RD50 workshop @ CERN, 29/11/2023

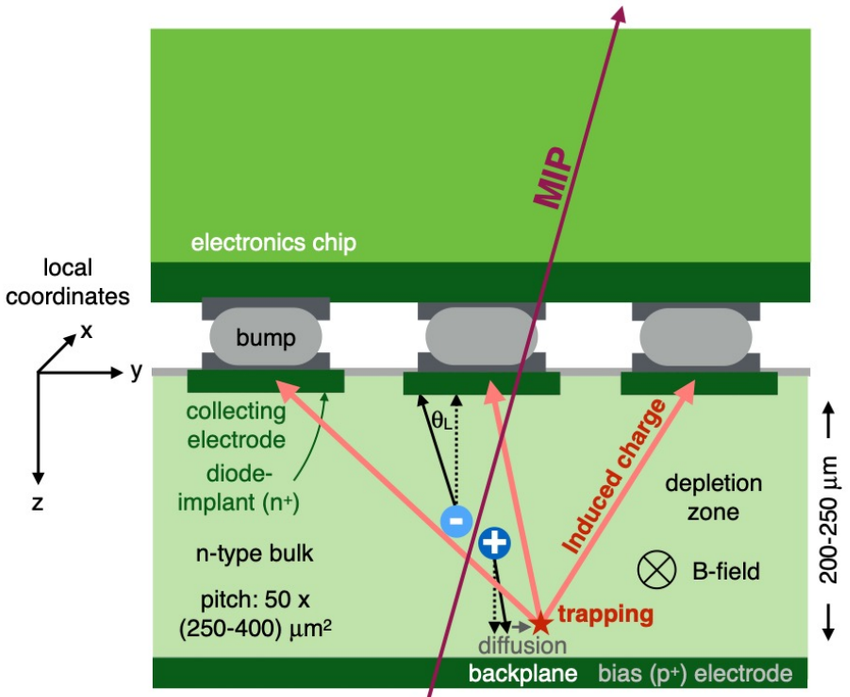
A Lightweight Algorithm for Modelling Radiation Damage effects in the MC events for HL-LHC experiments

Marco Bomben & Keerthi Nakkalil
APC & Université de Paris

Radiation damage modelling : ATLAS approach

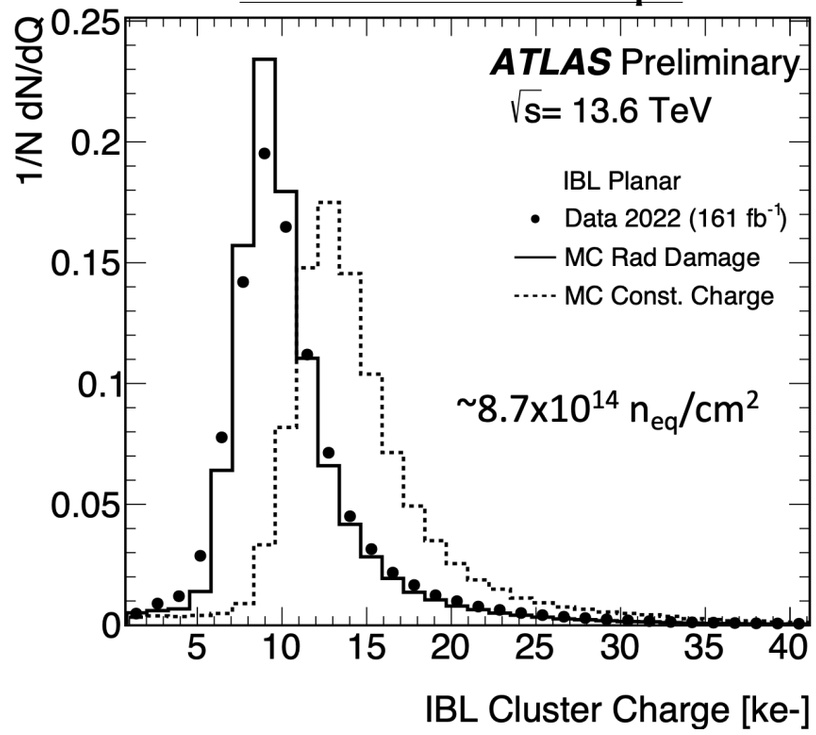
Run2 and Run3 strategy

- 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)



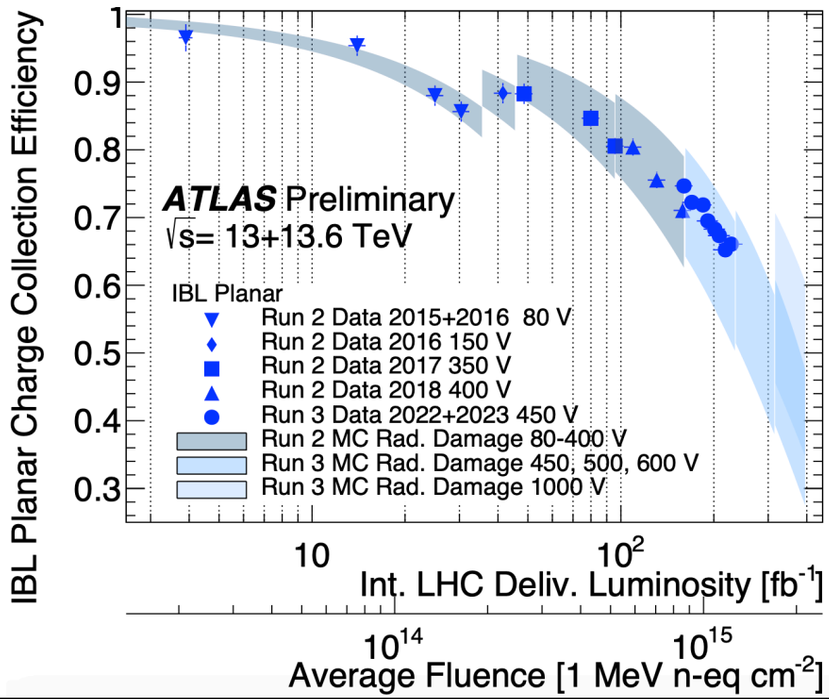
https://iopscience.iop.org/article/10.1088/1748-0221/14/06/P06012

ATL-COM-INDET-2022-027.pdf



Most Probable Values match at 1% level!

ATL-COM-INDET-2023-008.pdf

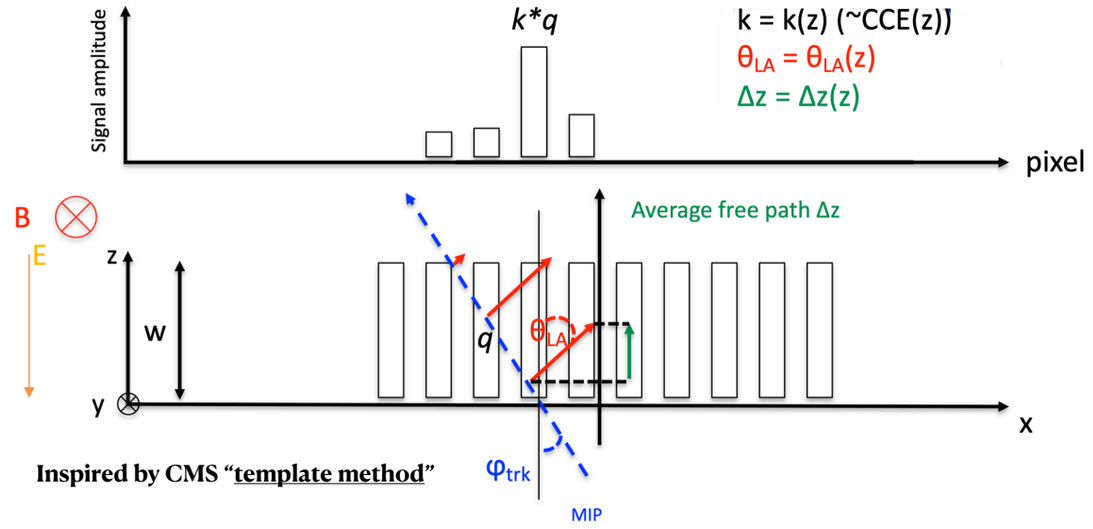


Excellent agreement over almost two order of magnitudes of fluence!

Radiation damage modelling : ATLAS approach

HL-LHC strategy

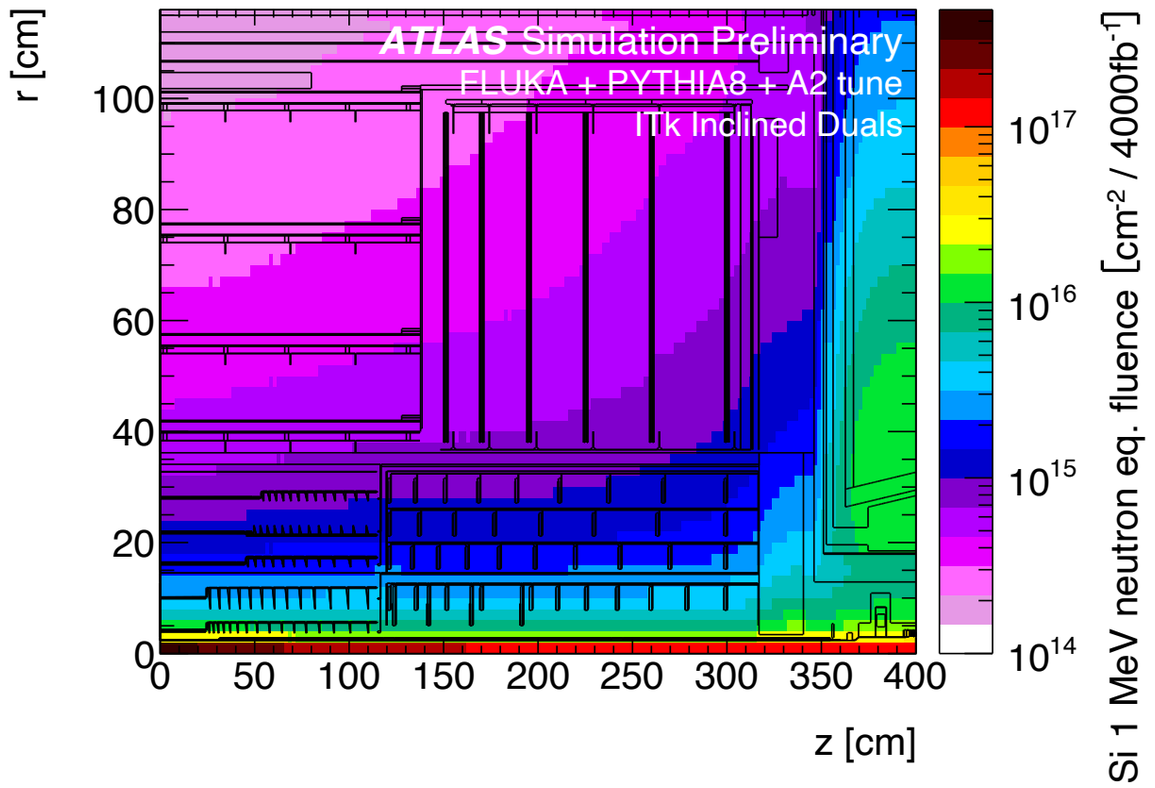
- HL-LHC : ATLAS/CMS pixel detectors exposed to unprecedented levels of radiation damage
  - ✦ Peak luminosity: $1x10^{34} \rightarrow 5-7x10^{34}cm^{-2}s^{-1}$
  - ✦ Average collisions/BC: ~30→ ~200
  - ✦ Integrated luminosity: 350 → 4000/fb
- Expected increase of particles density and rates in HL-LHC -> need for a faster algorithm
  - ✦ New strategy is planed : charge reweighing from look-up tables



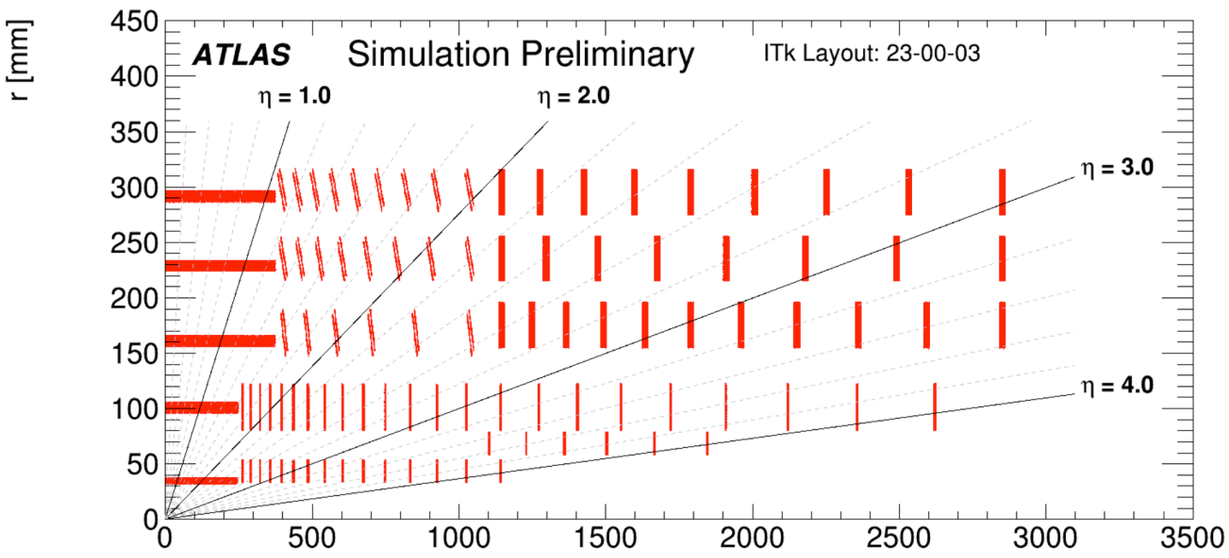
Inspired by CMS "template method"

- 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**

https://twiki.cern.ch/twiki/pub/AtlasPublic/RadiationSimulationPublicResults/s22duala_simev_itk.pdf



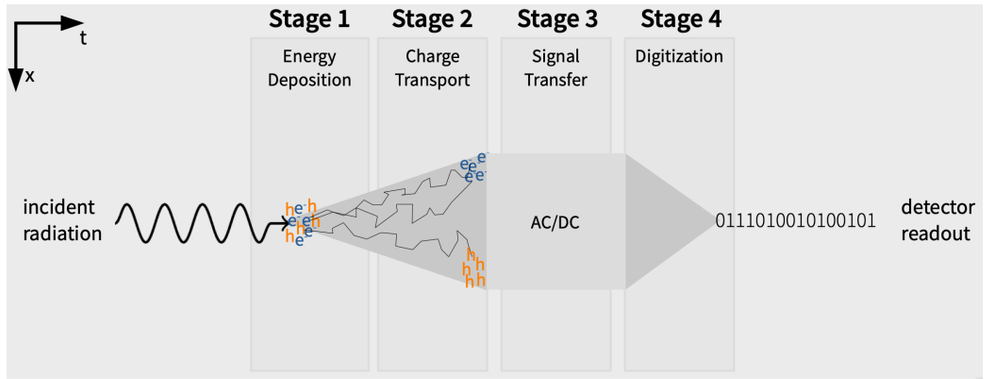
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-024/fig_01b.png



Allpix-squared framework

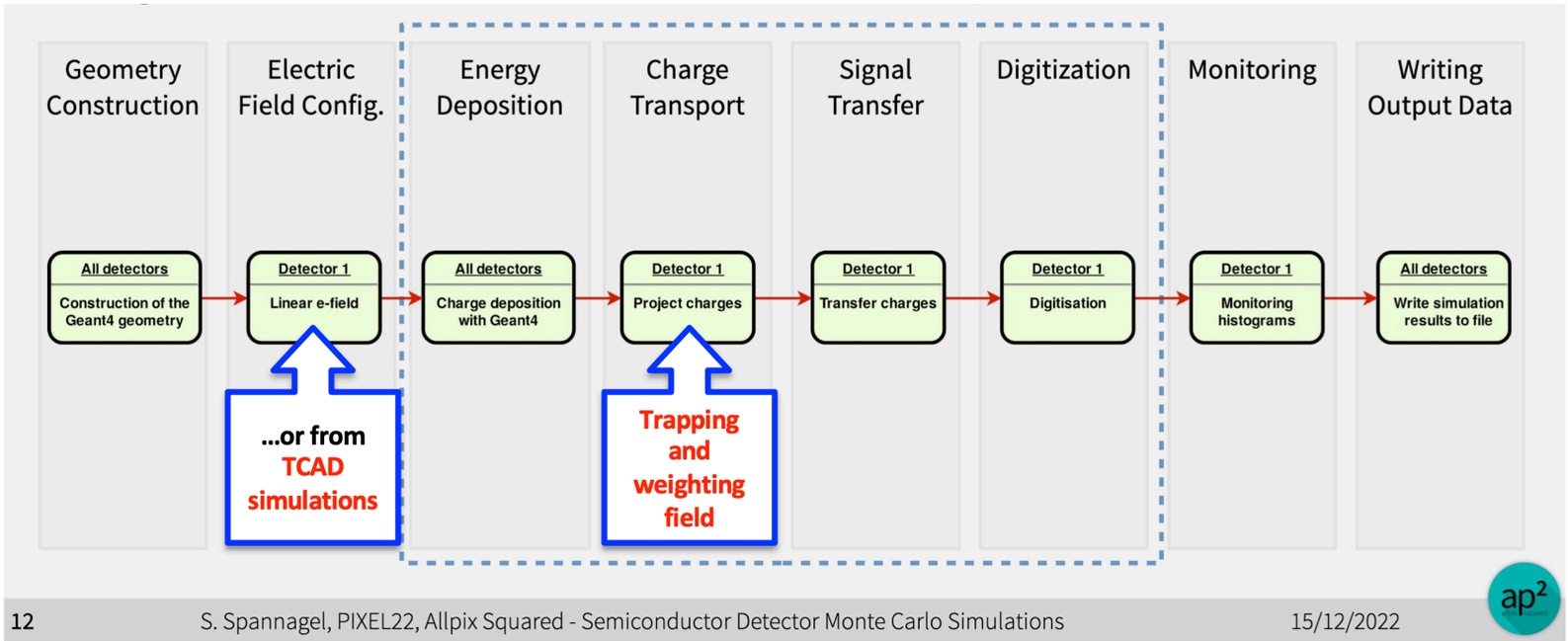
Simulation flow

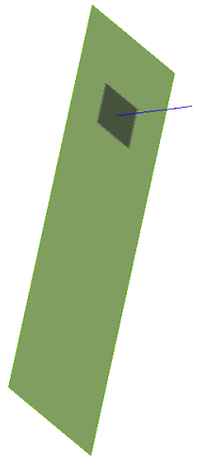
- Modular, generic simulation framework aiming at facilitating the different steps of the simulation of semiconductor detectors



- Building blocks follow individual steps of signal formation in detector

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





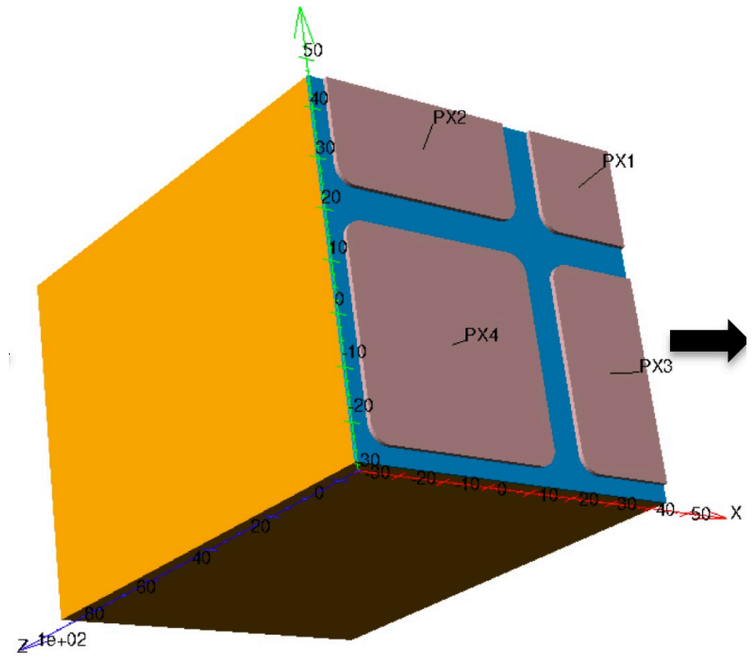
```
[Allpix]
log_level = "INFO"
log_format = "DEFAULT"
detectors_file = "planar_detector.conf"
number_of_events = 125000
root_file = "histos_125kEvents_100um_4e15_600V"
random_seed = 0

[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/EField1pixel_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","De
positedCharge"
```

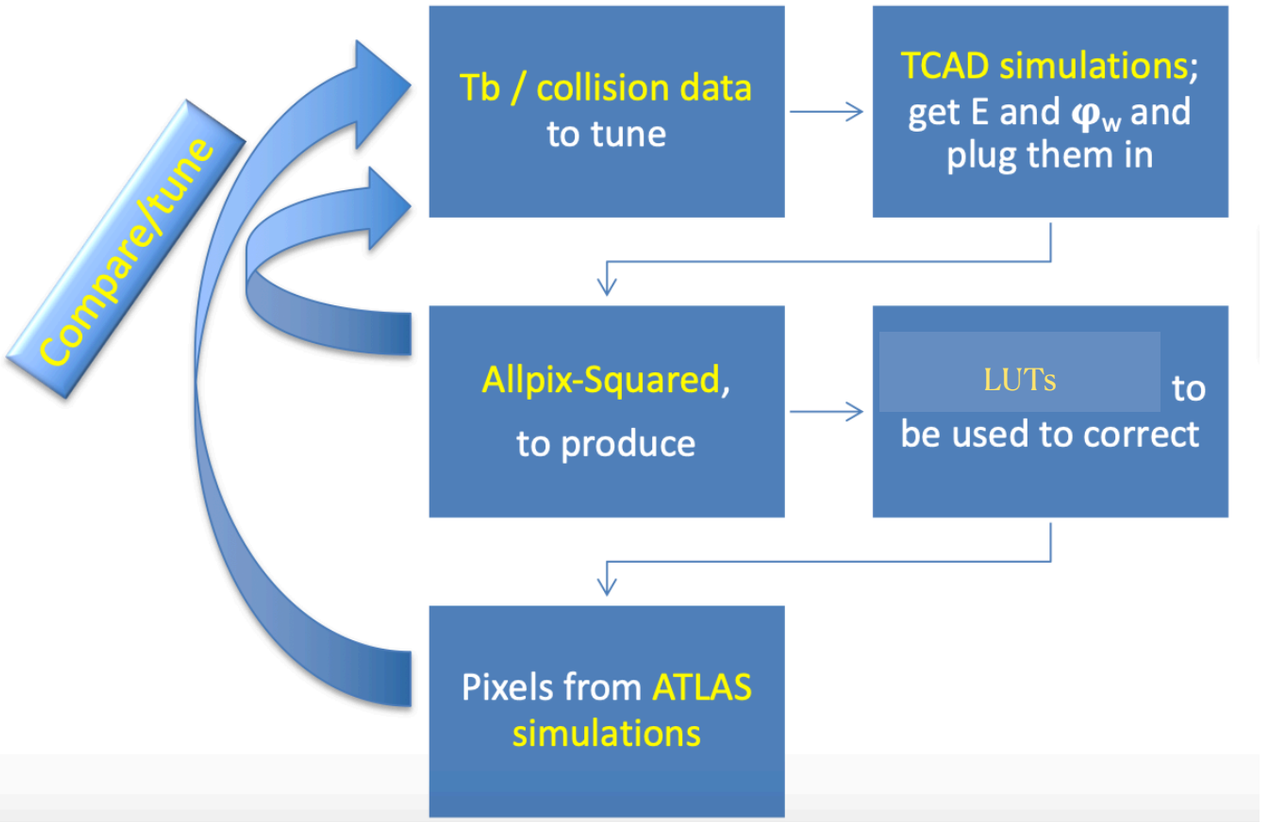
Allpix-squared for radiation damage digitiser

Implementation strategy

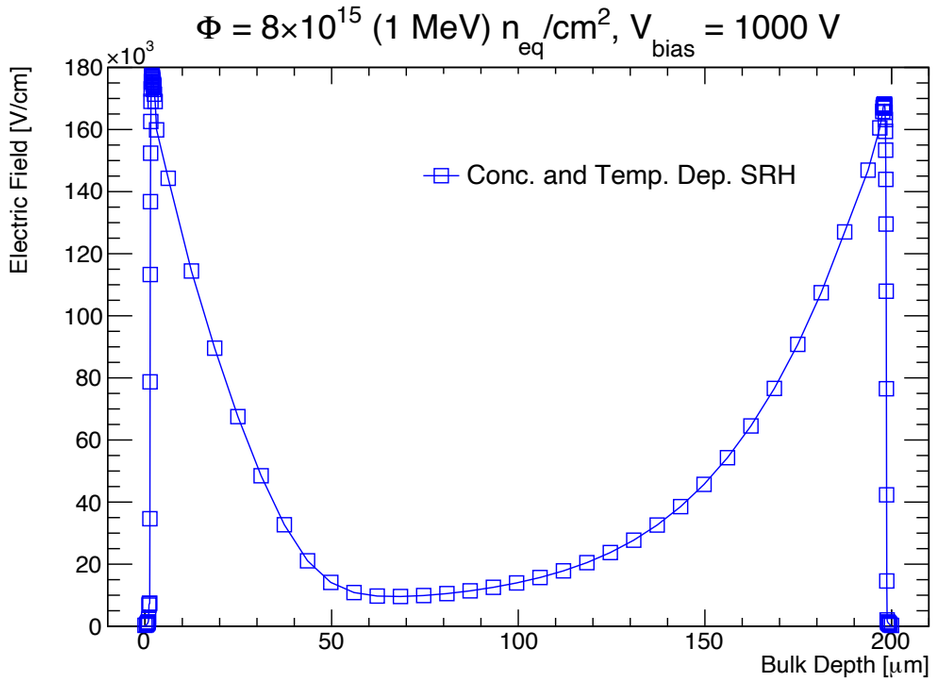
- Simulate sensors before and after irradiation, per geometry and per fluence
- Save k factor = collected charge after/before irradiation for a pixel struck at a certain Z position
- Evaluate Lorentz angle deflection as a function of Z position
- Average free path as a function of Z



1/4 of 3x3 pixel matrix
n-on-p
100 um thick
50um pitch



LHCb TCAD radiation damage model

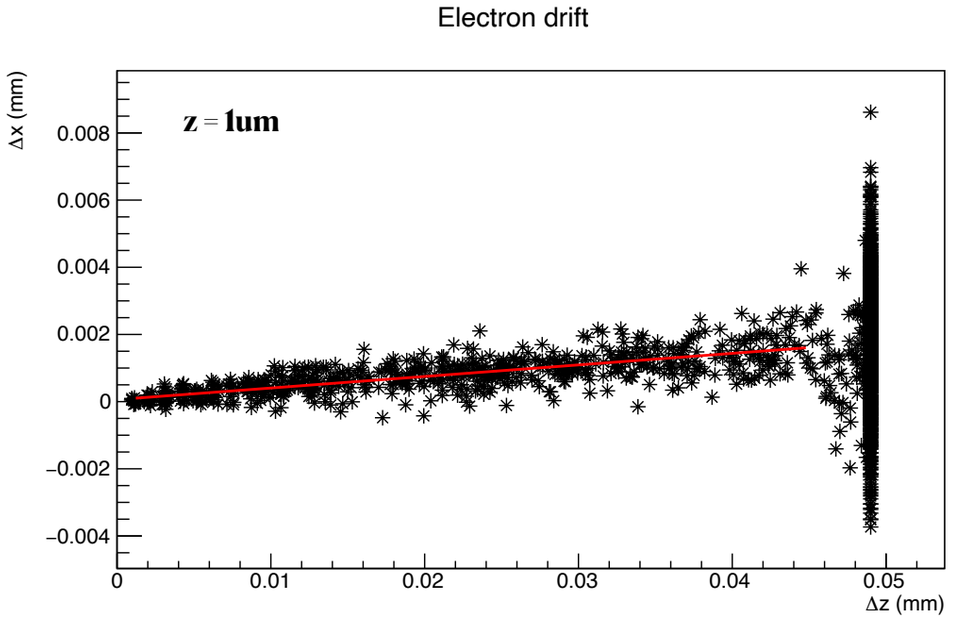


MBomben, APC,Paris

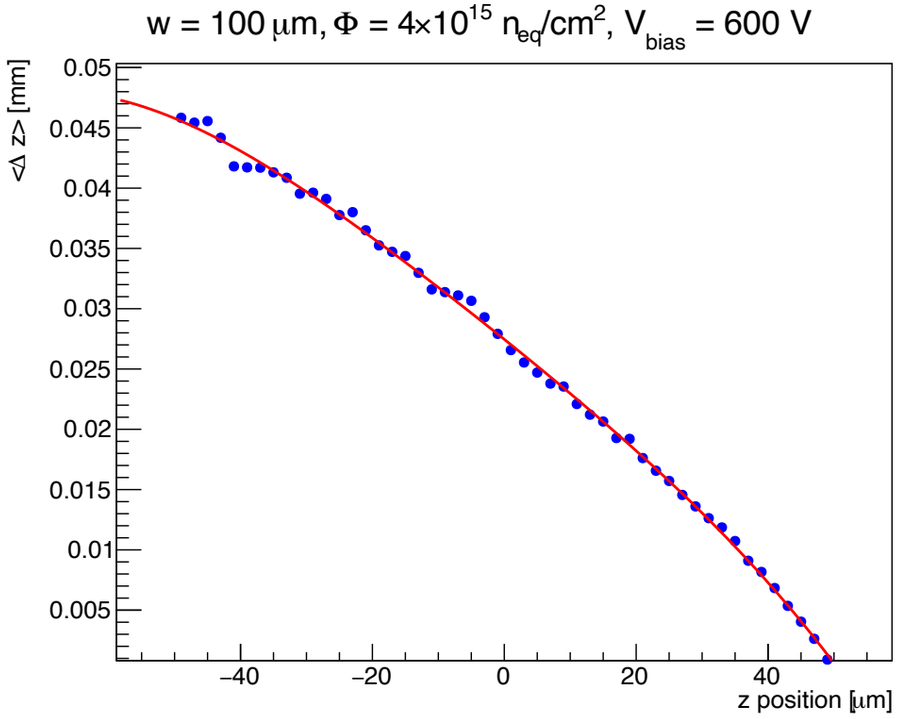
LUTs from Allpix-Squared

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 $\mathbf{4x10^{15}\ n_{eq}/cm^2}$ and **600 V**



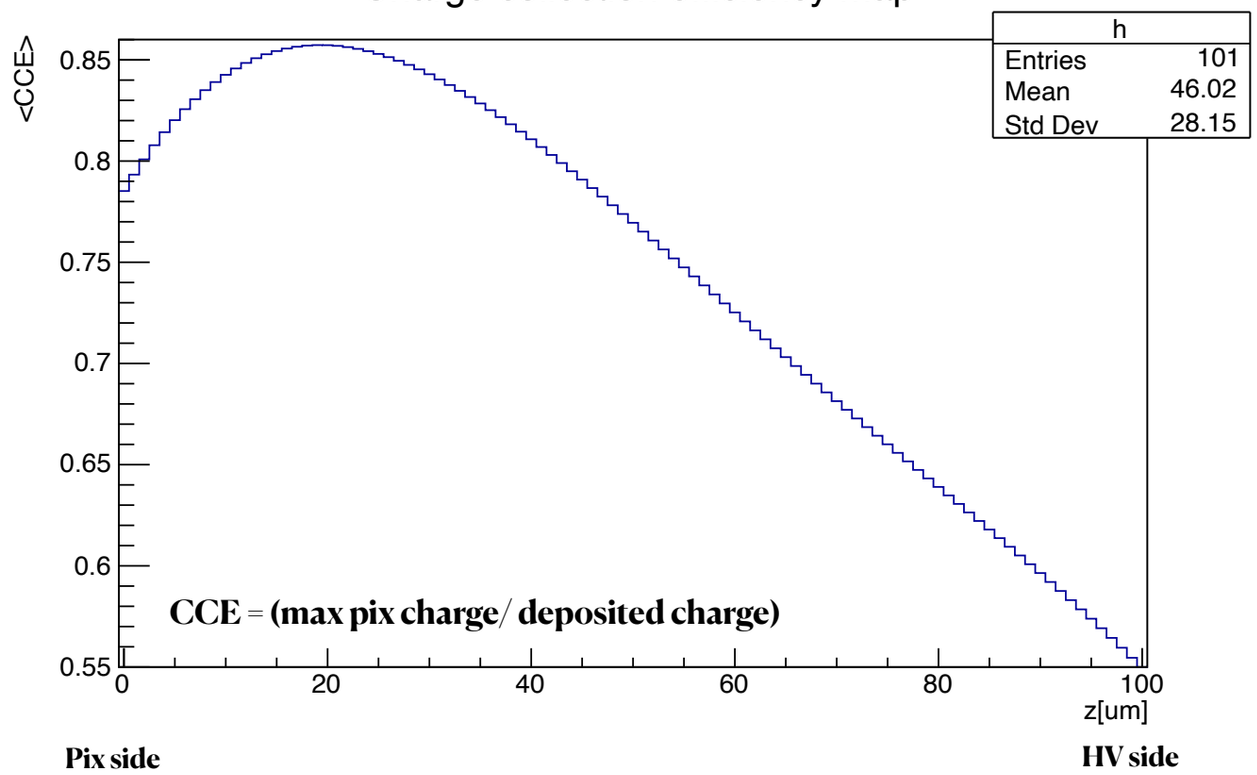
- **Creation of CCE LUT**
  - ✦ CCE per event = (max pixel charge)/(deposited charge)
  - ✦ CCE LUT obtained by taking the most probable CCE values (**MPV**) at various x, y deposition position for each z position
- **Creation of tan(LA) LUT**
  - ✦ Perform a pol1 fit to the distribution of electron drift for each z position (delx vs. delz) to extract the tanLA
- **Creation of delZ LUT**
  - ✦ Perform a pol4 fit to distribution of delz (propagatedzpos - depz) vs z to fill delZ LUT



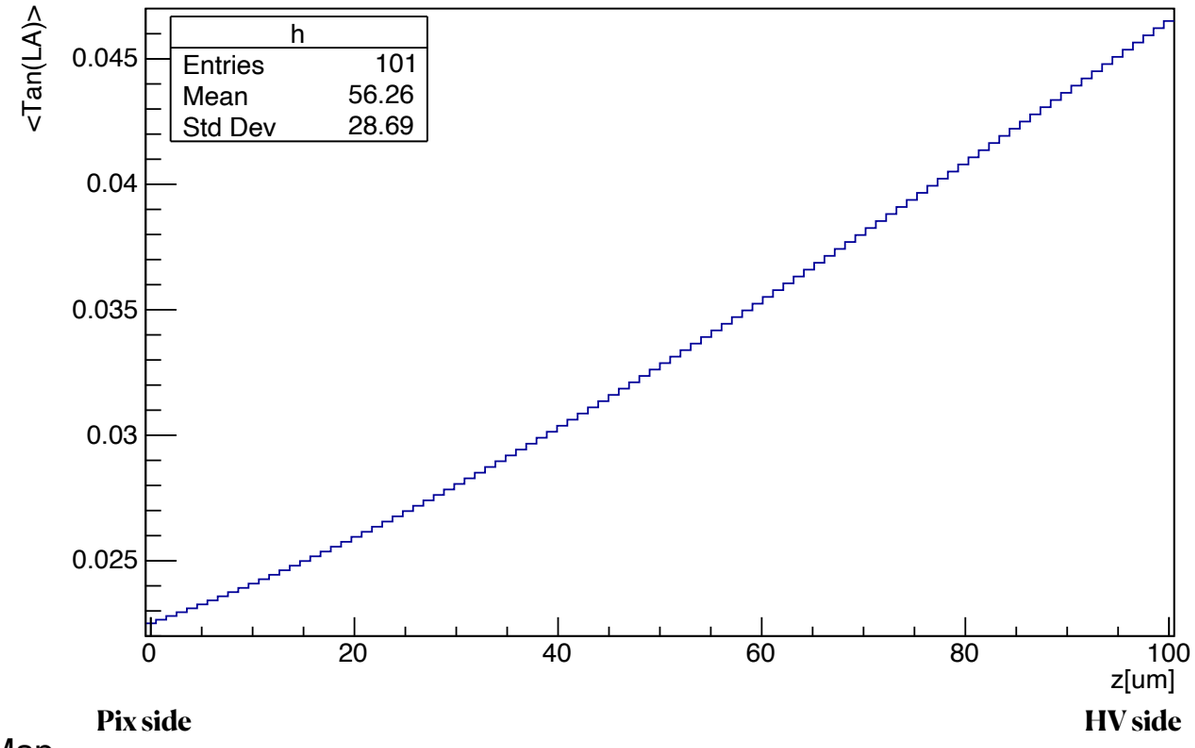
LUTs from Allpix-Squared

LUTs

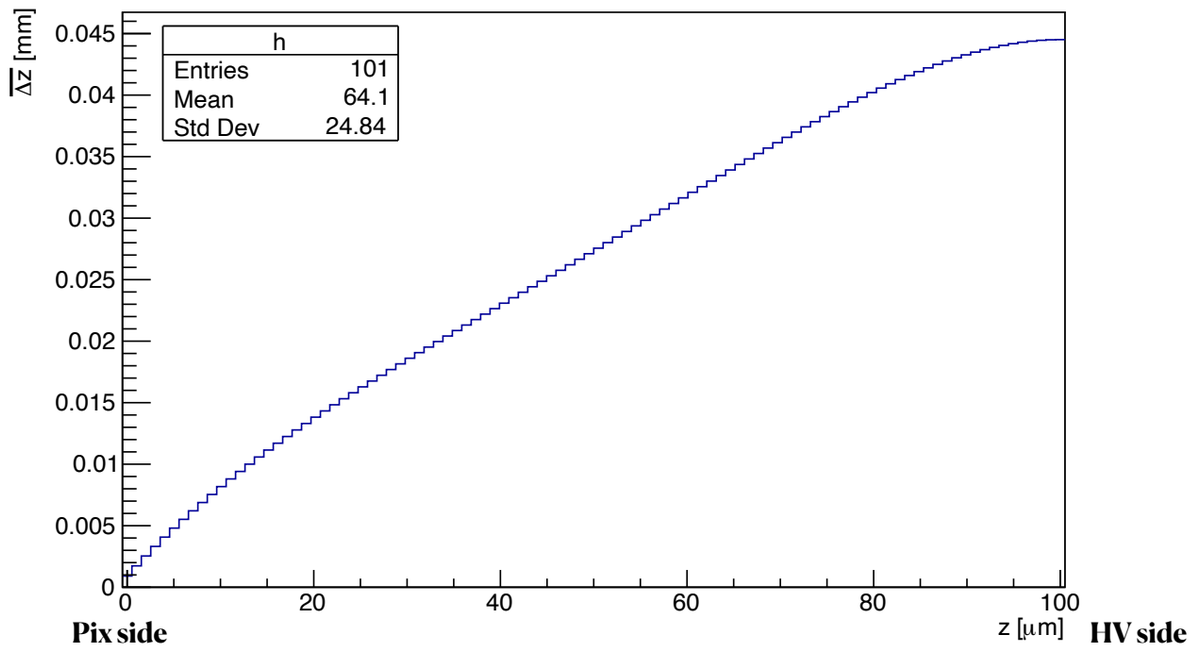
Charge collection efficiency map



Tan Lorentz Angle Map



Δz Map



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(Z) = CCE(Z_deposited)*q(Z_deposited)
    - Z_propagated = Z_deposited + $\Delta Z(Z_{deposited})$
    - x_propagated = x_deposited + $tan(\theta_L)(Z_{deposited})$ * $\Delta Z(Z_{deposited})$
  - 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 : LUT propagator codes
- Performed closure tests with: point charge deposition, line charge deposition, **120 GeV Pions** using LUTs generated with the "scan" model of charge deposition
  - Pixel week Nov'23 : slides
  - AUW Nov'23 : slides

Closure test

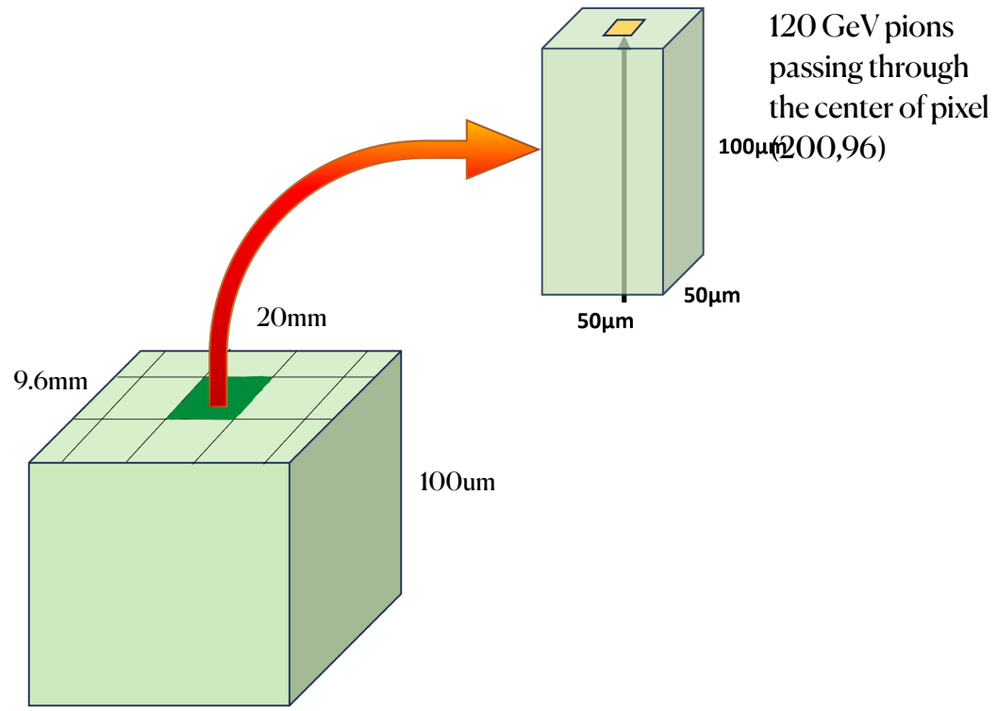
Simulation of 120GeV Pions

- Each event has a single 120GeV pion passing through the sensitive volume, simulate 1000 events
  - ✦ Normal incidence, eta = 1, eta = 1.4 (eta values of 100um barrel ITk pixels)
- # e-h pairs created by a given energy deposition calculated using : mean pair creation energy (Si =3.64eV), fluctuations modelled: Fano factor (0.115)
- Scale the charges using **CCE** LUT
- Propagate the carriers using **tan(LA)** and **ΔZ** LUTs
- Compare the results with full AP2 simulation

Highly collimated beam of 120GeV pions

```
[DepositionGeant4]
log_level = "DEBUG"
physics_list = FTFP_BERT_LIV
particle_type = "Pi+"
source_energy = 120GeV
source_position = 25um 25um -1mm
source_type = "beam"
beam_direction = 0 0 1
beam_divergence = 0mrad 0mrad
number_of_particles = 1
```

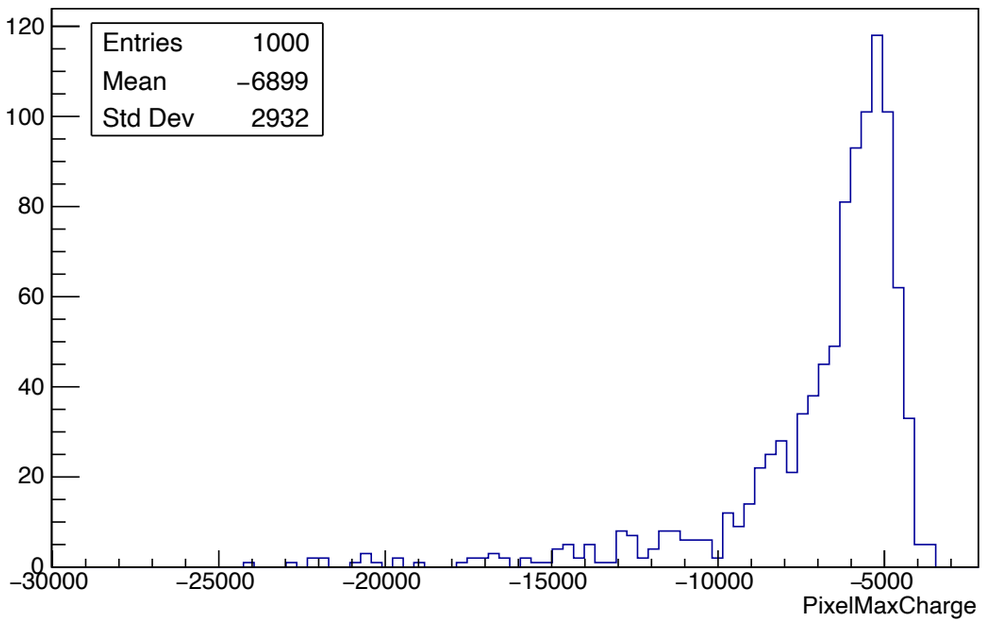
Pions are deposited exactly in the middle of pix (200,96)

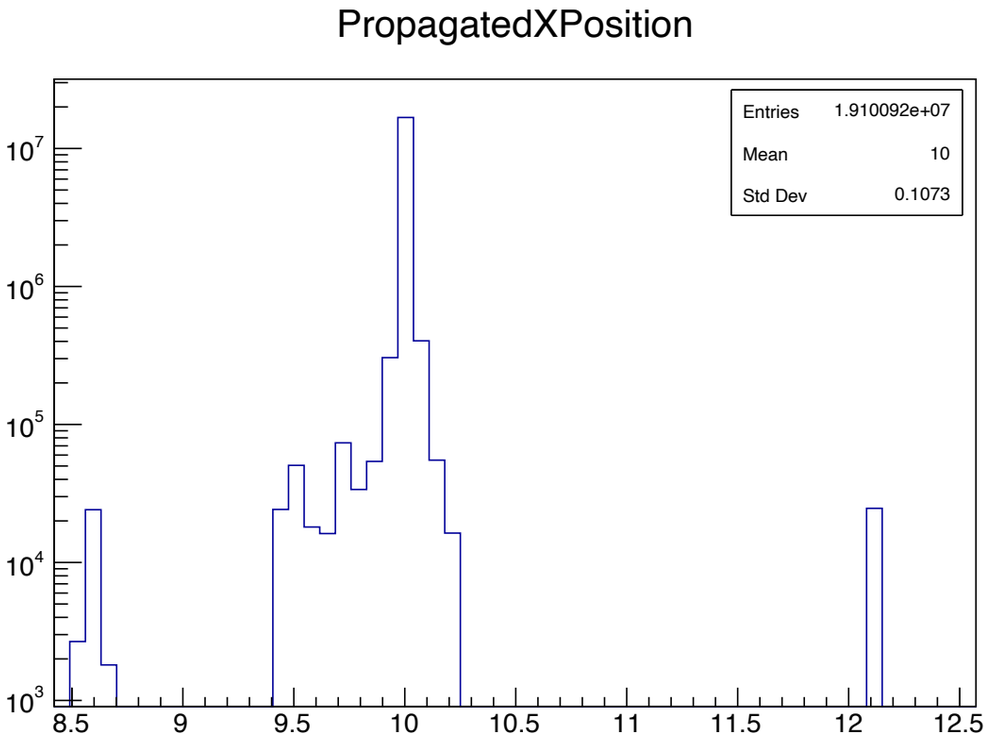


Normal Incidence

Pixel maximum charge & PropagatedXPosition

Full simulation





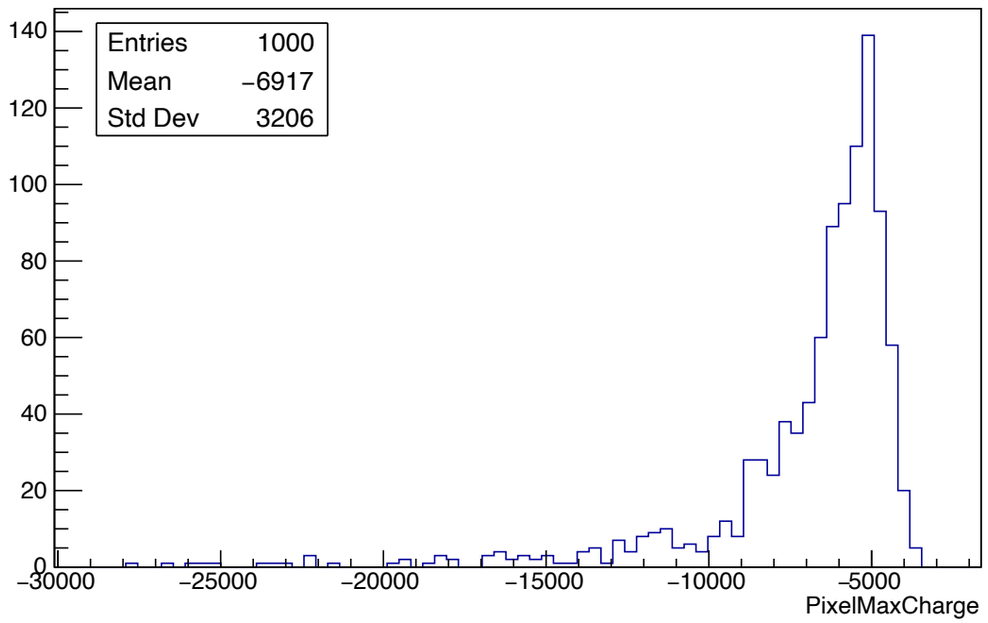
Rel err mean: 0.26%

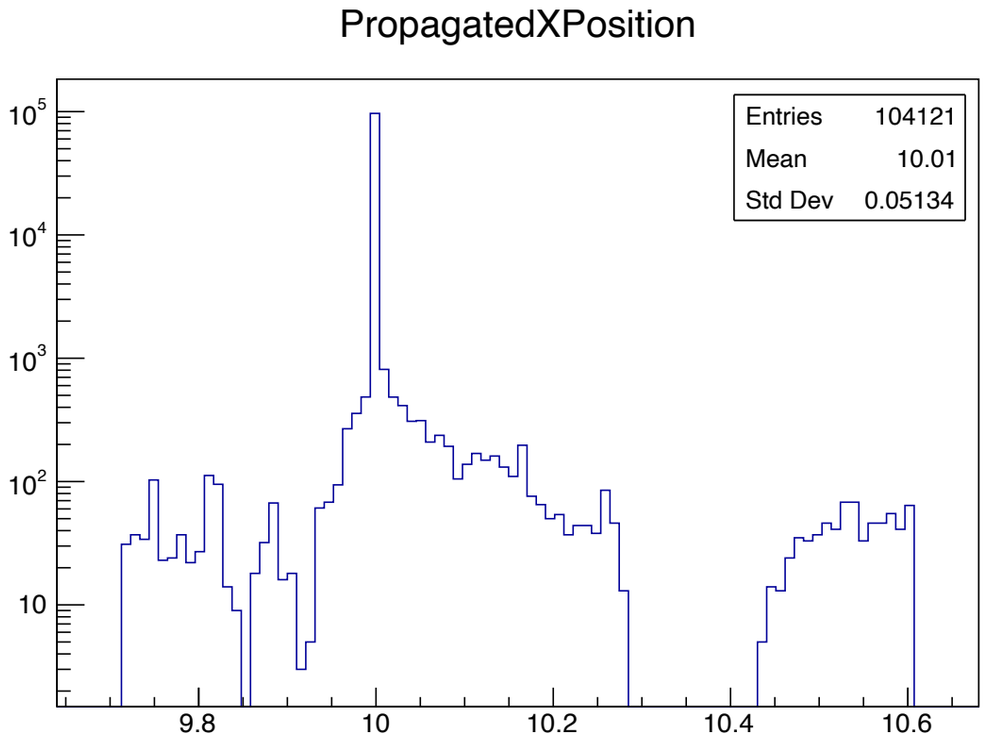
Rel err sigma: 9.3%

Excellent agreement !!

Rel err mean: 0.1%

Closure test

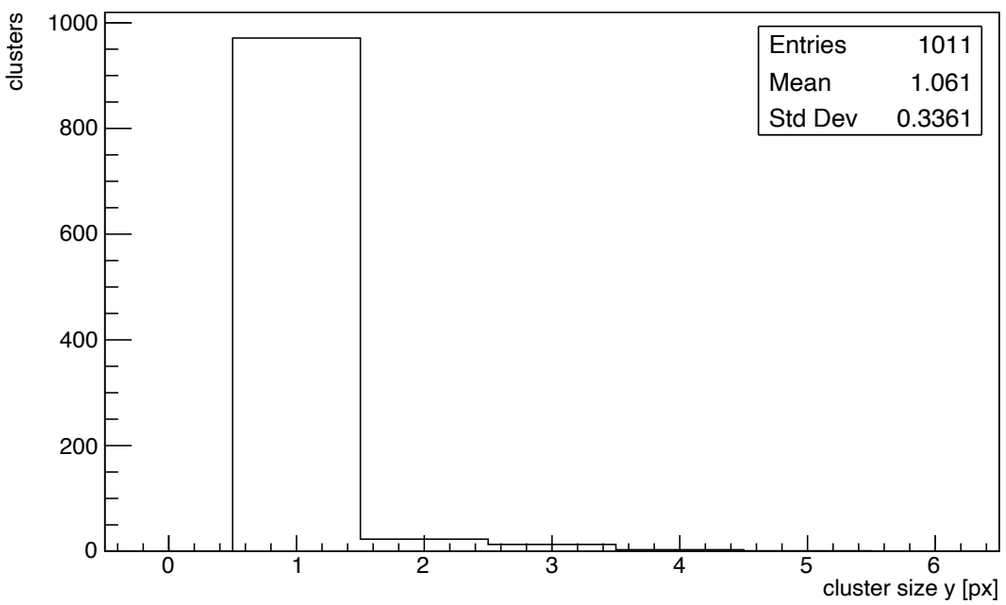




Normal Incidence

Cluster size & Cluster charge

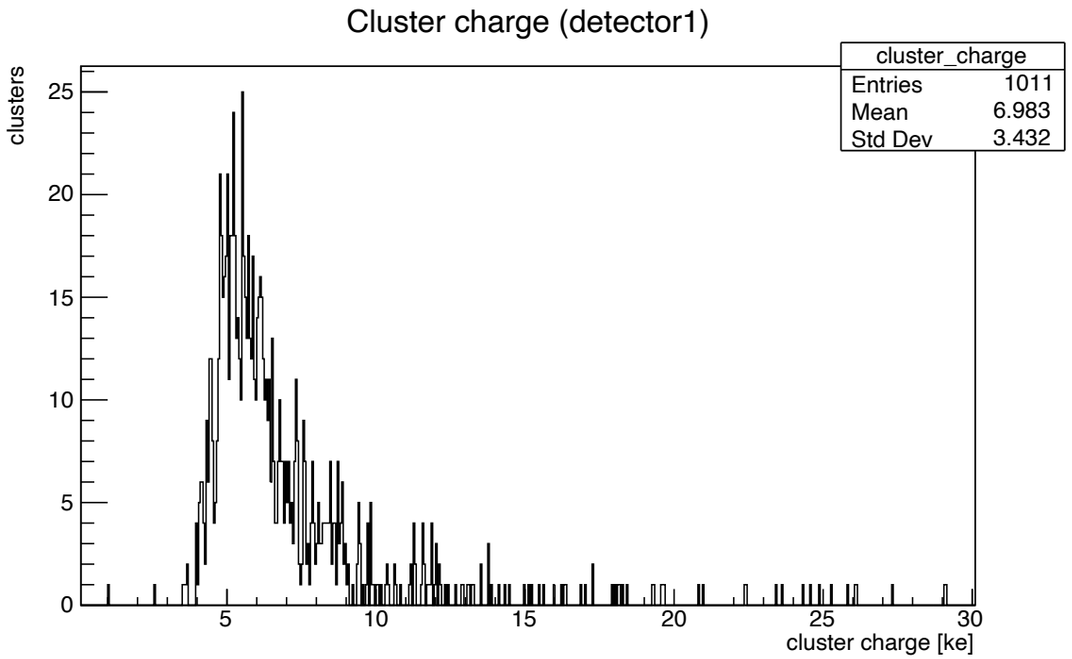
Full simulation



Rel err mean: 1%

Rel err sigma: 0.83%

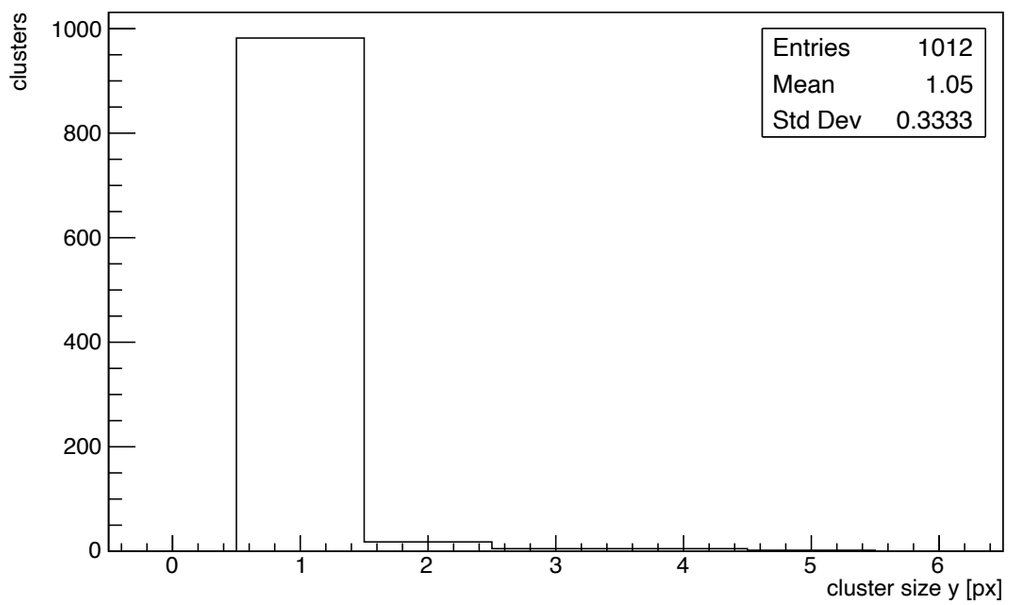
Excellent agreement !!

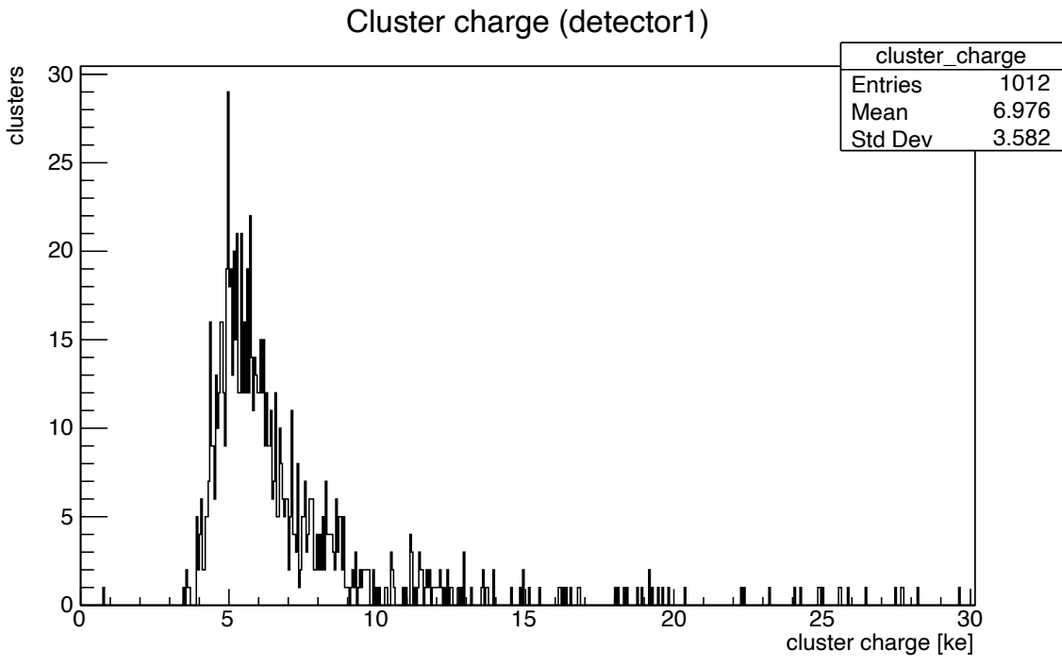


Rel err mean: 0.1%

Rel err sigma: 4.4%

Closure test

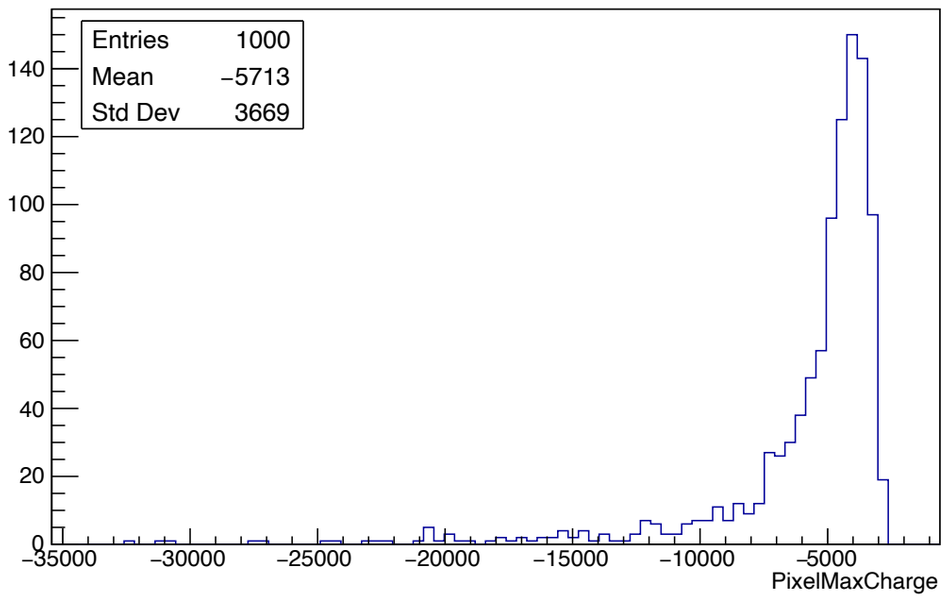


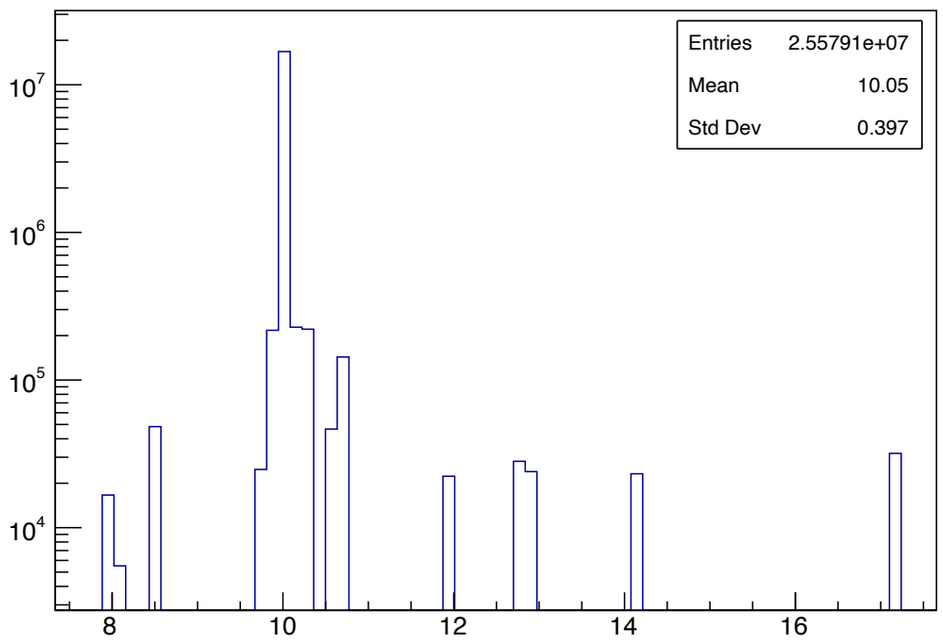


Eta = 1 ($\theta = 0.705 rad$)

Pixel maximum charge & PropagatedXPosition

Full simulation





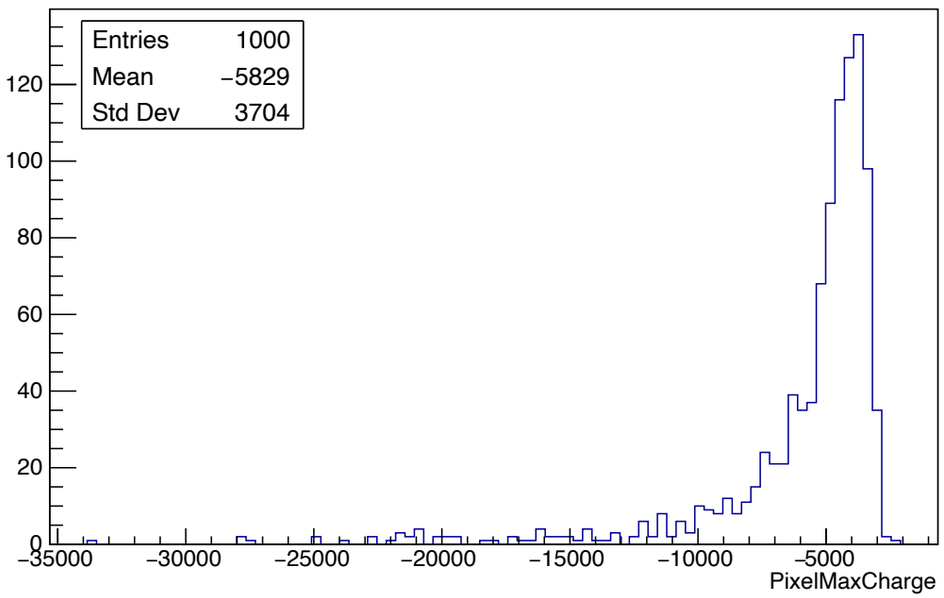
Rel err mean: 2.0%

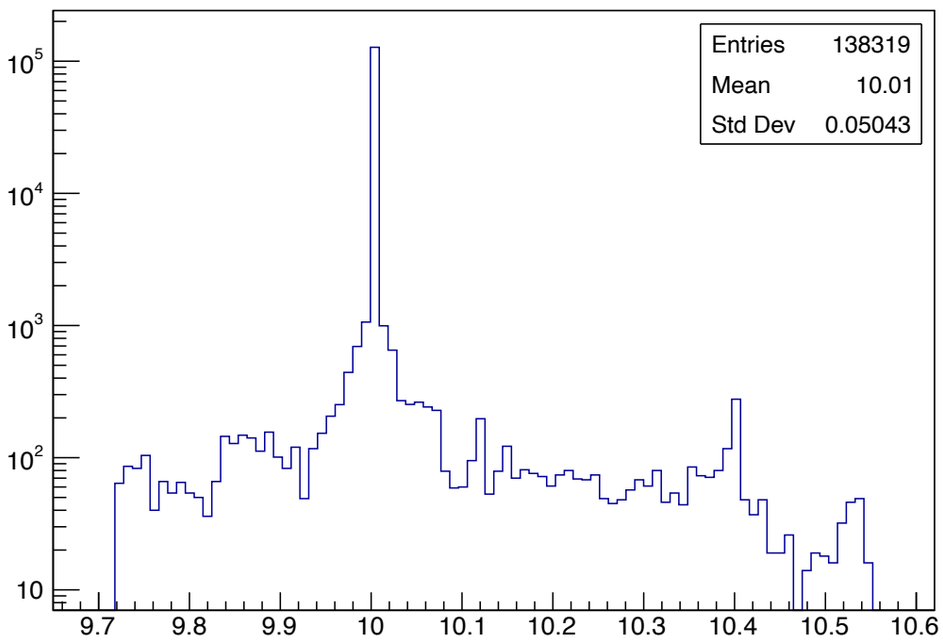
Rel err sigma: 0.1%

Excellent agreement !!

Rel err mean: 0.4%

Closure test

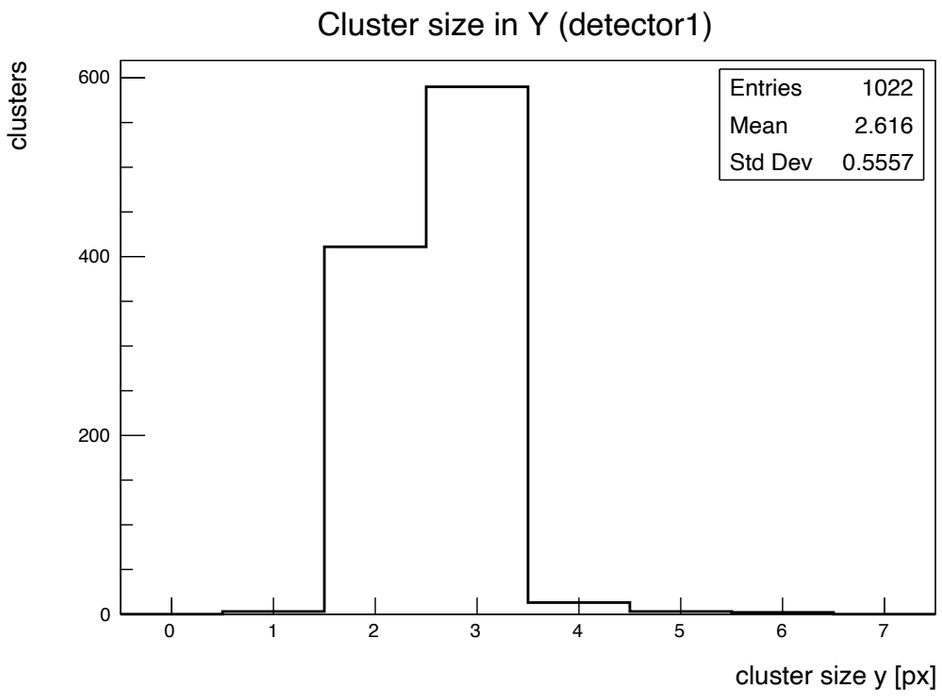


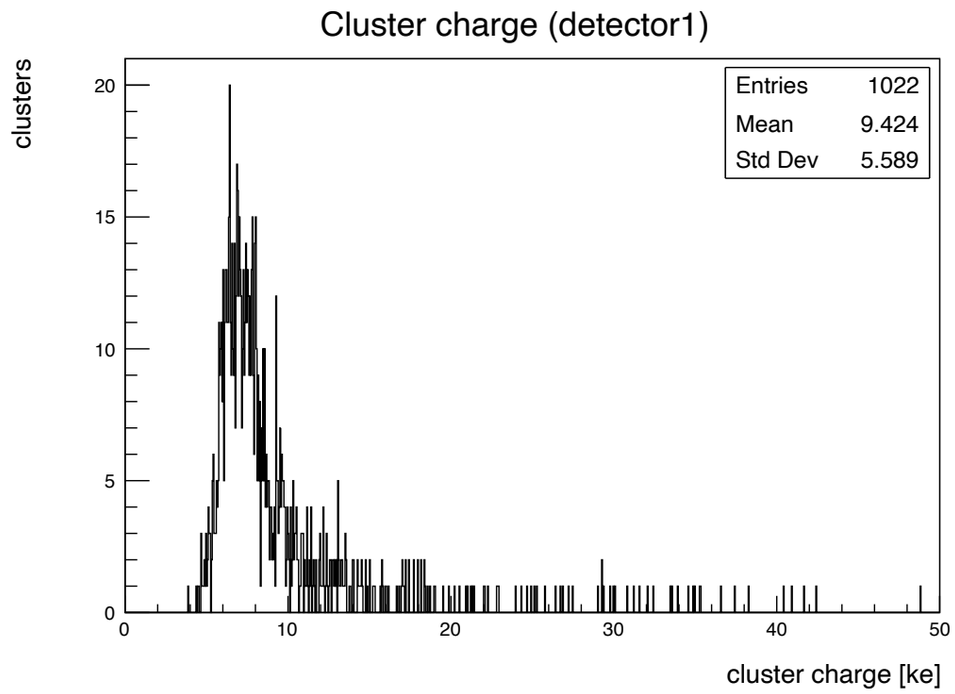


Eta = 1 ($\theta = 0.705 rad$)

Cluster size & Cluster charge

Full simulation





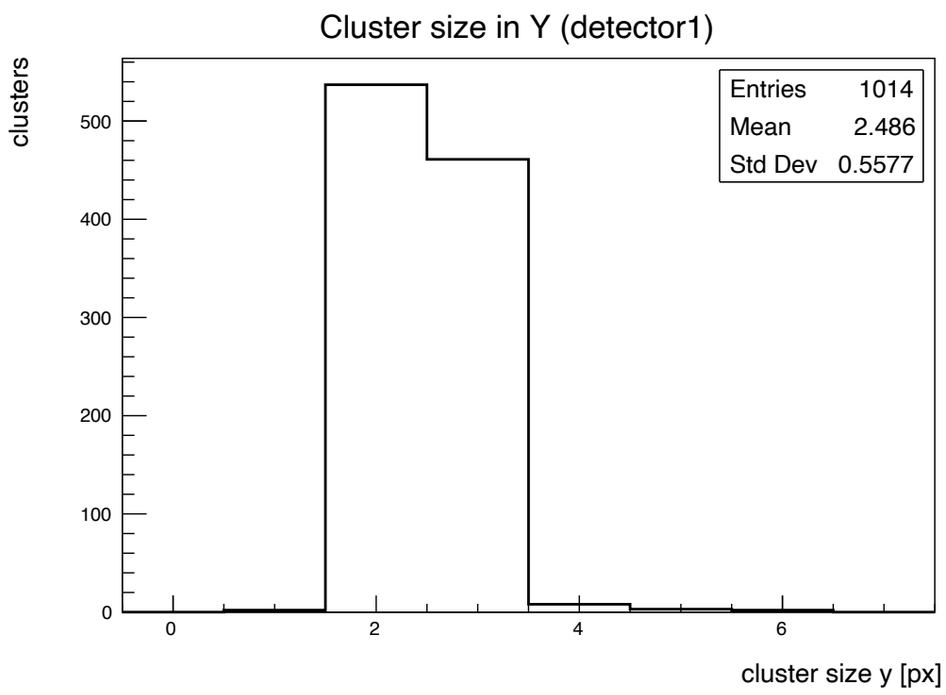
Rel err mean: 4.9%

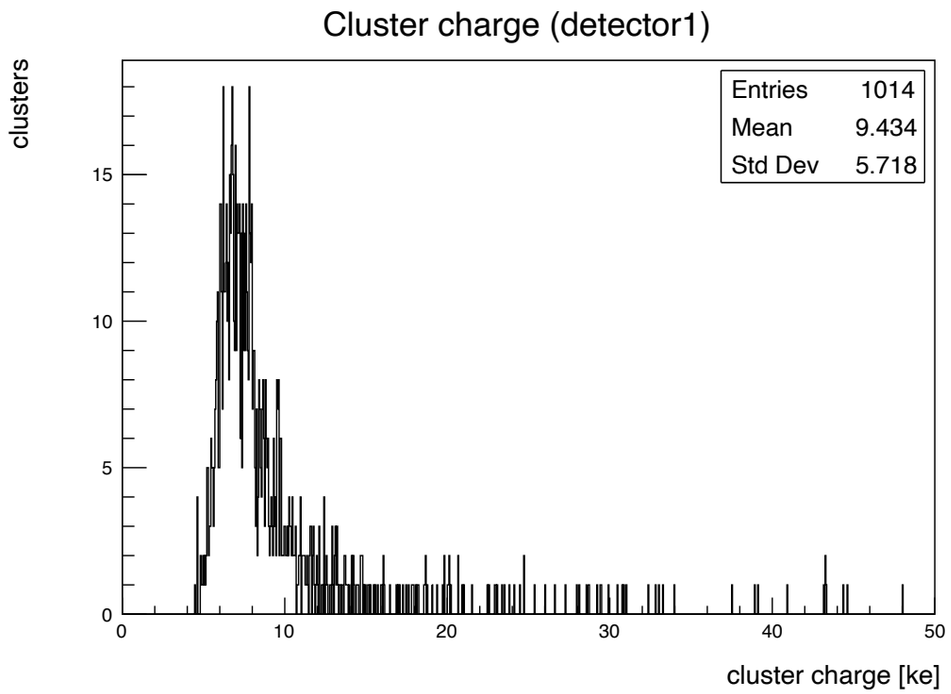
Excellent agreement !!

Rel err mean: 0.11%

Rel err in sigma: 2.3%

Closure test

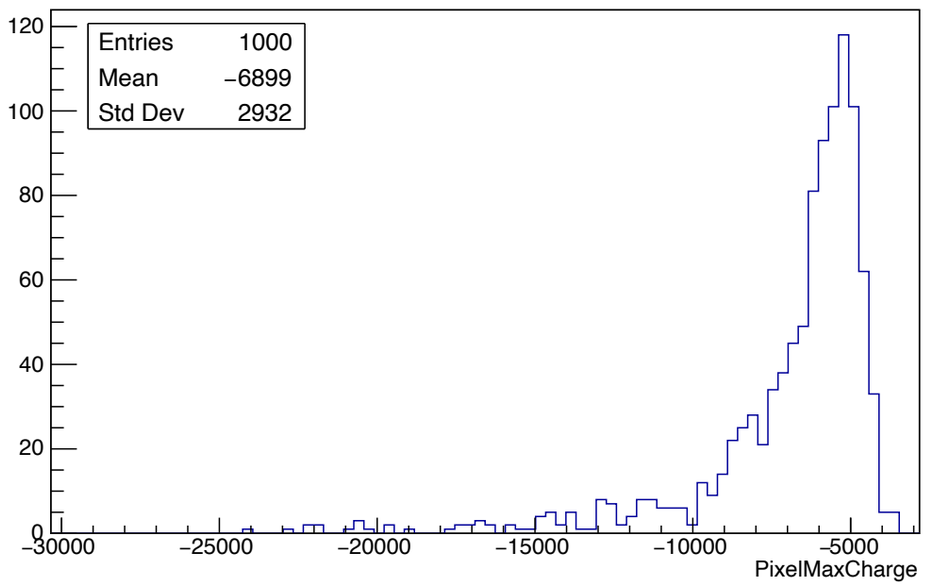


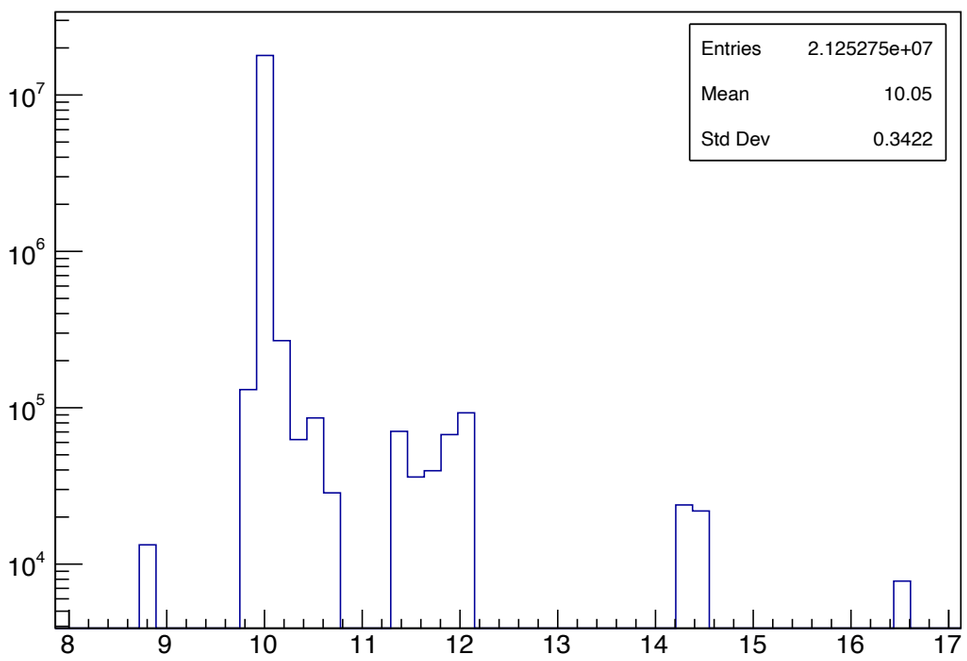


Eta = 1.4 ($\theta = 0.483 rad$)

Pixel maximum charge & PropagatedXPosition

Full simulation





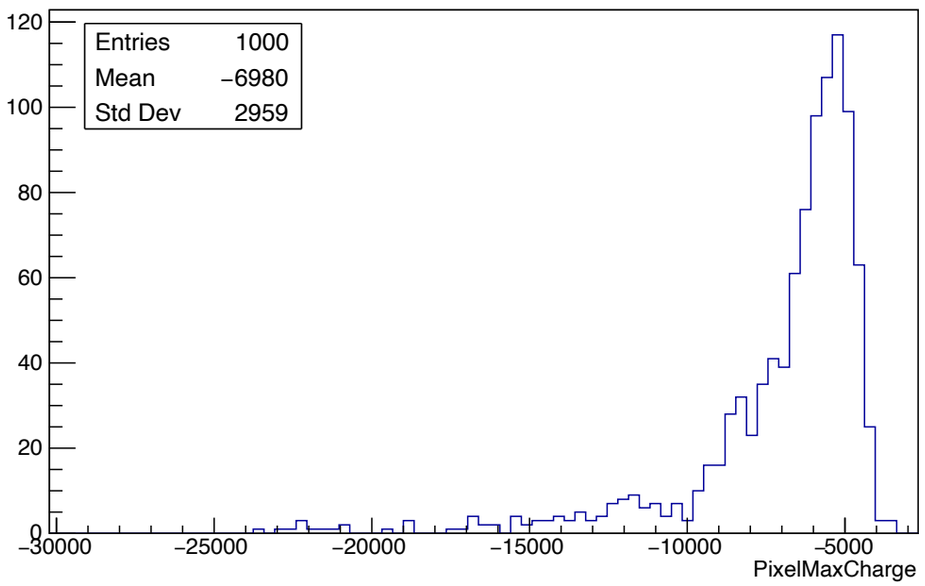
Rel err mean: 1.2%

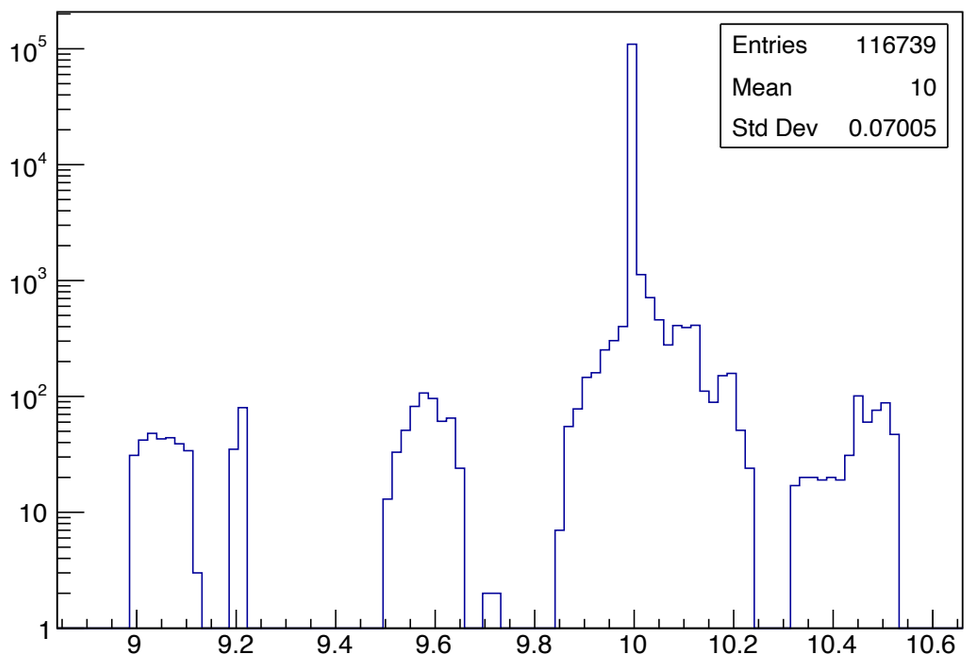
Rel err sigma: 0.92%

Excellent agreement !!

Rel err mean: 0.49%

Closure test

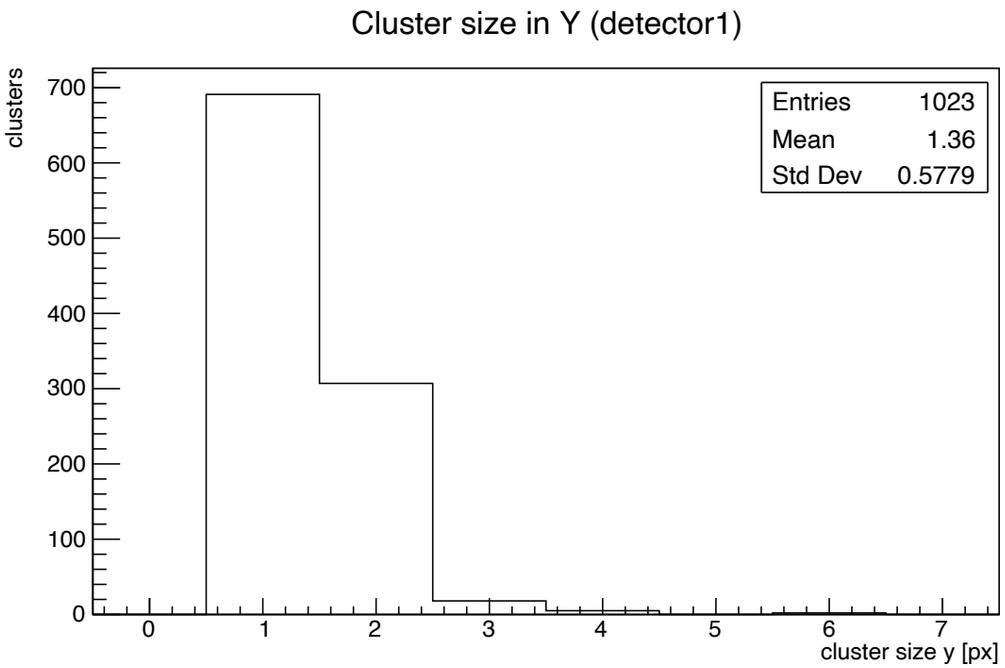


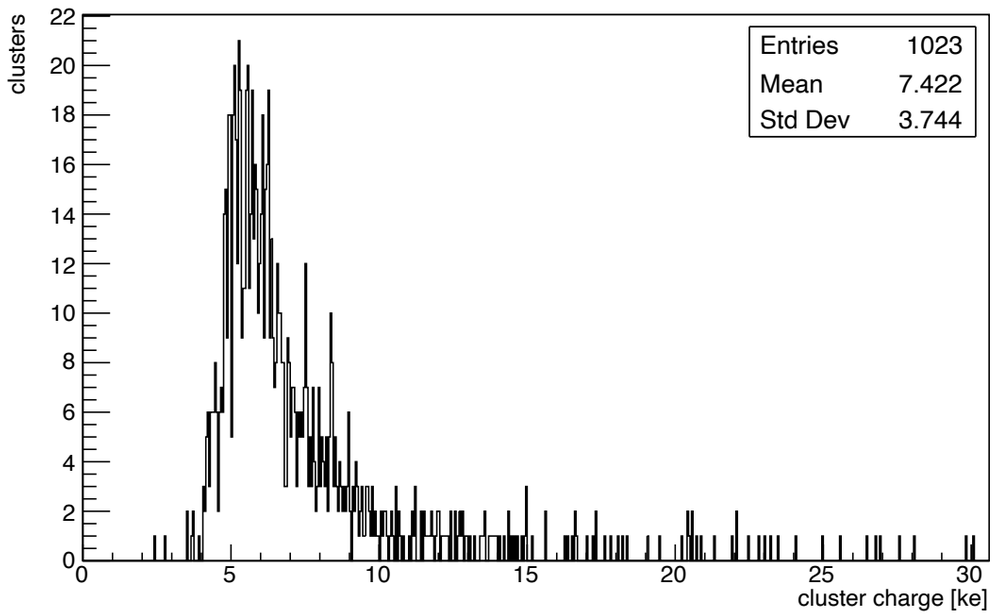


Eta = 1.4 ($\theta = 0.483 rad$)

Cluster size & Cluster charge

Full simulation





Rel err mean: 5.1%

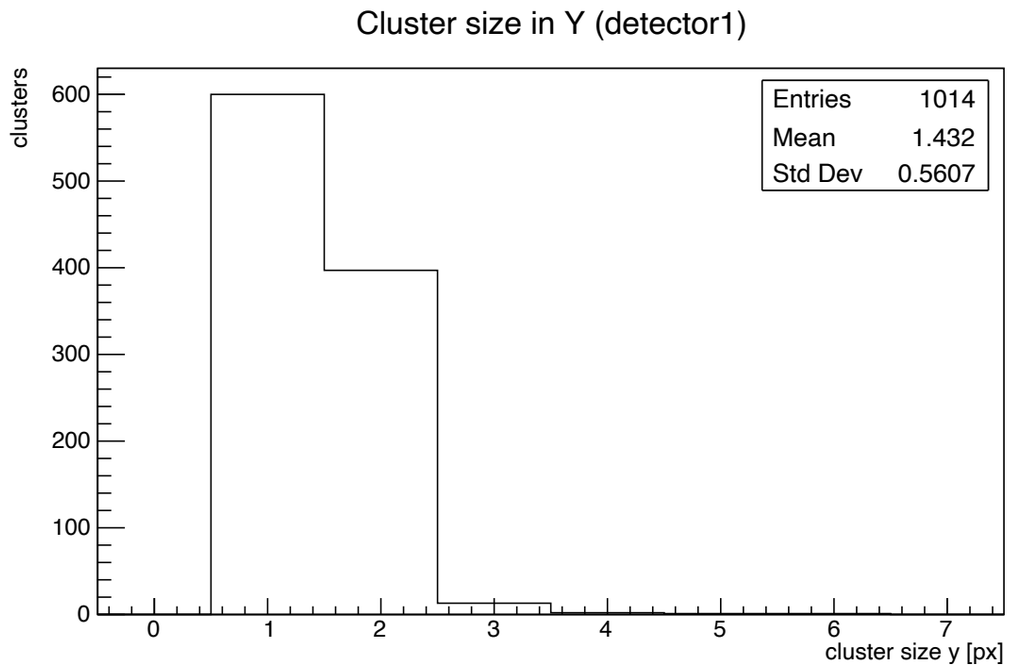
Rel err sigma: 3%

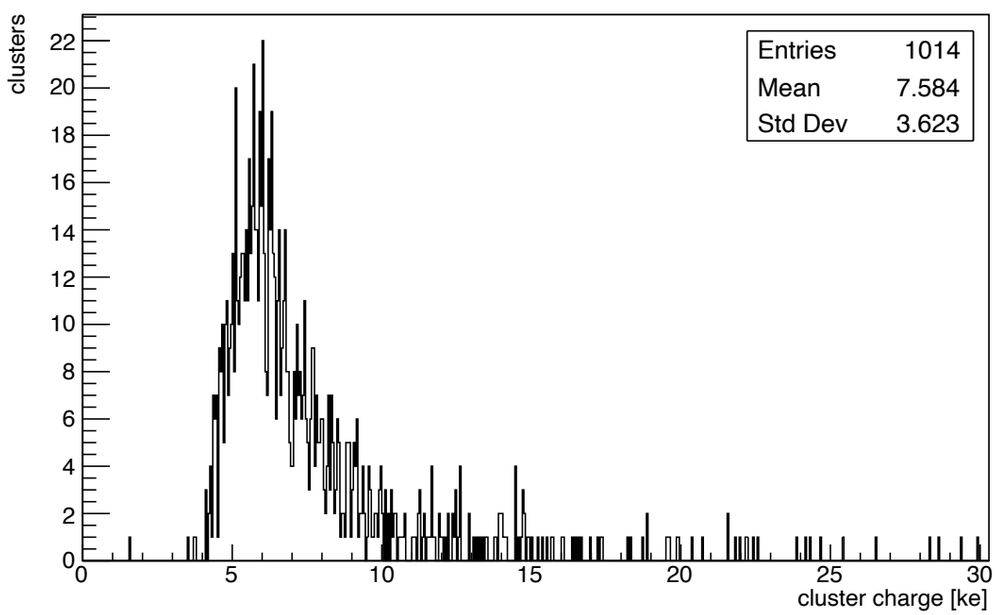
Excellent agreement !!

Rel err mean: 2.2%

Rel err sigma: 3.2%

Closure test





Closure test results

Relative errors on mean: putting everything together!

#	Pixel max charge	Cluster size	Cluster Charge
Normal Incidence	0.26%	1 %	0.1%
$\eta = 1(\theta = 0.705rad)$	2 %	4.9%	0.11%
$\eta = 1.4(\theta = 0.483rad)$	1.2%	5.1%	2.2%

- Closure test at normal incidence is in excellent agreement with the full simulation
- Good agreement in the mean cluster charge distributions in all the cases -> important variable for track reconstruction
- Despite using a simple method/strong approximation, achieved very good results!

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 plus detailed 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, ΔZ vs Z LUTs from Allpix-squared using "scan" model V
- Validated the approach using closure tests: point charge depositions, line charge deposition, **120GeV Pions** using **[LUTPropagator]** **Planning to merge in the official AP2 repository**
- Similar efforts in progress for 3D and strip detectors
- Next steps :
  - ✦ Tests with Pions incident at different beam energies
  - ✦ Anticipating the 2024 TB campaign for ITkPixV2 modules to validate our approach with the TB data

Thank you so much for your attention !! :)