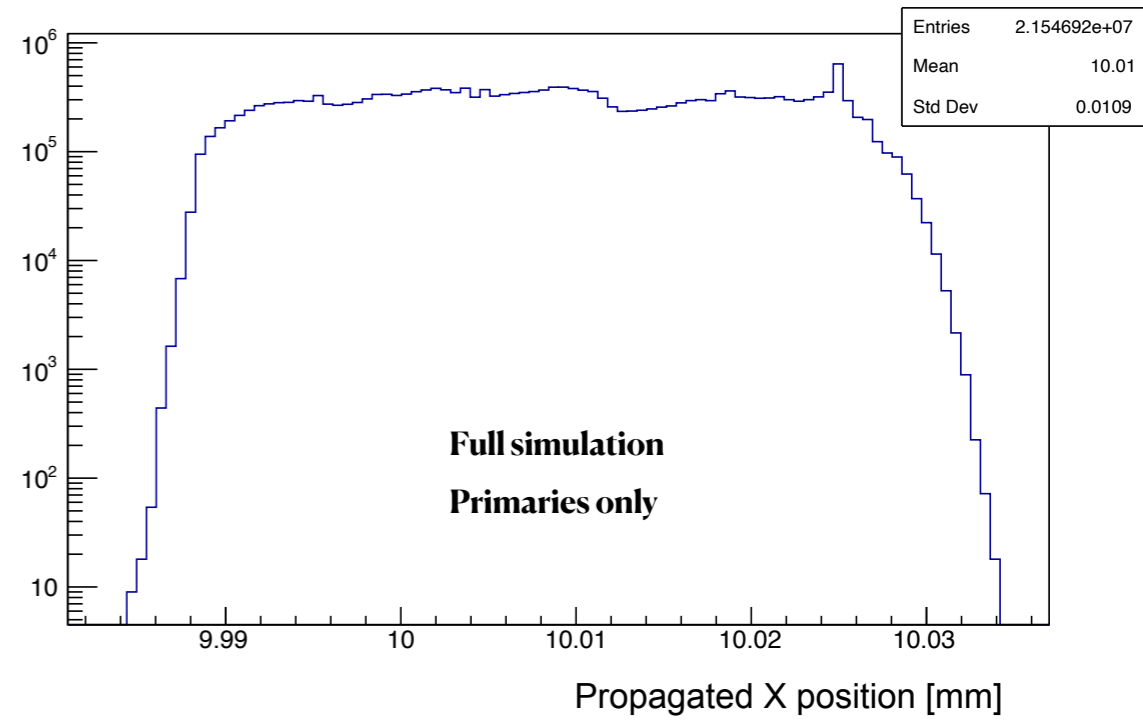


# Propagated X Position

Pt = 1GeV, Eta = 1 ( $\theta_{trk} = 0.866$  rad), -0.25 rad phi



Filtering  
secondaries

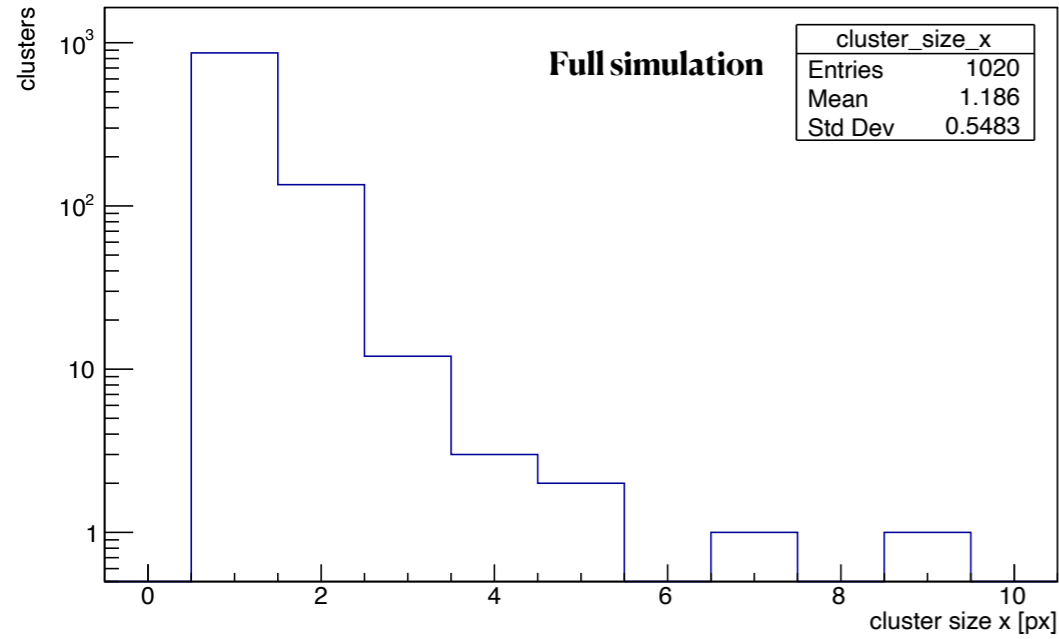


Diff = 0um

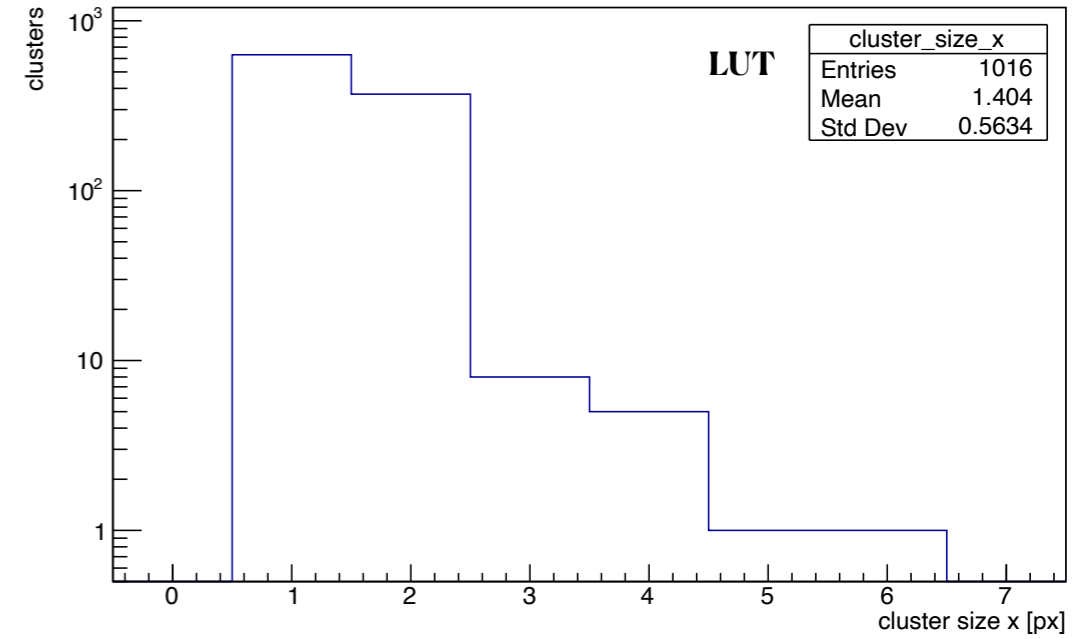
# Cluster size X & Y

Pt = 1GeV, Eta = 1 ( $\theta_{trk} = 0.866$  rad), -0.25 rad phi

Cluster size in X (detector1)

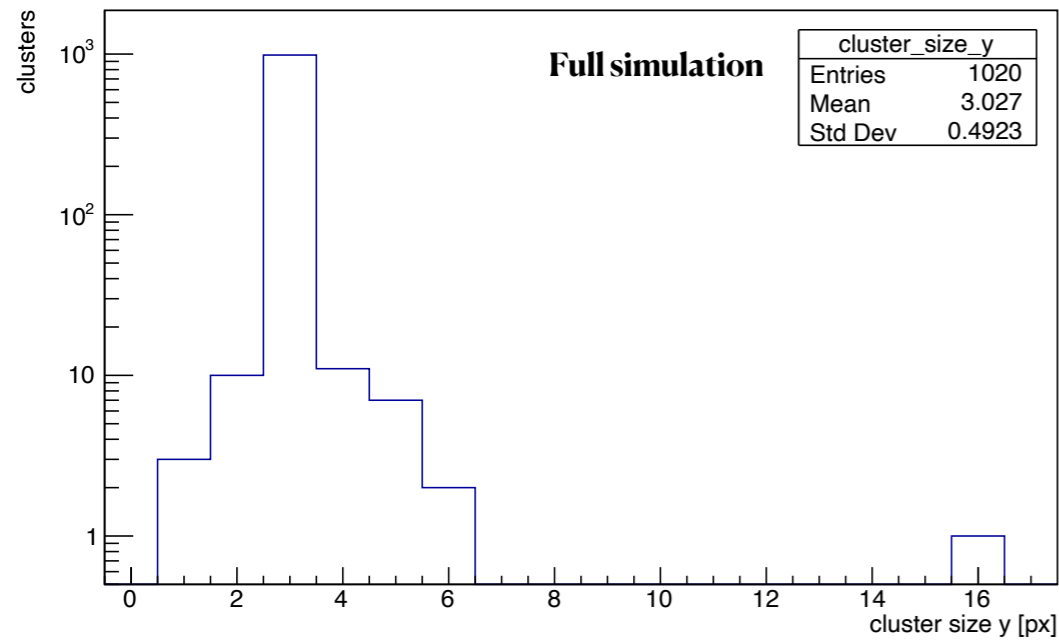


Cluster size in X (detector1)

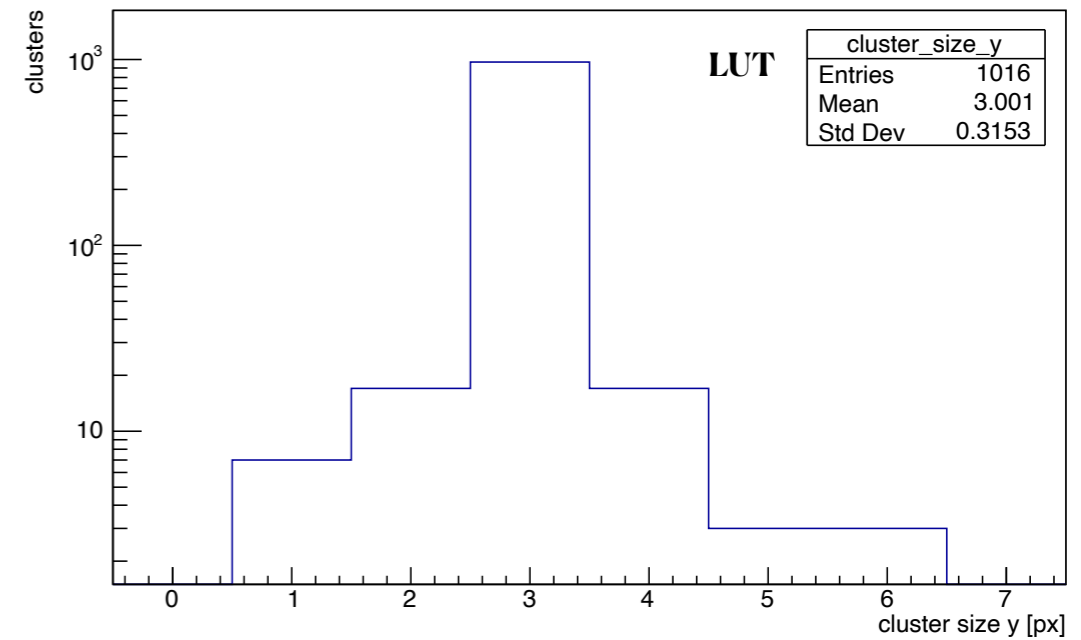


Rel err mean: 18.38 %

Cluster size in Y (detector1)



Cluster size in Y (detector1)

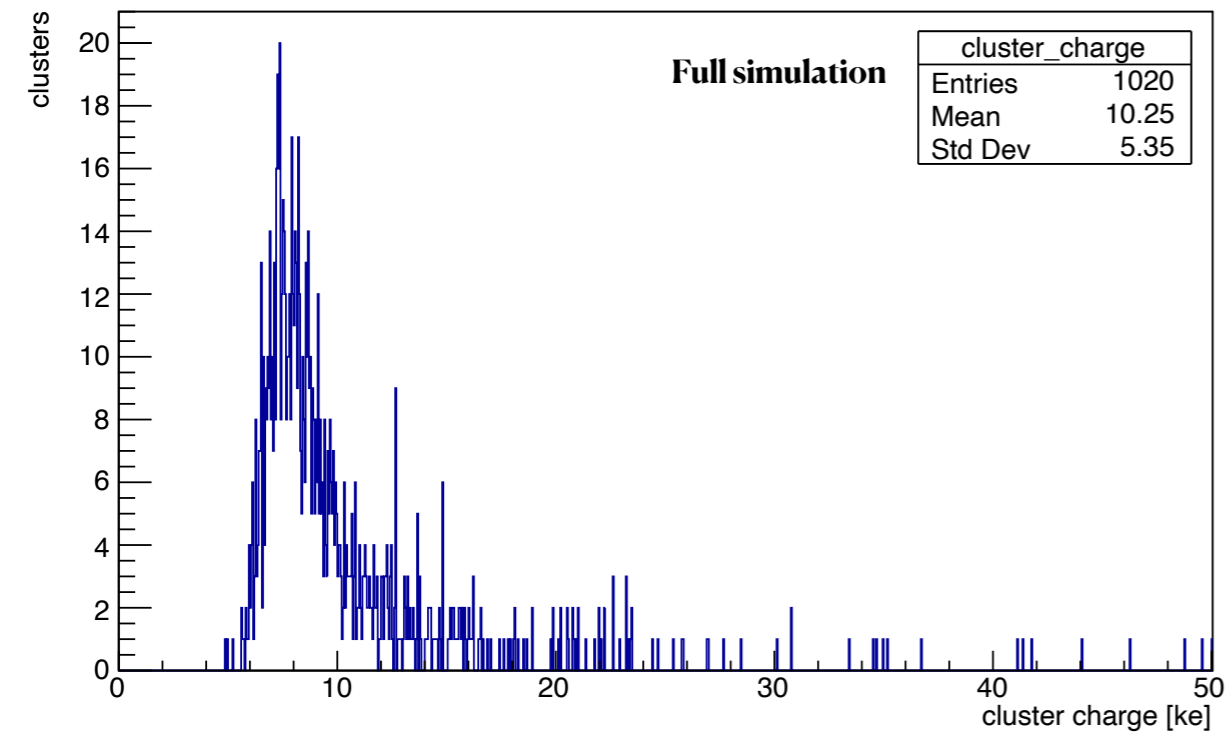


Rel err mean: 0.86 %

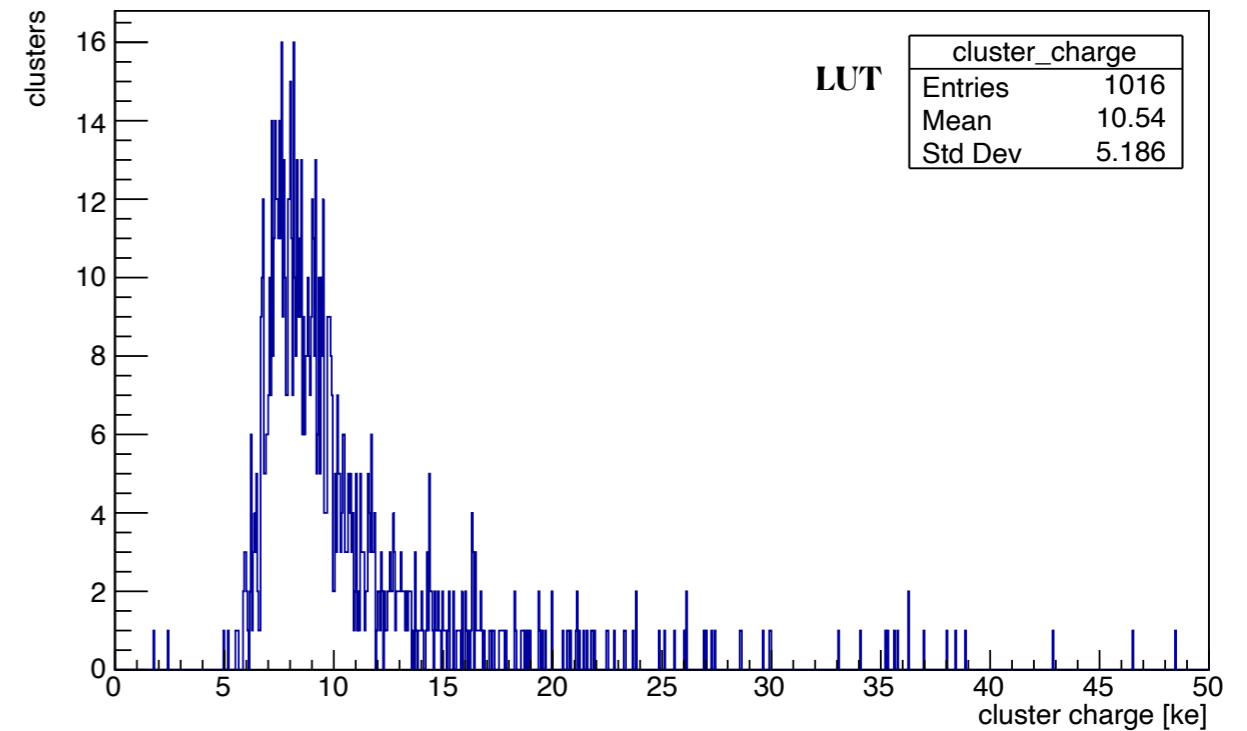
# Cluster charge

Pt = 1GeV, Eta = 1 ( $\theta_{trk} = 0.866$  rad), -0.25 rad phi

Cluster charge (detector1)



Cluster charge (detector1)

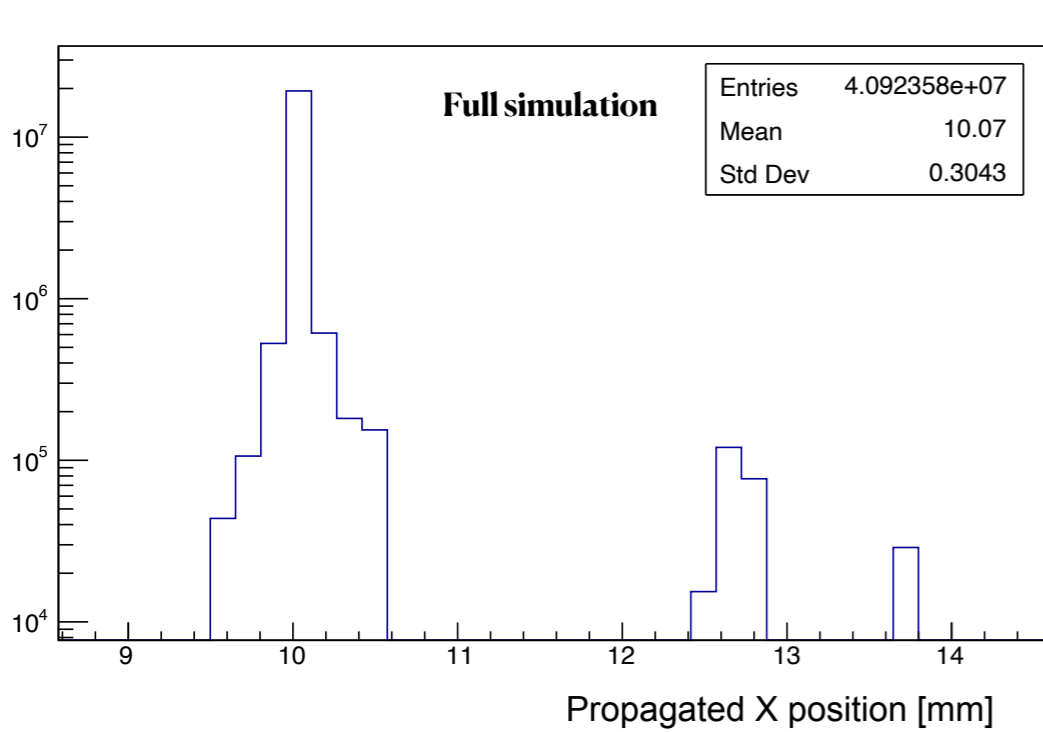


Rel err mean: 2.8%

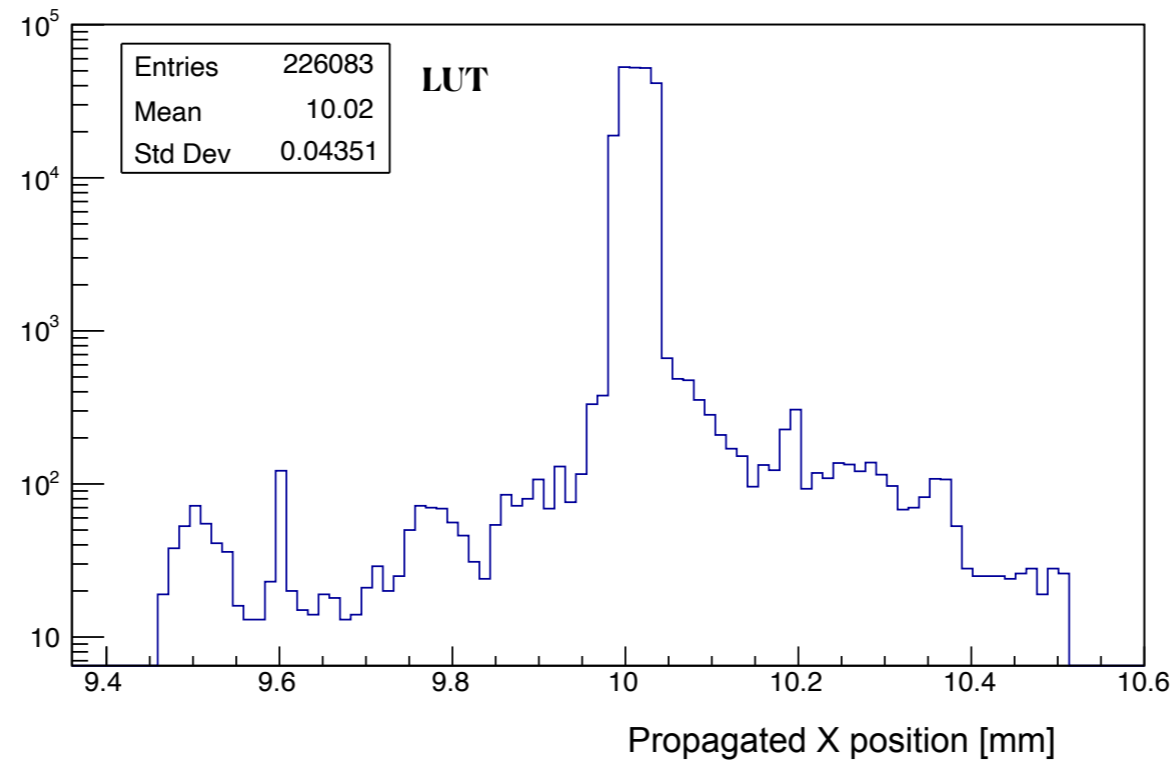
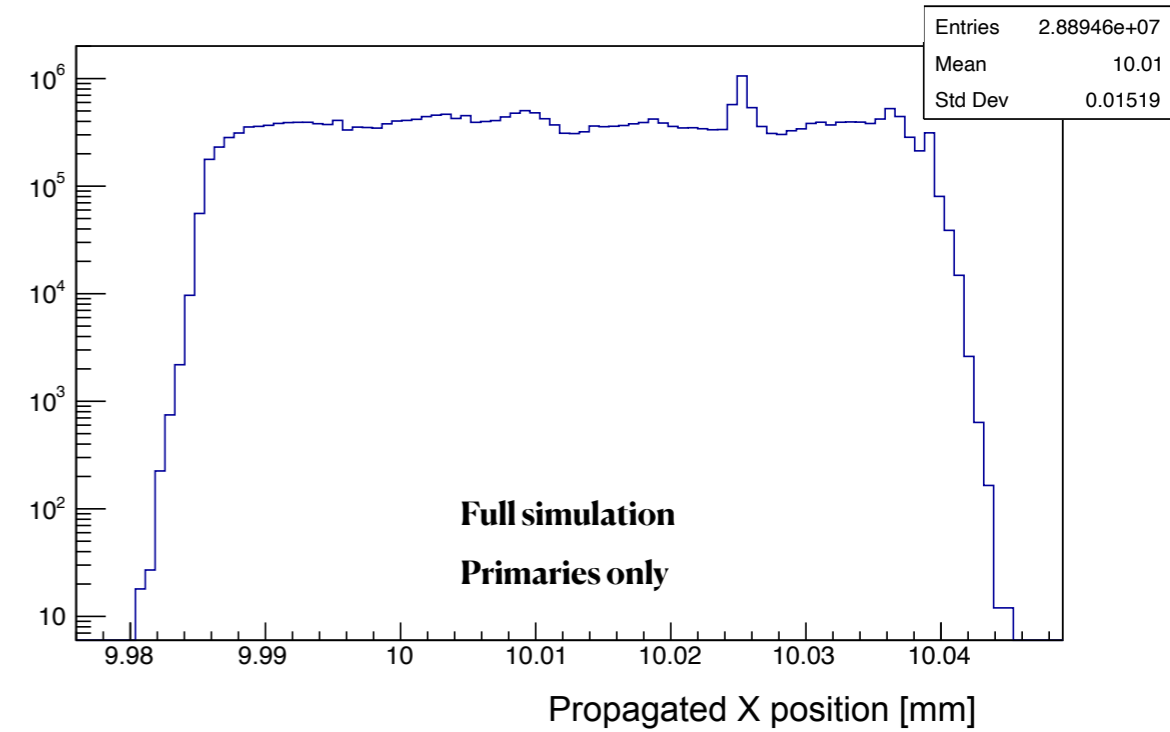
**$P_t = 1 \text{ GeV}, \eta = 1.4$**

# Propagated X Position

Pt = 1GeV, Eta = 1.4 ( $\theta_{trk} = 1.088$  rad), -0.25 rad phi



Filtering  
secondaries

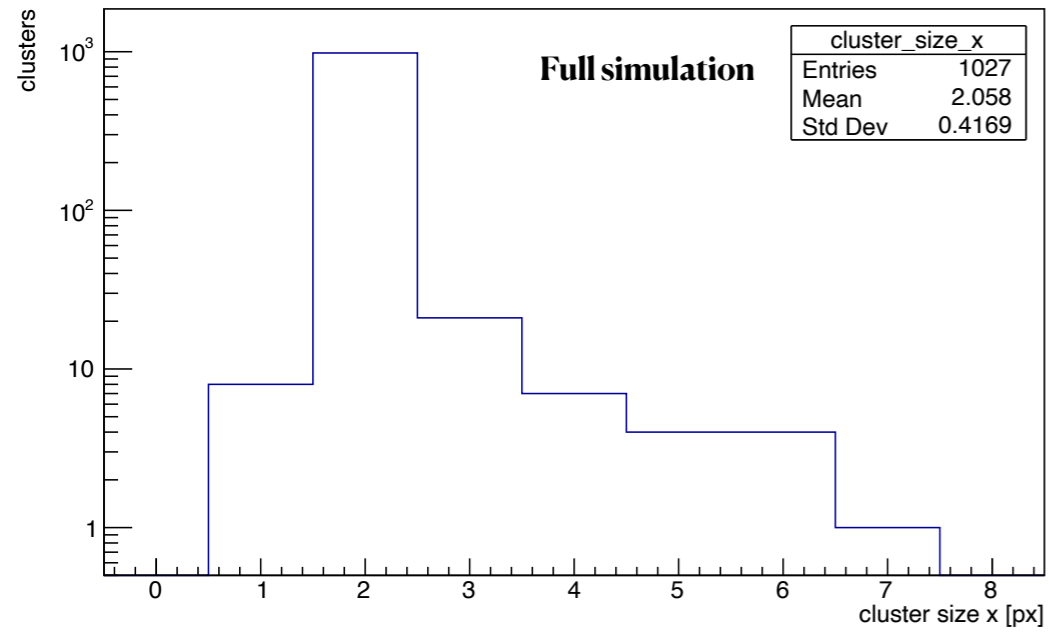


Diff = 10um  
Normalised diff = 0.2

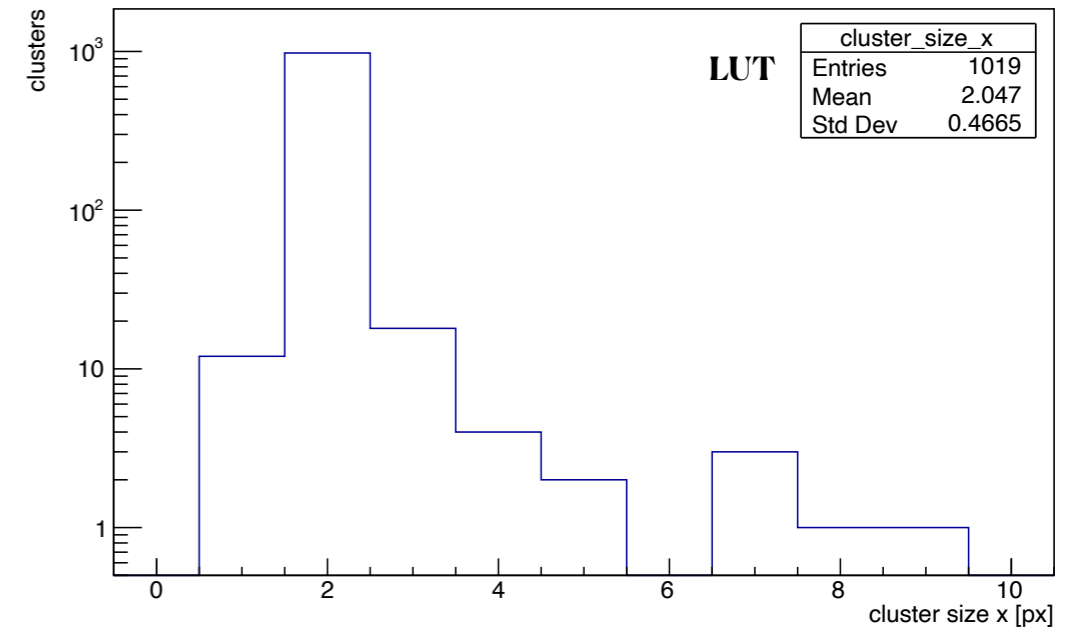
# Cluster size X & Y

Pt = 1GeV, Eta = 1.4 ( $\theta_{trk} = 1.088$  rad), -0.25 rad phi

Cluster size in X (detector1)

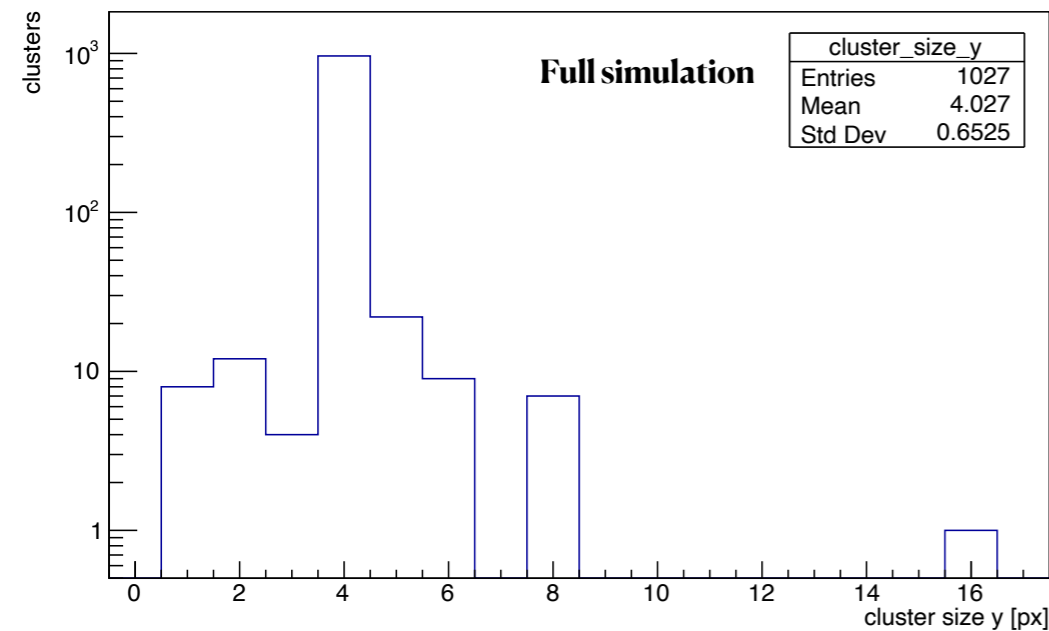


Cluster size in X (detector1)

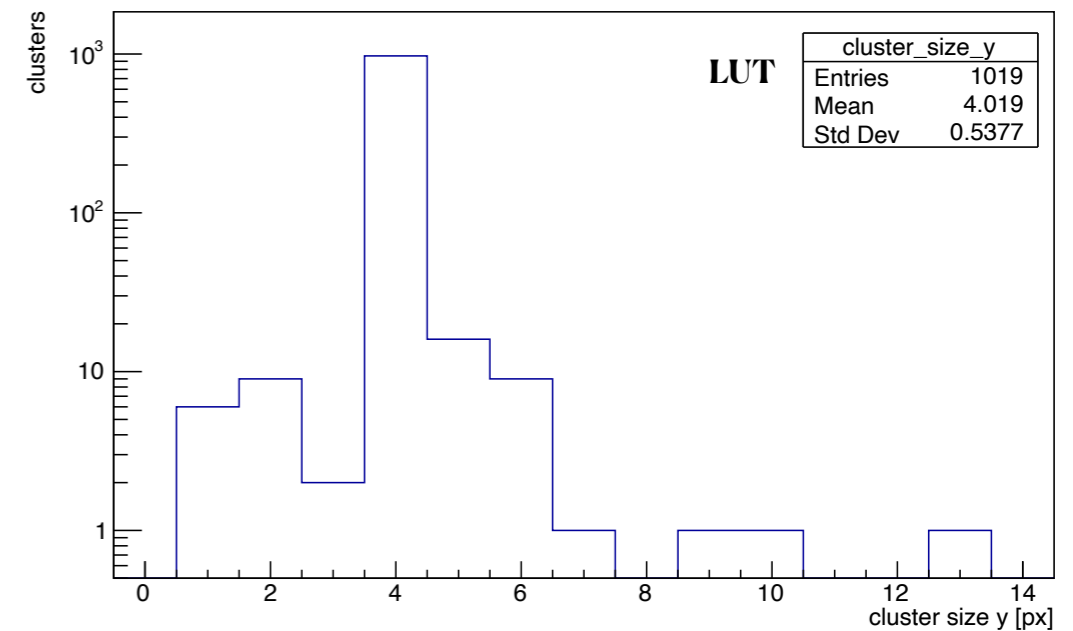


Rel err mean: 0.53%

Cluster size in Y (detector1)



Cluster size in Y (detector1)

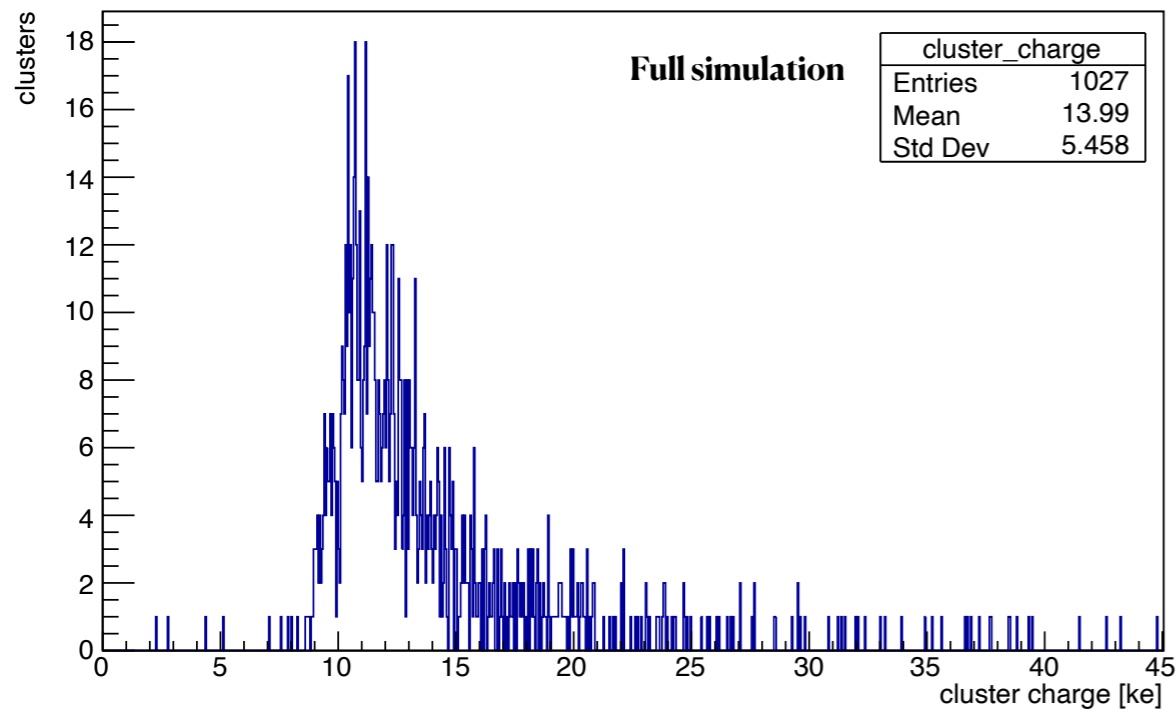


Rel err mean: 0.2%

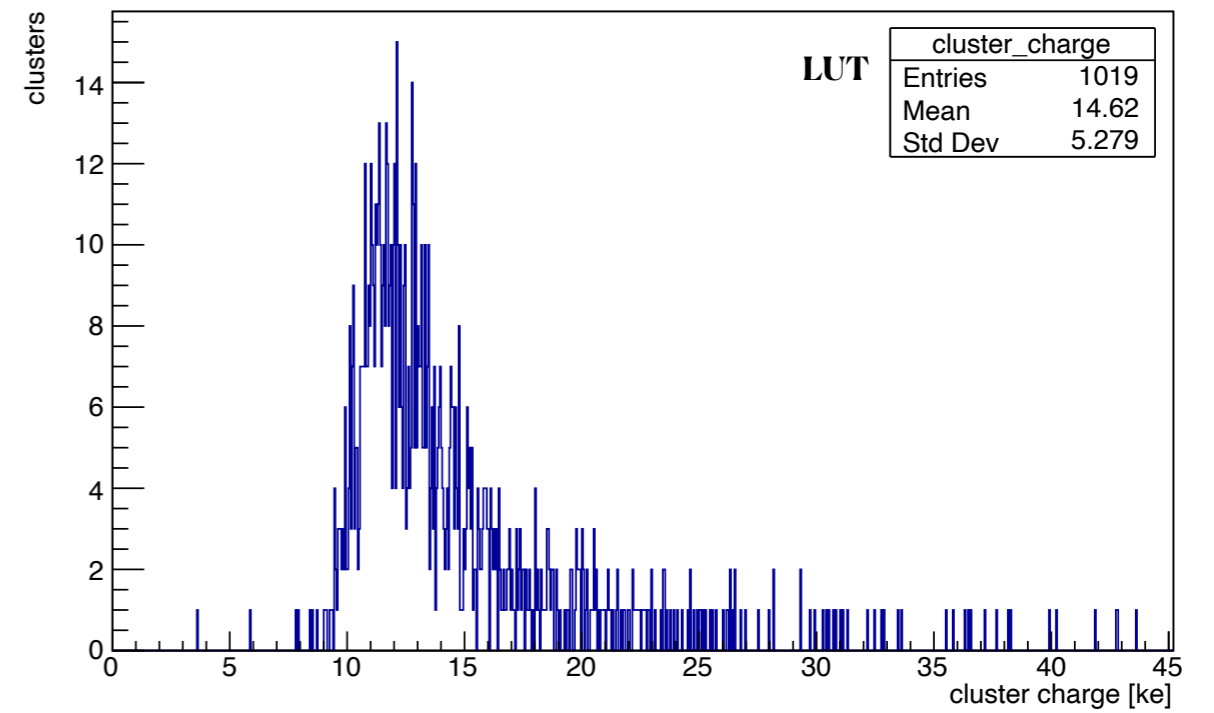
# Cluster charge

Pt = 1 GeV, Eta = 1.4 ( $\theta_{trk} = 1.088$  rad), -0.25 rad phi

Cluster charge (detector1)



Cluster charge (detector1)



Rel err mean: 4.50%

# Cluster size X (from FS) - Comparison of Unirradiated Vs Irradiated

## Pions of Pt = 100GeV

Eta	Cluster size X(pix) - Full simulation		
	Unirradiated(-50V)	Unirradiated (-150V)	Irradiated
Normal incidence	1.08	1.07	1.079
1 (theta_trk = 0.866Rad)	2.009	1.716	1.243
1.4 (theta_trk = 1.088 Rad)	2.051	2.051	2.068

- Unirradiated simulations

- Linear Efield, bias voltage = -50V, -150V  
depletion voltage = -10V
- Weighting potential maps from TCAD  
loaded
- Digitiser threshold = 600e

- Irradiated simulations

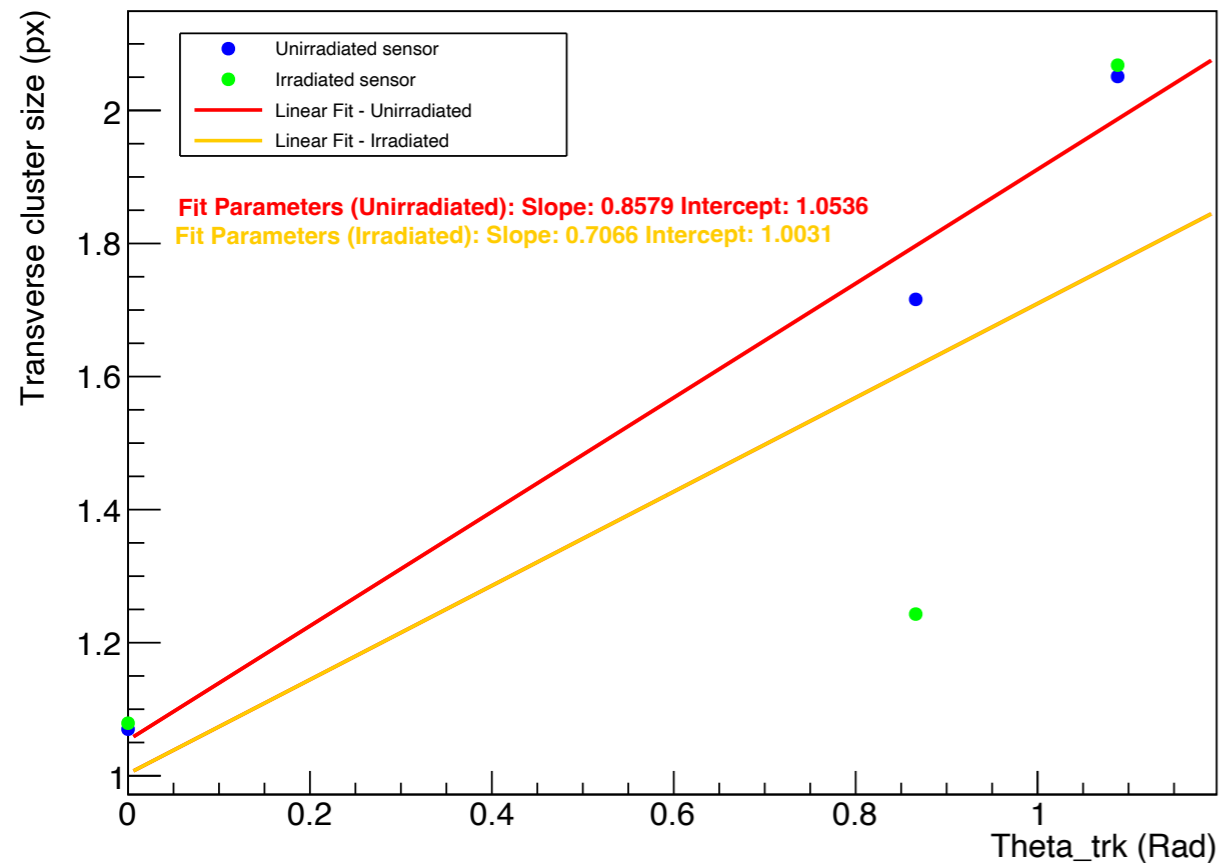
- TCAD Efield, fluence =  $4e^{15}$ neq/cm<sup>2</sup>,  
600V, trapping model = cmstracker
- Weighting potential maps from TCAD  
loaded
- Digitiser threshold = 600e



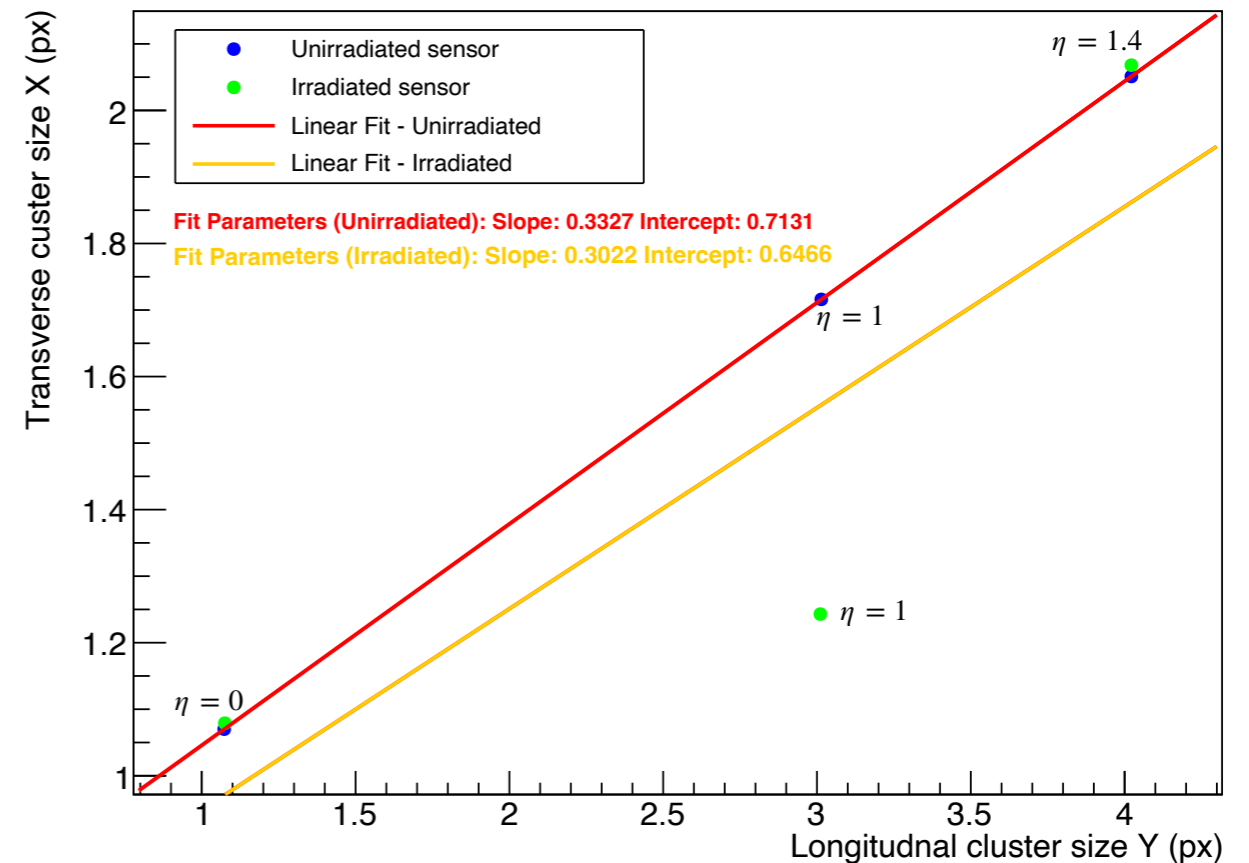
# Understanding Transverse Cluster Size

100 GeV Pions, FS, Unirradiated vs Irradiated, -0.25Rad Y

Cluster size X vs  $\theta_{trk}$



Cluster size X vs Cluster size Y



- CSX at eta = 1 and eta = 1.4 very similar for irradiated and unirradiated sensors
- Significant differences seen at eta = 1

- CSX increases with increase in CSY for unirradiated and irradiated sensor -> similar trend seen in data
- $N_x \sim N_y * P_{(sharing,x)}$ !!!
- Probability of sharing in the transverse plane for unirradiated sensors = 0.33

# Realistic simulation studies of ITk barrel pixels

## Investigating Pt and $\eta$ dependencies

- Barrel layer ITk pixel modules tilted in the phi (**-0.25 Rad**) to compensate for Lorentz angle deflection
- Studies with a **100um** thick planar pixel sensors (**50 um x 50 um**) at a fluence of  **$4 \times 10^{15}$  neq/cm<sup>2</sup>** and **600V**
  - ♦ Pions ( $\pi^+$ ) with **Pt = 100 GeV, 10 GeV and 1 GeV** at  $\eta = 0, 1$  and **1.4** (theta\_trk = 0 Rad, 0.866 Rad and 1.088 Rad respectively)
    - ❖ Each event has a single pion passing through the detector ; 1000 events simulated
- # e-h pairs created calculated using : mean pair creation energy (Si = 3.64eV), fluctuations modelled: Fano factor (0.115)
- Comparison of Allpix-Squared full simulation (FS) with Closure test (LUT)
  - ♦ LUTPropagator module : Scale the charges using **CCE LUT** , propagate the carriers using **tan(LA)** and  **$\Delta Z$  LUTs**
- Comparison variables : propagated X position, cluster size x, cluster size y, cluster charge

