APSQ User WS@University of Oxford , 22 - 24 May 2024

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

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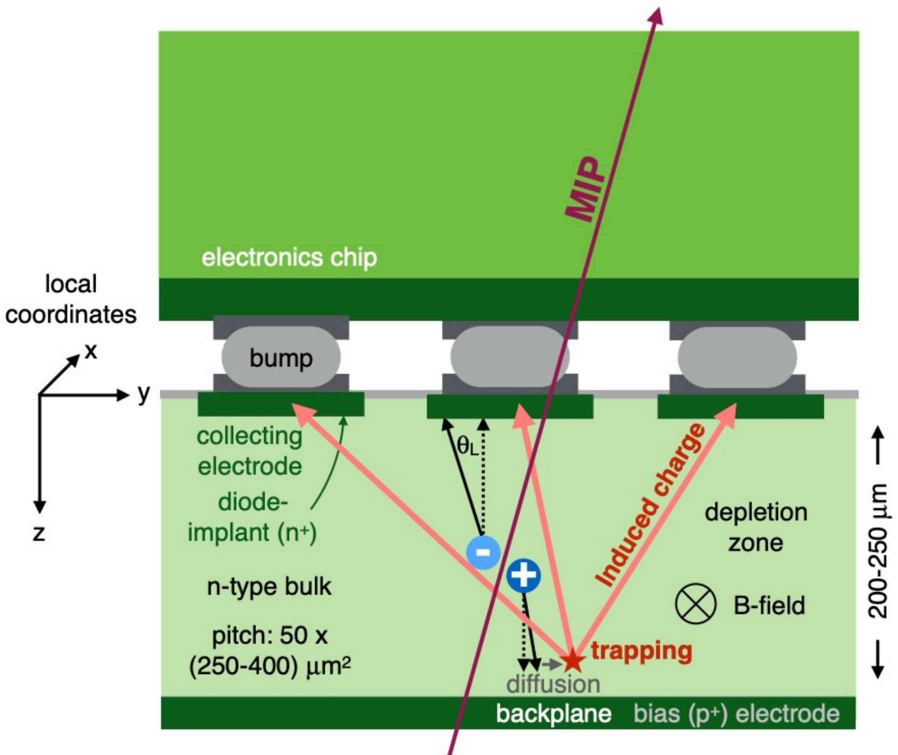
Radiation damage modelling : ATLAS approach

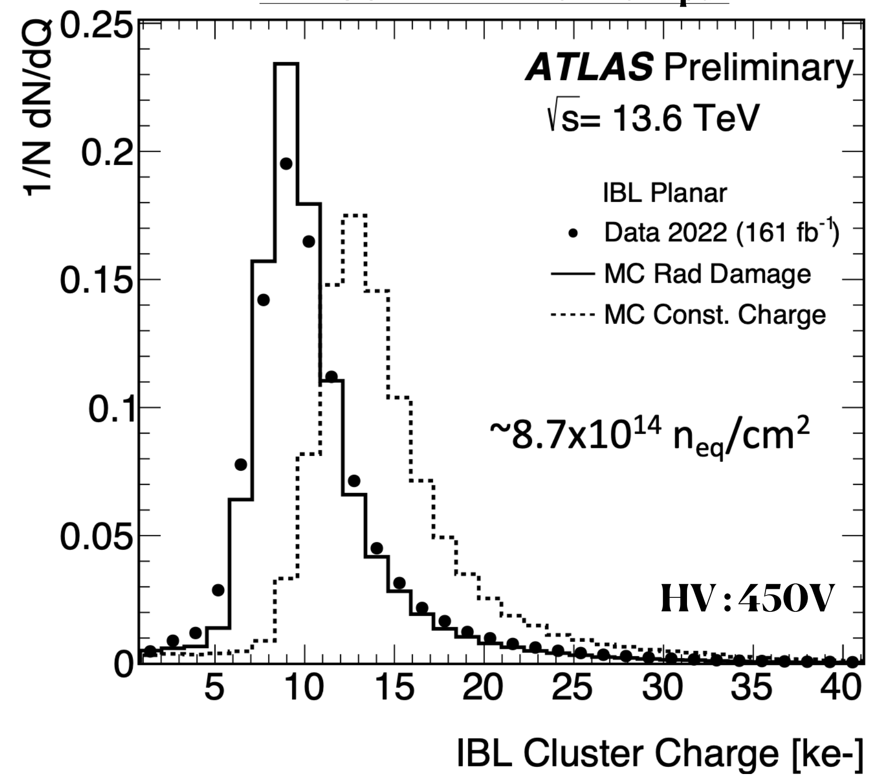
Run2 and Run3 strategy

- 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)



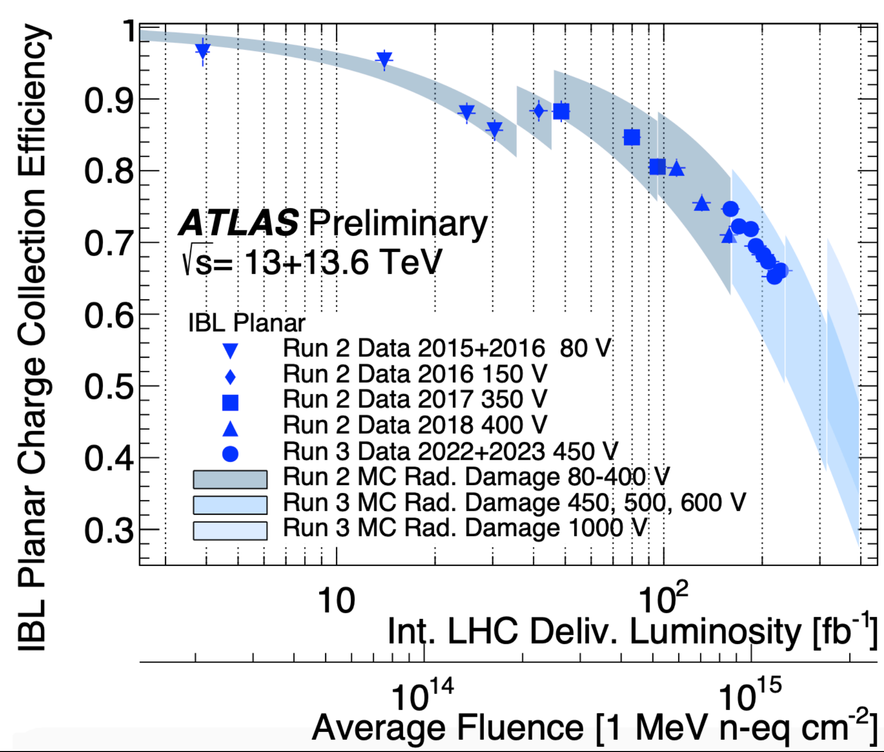
https://iopscience.iop.org/article/10.1088/1748-0221/14/06/P06012

ATL-COM-INDET-2022-027.pdf



Most Probable Values match at 1 % level!

ATL-COM-INDET-2023-008.pdf

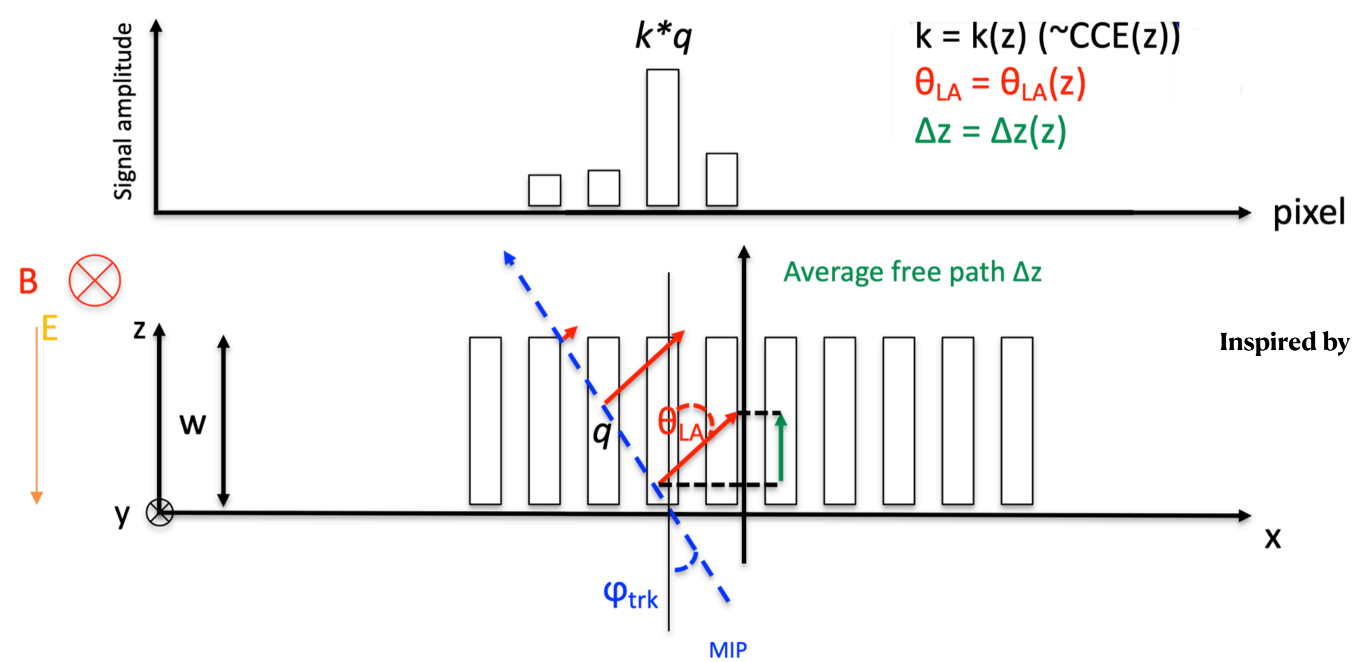


Excellent agreement over almost two order of magnitudes of fluence!

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 (**LUT**s)



Inspired by CMS "template method"

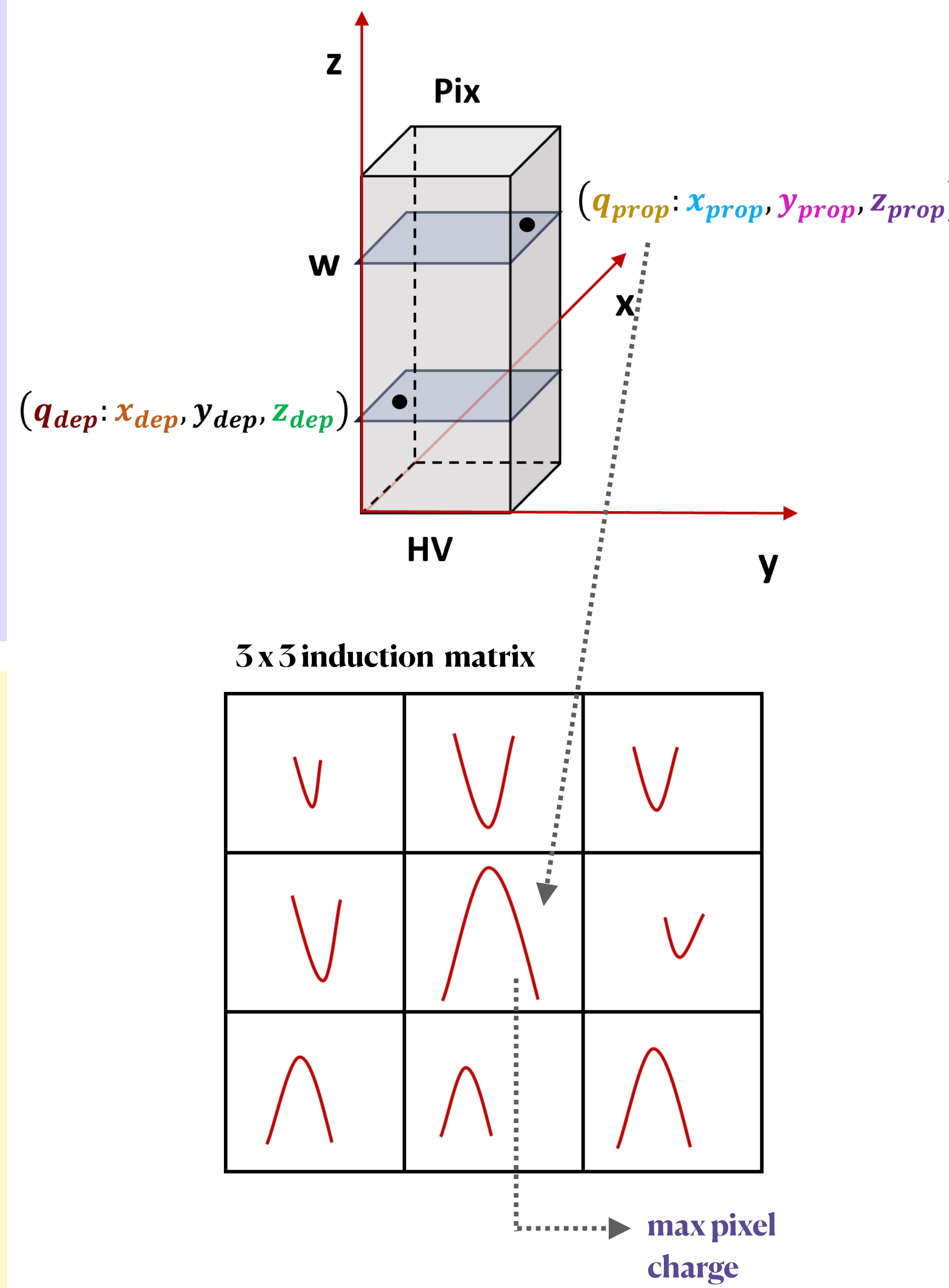
- Idea : For each simulated charge q at depth **z** find in which pixel it will end up, by how much **(*k*) the signal will be reduced**
  - ✦ Goal: Simulated pixels in MC is corrected using these information before digitisation -> correction scheme implemented using **Allpix-squared** (doi:10.1016/j.nima.2018.06.020)

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 2 µm along z
  - ✦ Simulation for **100 µm** thick **planar** sensor at **4x10^{15} n_{eq}/cm^{2}** and **600 V**

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



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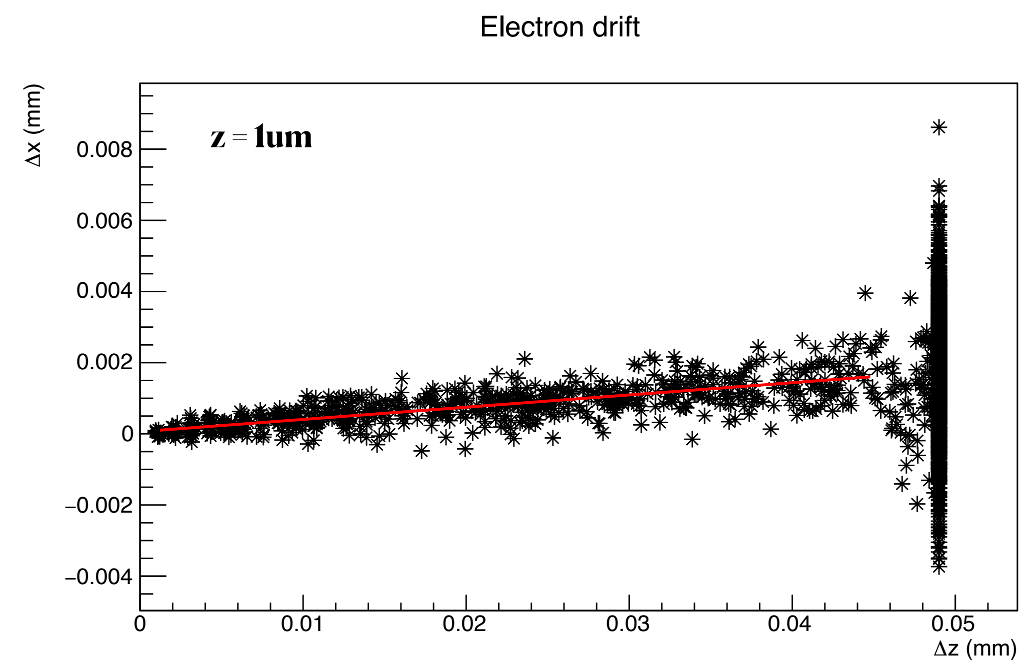

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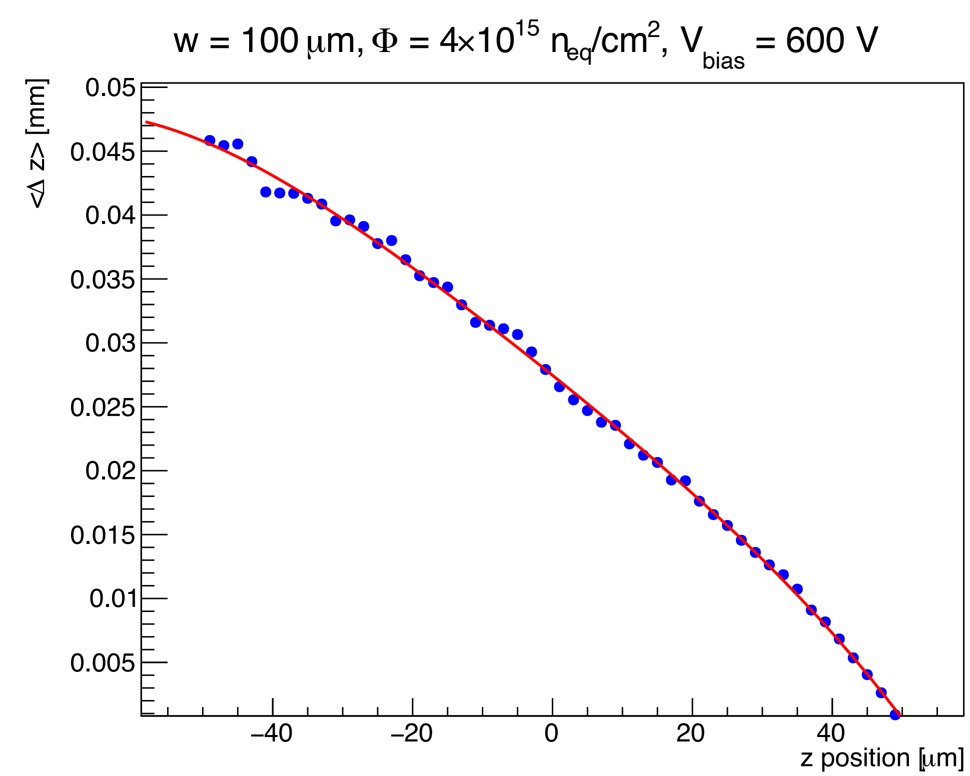
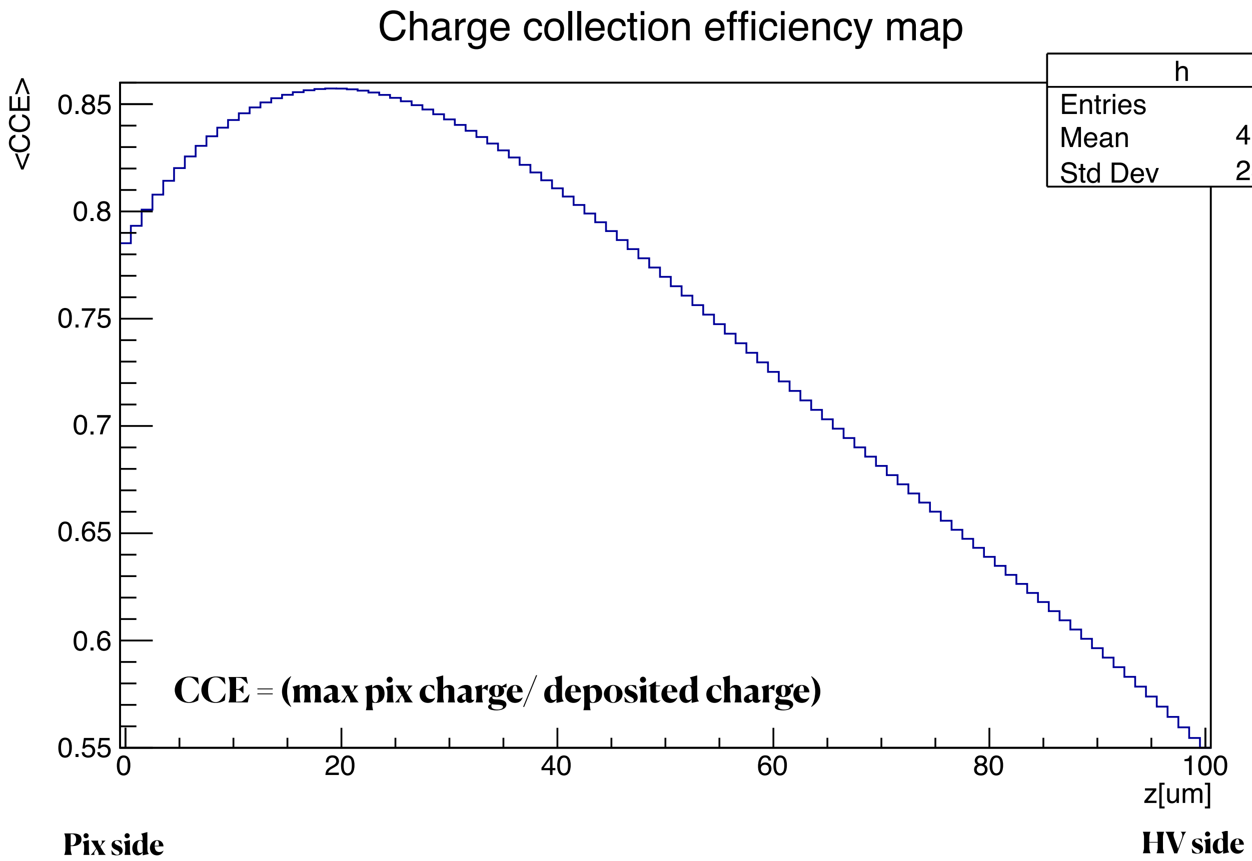
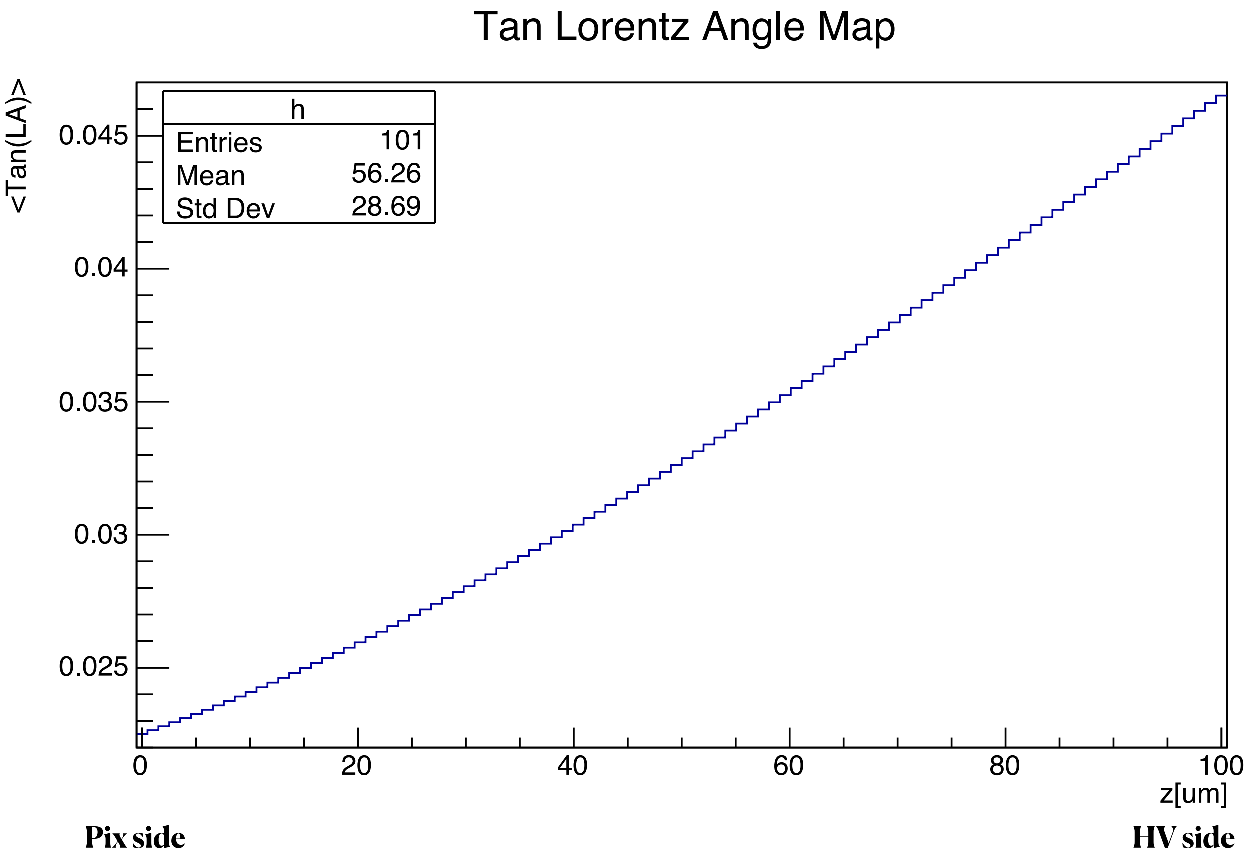
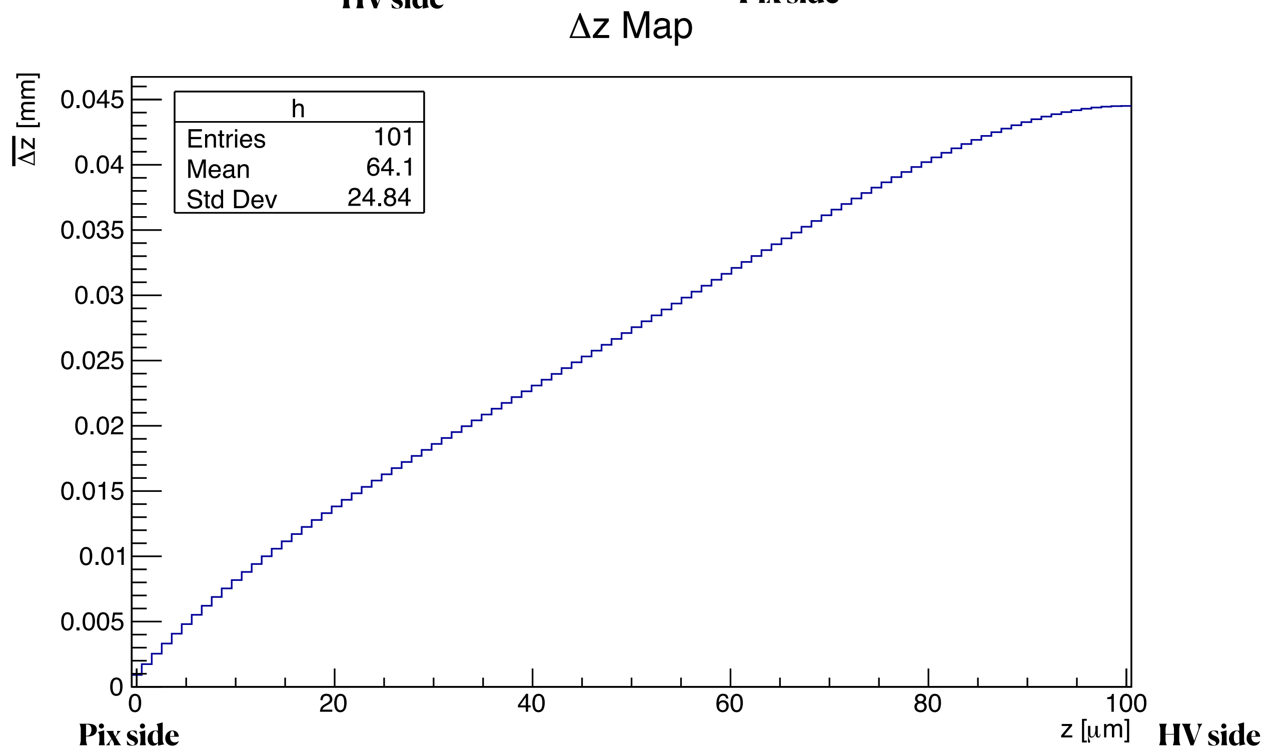


LUTs from Allpix-Squared

LUTs



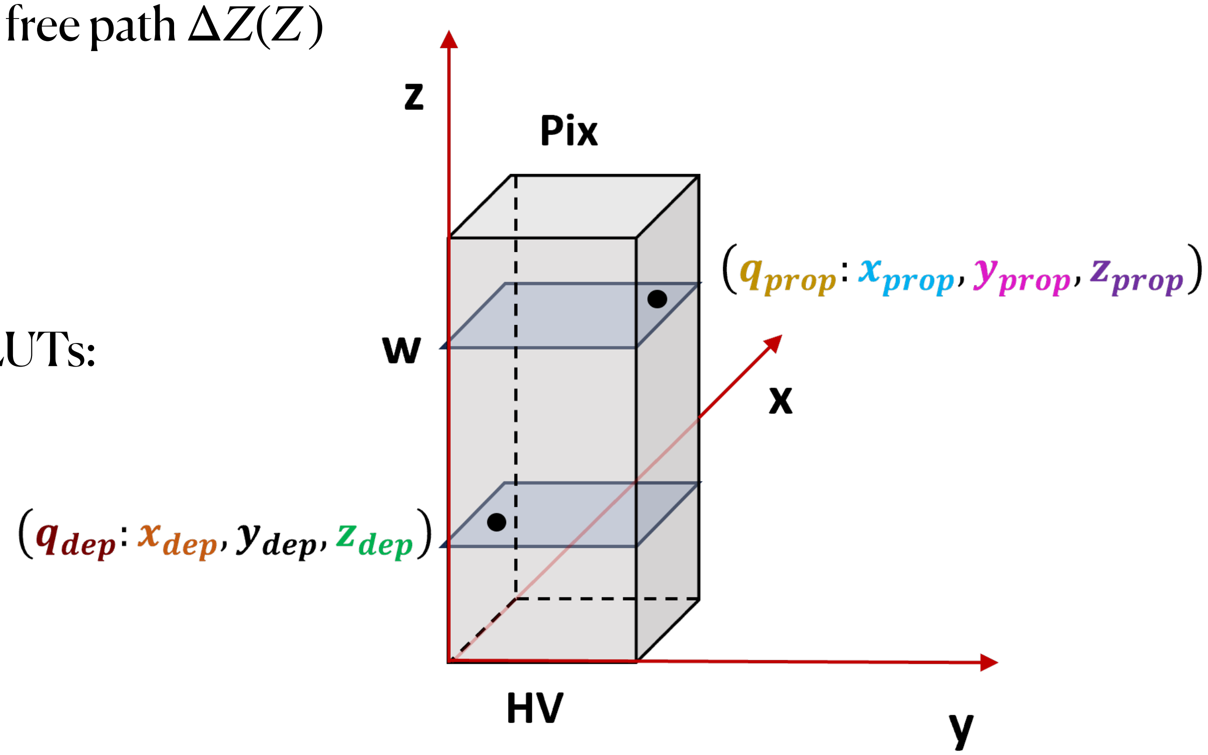




- Fluence = $4x10^{15}\ n_{eq}/cm^2$
- Voltage = 600V
- Thickness = 100 μm
- Pitch = 50 μm x 50 μm

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

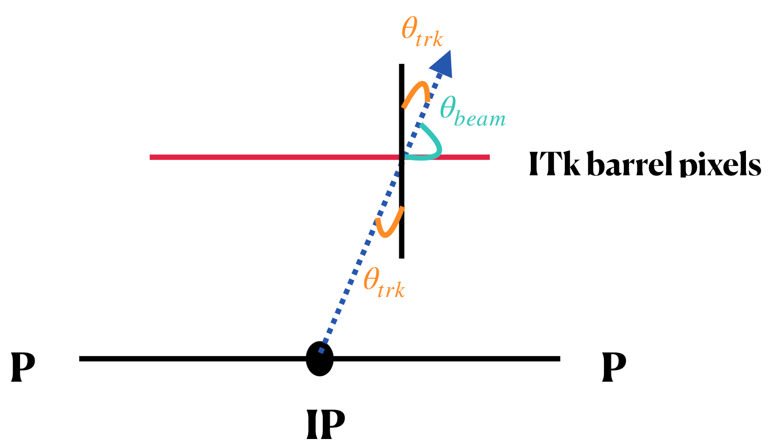


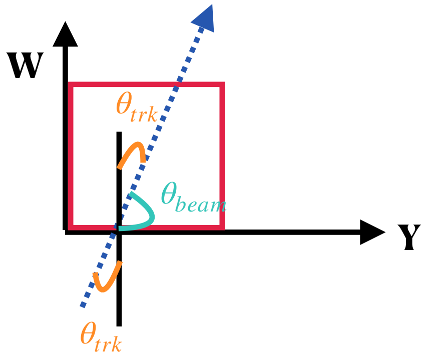
- Developed a new module in Allpix-squared : LUTPropagator
- Performed closure tests with: point charge deposition, line charge deposition, **120 GeV Pions** using LUTs generated with the "scan" model of charge deposition
  - RD50 Dec'23 : slides
  - Allpix-Squared user workshop May23 : slides

Realistic simulation studies of ITk barrel pixels

Investigating Pt and η 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 µm x 50 µm**) at a fluence of **4x10^15 neq/cm2** and **600V**
    - Pions (π^+) with **Pt** = **100 GeV, 10 GeV** and **1 GeV** at η = **0, 1 and 1.4** (θ_{trk} = 0 rad, 0.866 rad and 1.088 rad respectively)
        - Each event has a single pion passing through the detector ; 1000 events simulated

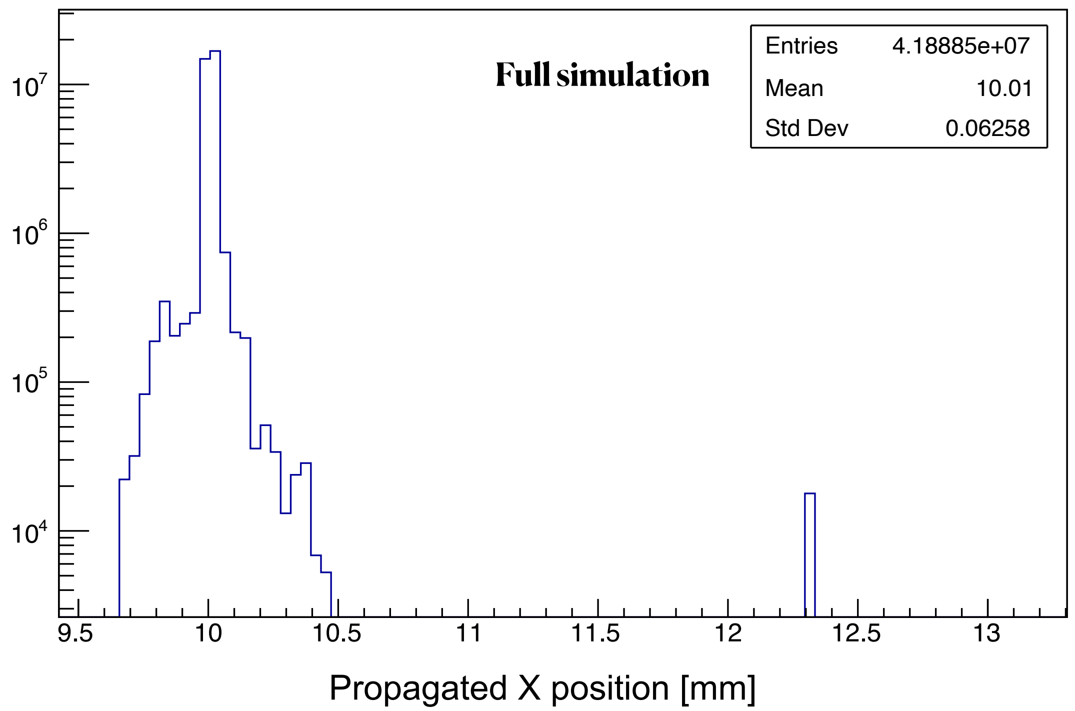




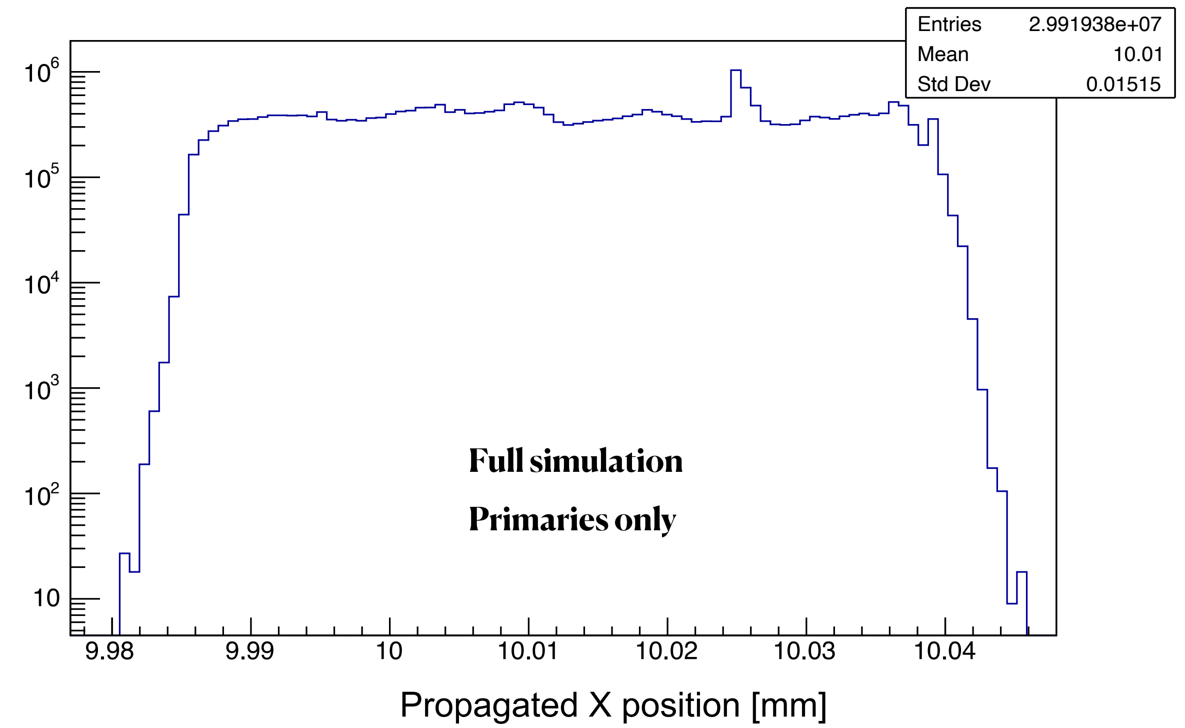
- Comparison of Allpix-Squared full simulation (FS) with LUTPropagator based simulations (LUT)
    - LUTPropagator module : Scale the charges using **CCE** LUT , propagate the carriers using **tan(LA)** and **ΔZ** LUTs
- Comparison variables : propagated X position, cluster size x, cluster size y, cluster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

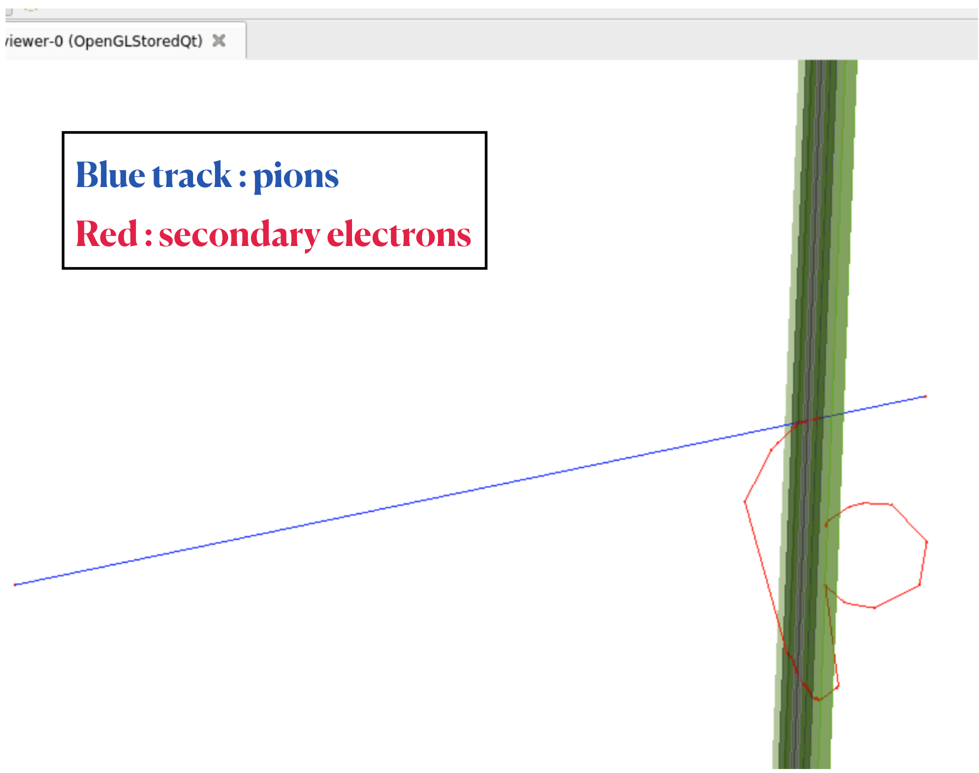
PropagatedXPosition

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



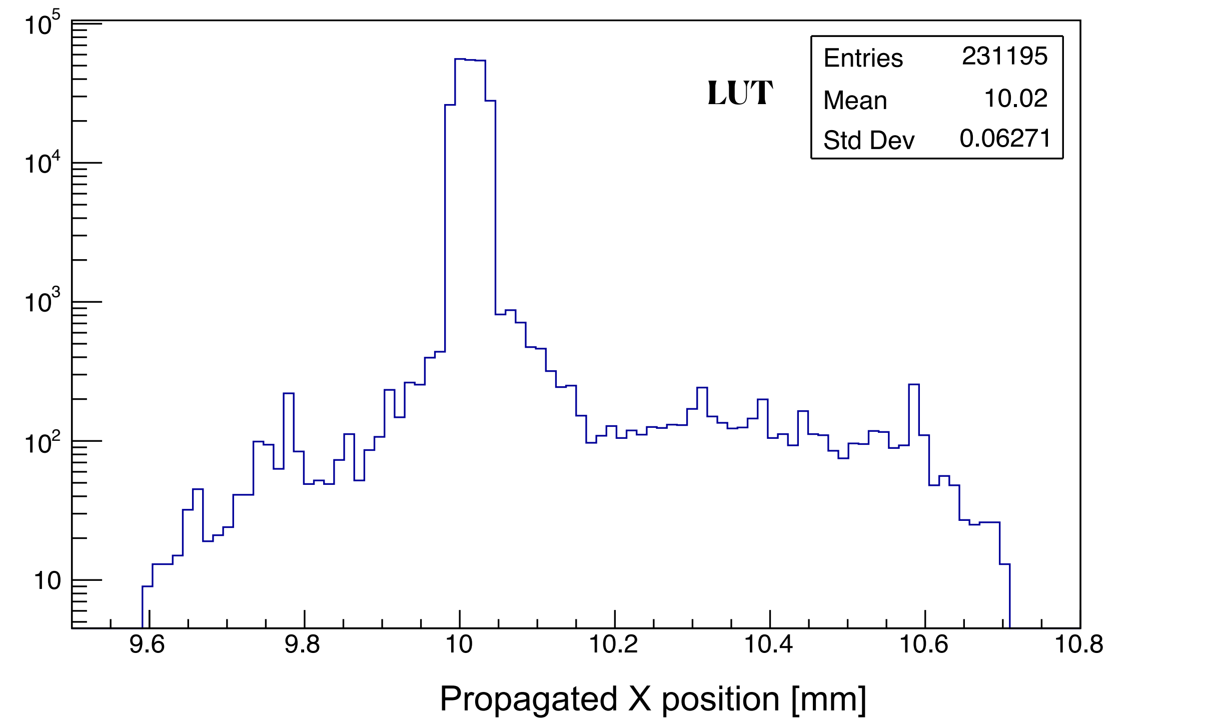
Filtering secondaries





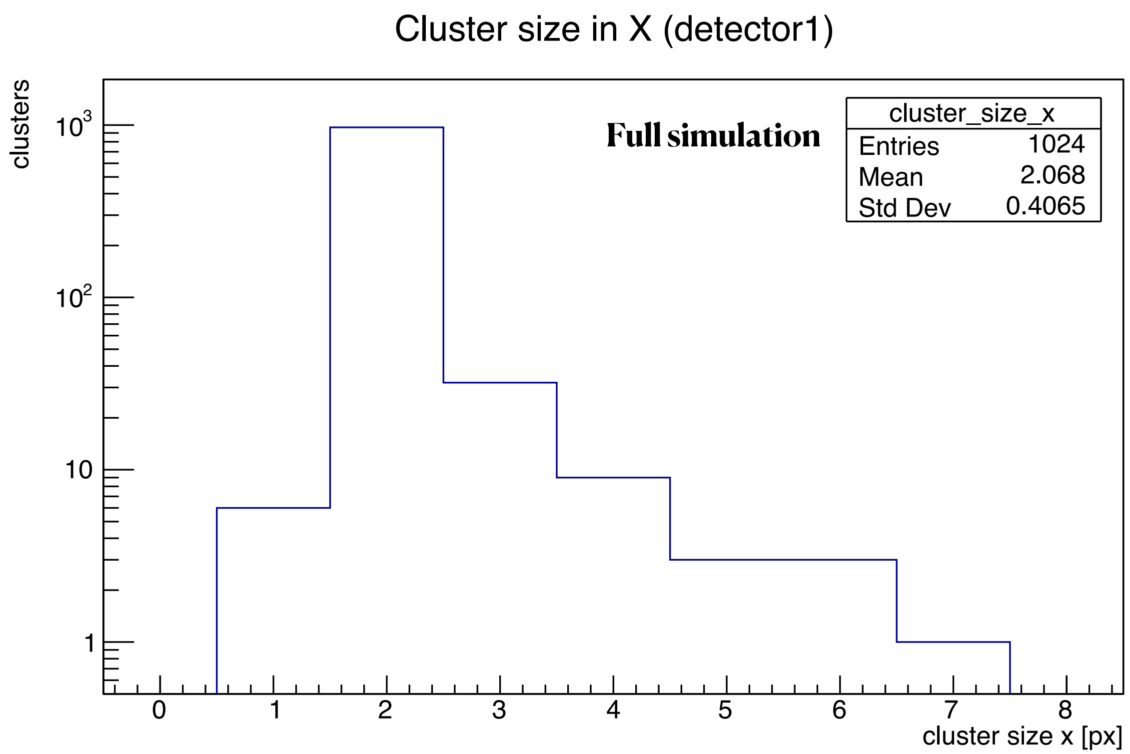
Diff = 7.4um

Diff/pitch = 14.8%

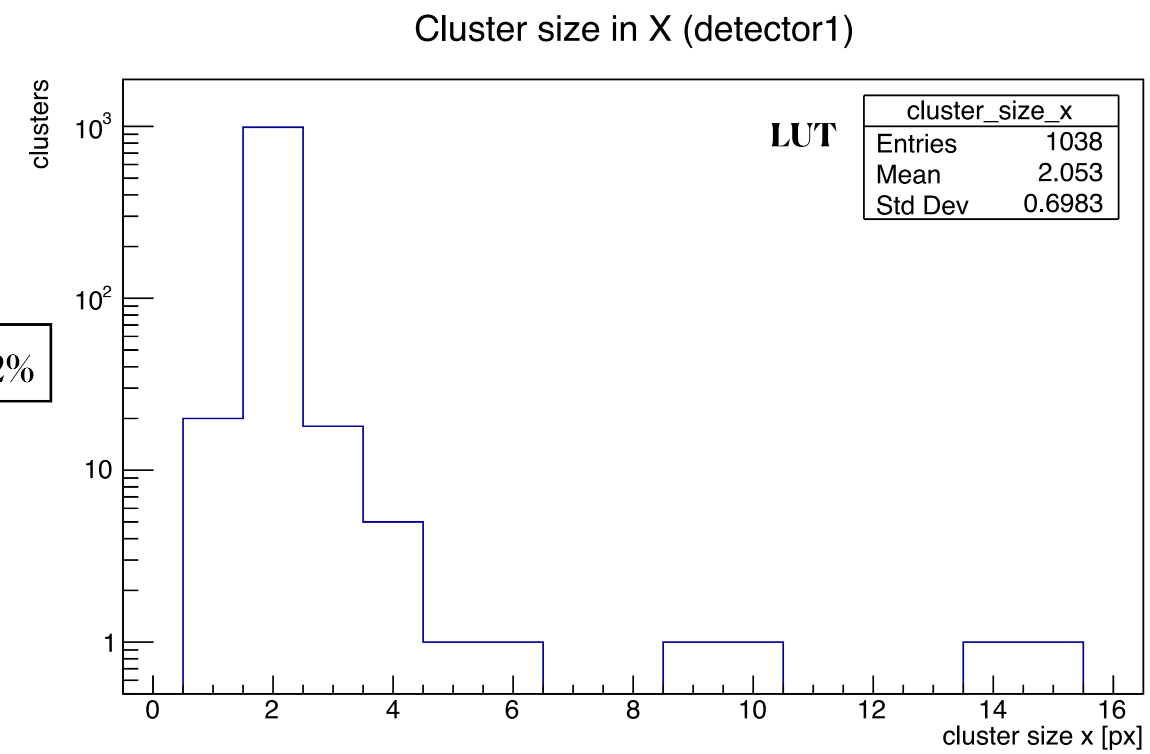


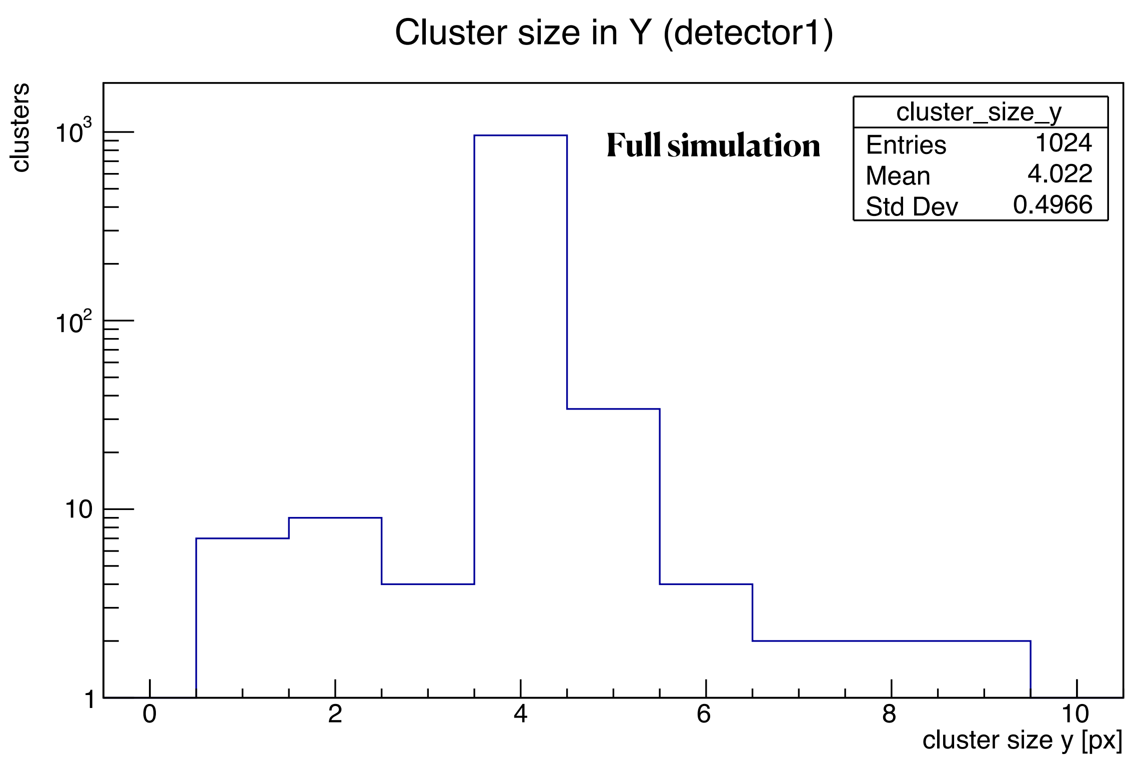
Cluster size - X,Y

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

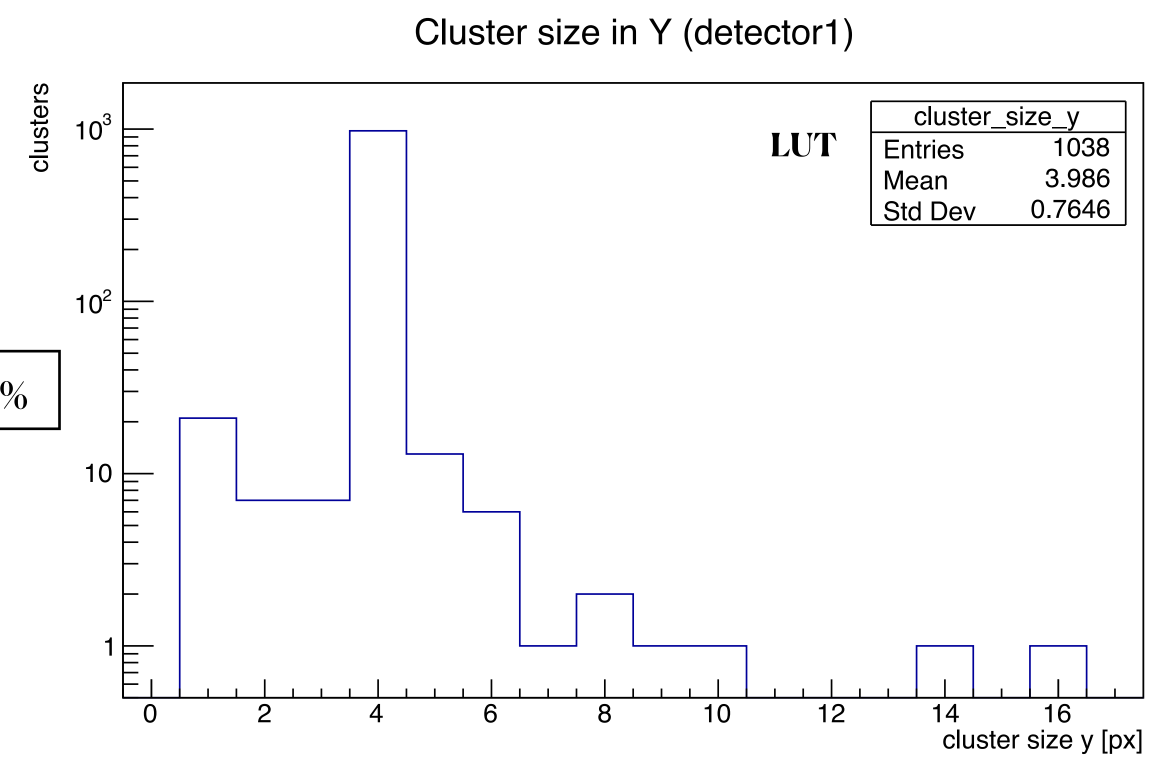


Rel err mean: 0.72%



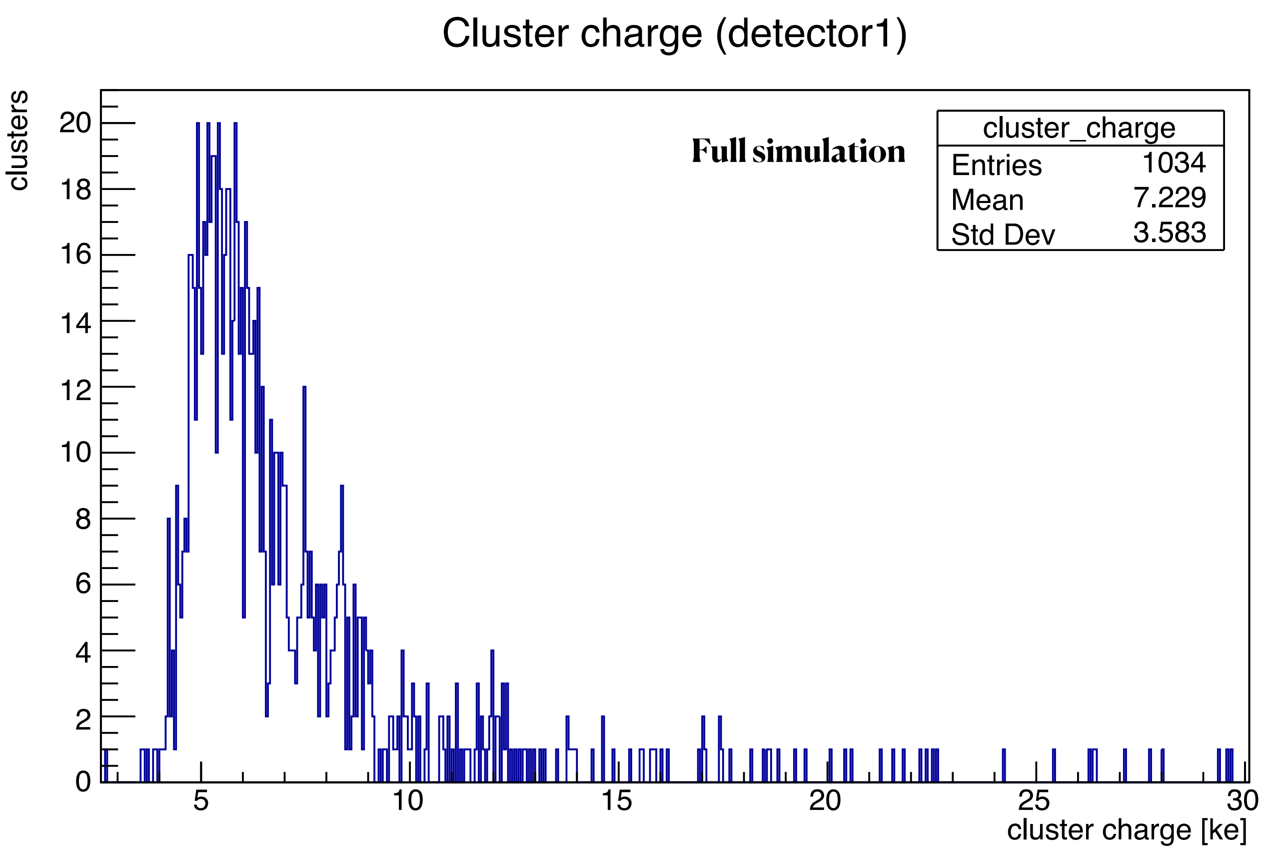


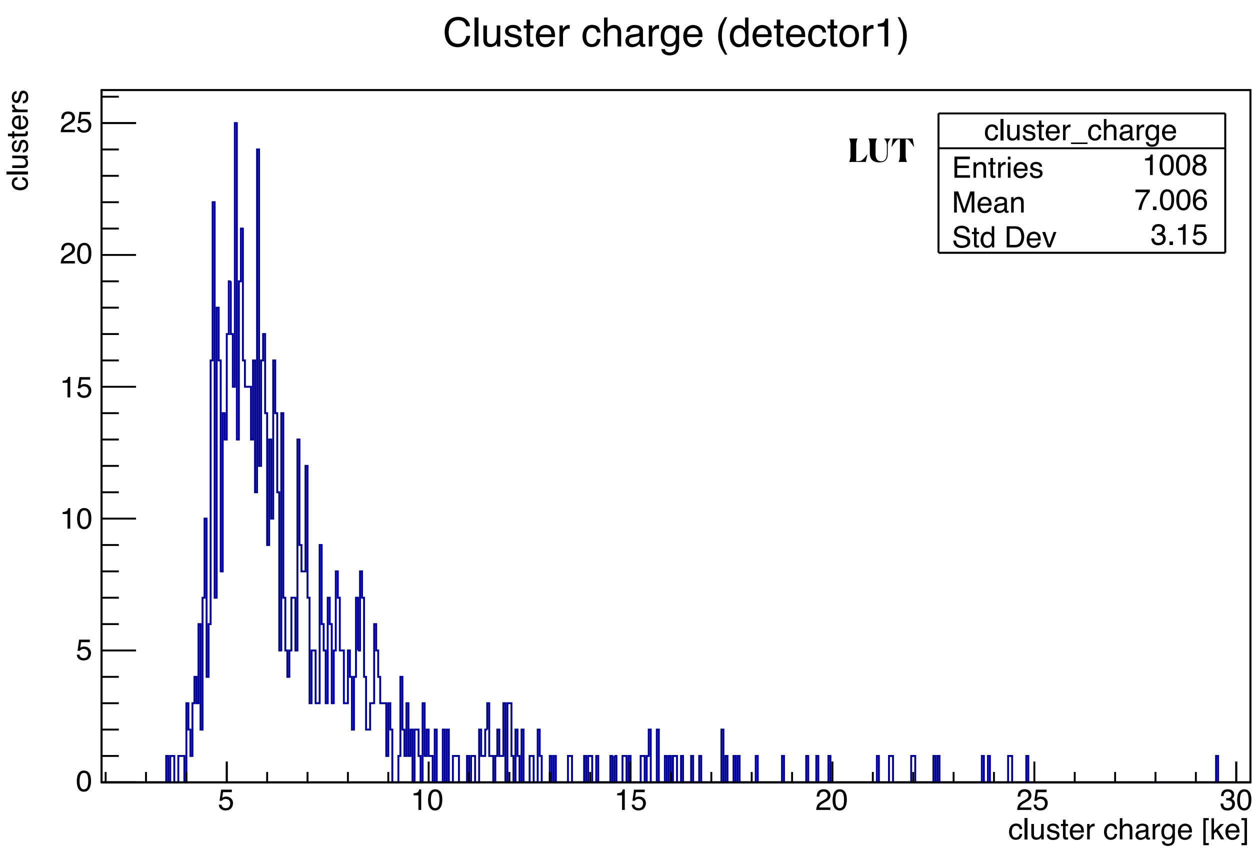
Rel err mean: 0.89%



Cluster charge

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





Rel err mean: 3.1%

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

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
- Excellent agreement btw FS and LUT for cluster size X at different eta = 0 , 1.4, larger differences seen at eta = 1 for Pt = 100GeV and 10GeV (backup slides #20-21)
- Transverse cluster size (X) increases with higher eta values in both FS and LUT
  - Similar trend observed in ATLAS pixel data
  - Transverse cluster size ∝ 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

Cluster size X at Pt = 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
  - Discrepancy in cluster size X is limited to a narrow region around eta = 1

Beam divergence studies

Transverse cluster size, Pt = 120GeV, Eta = 1 (θ_{trk} = 0.866 rad), -0.25 rad phi

- Beam divergences for simulations at eta = 1 were increased by ± 10 mrad -> eta : [0.99, 1.01]

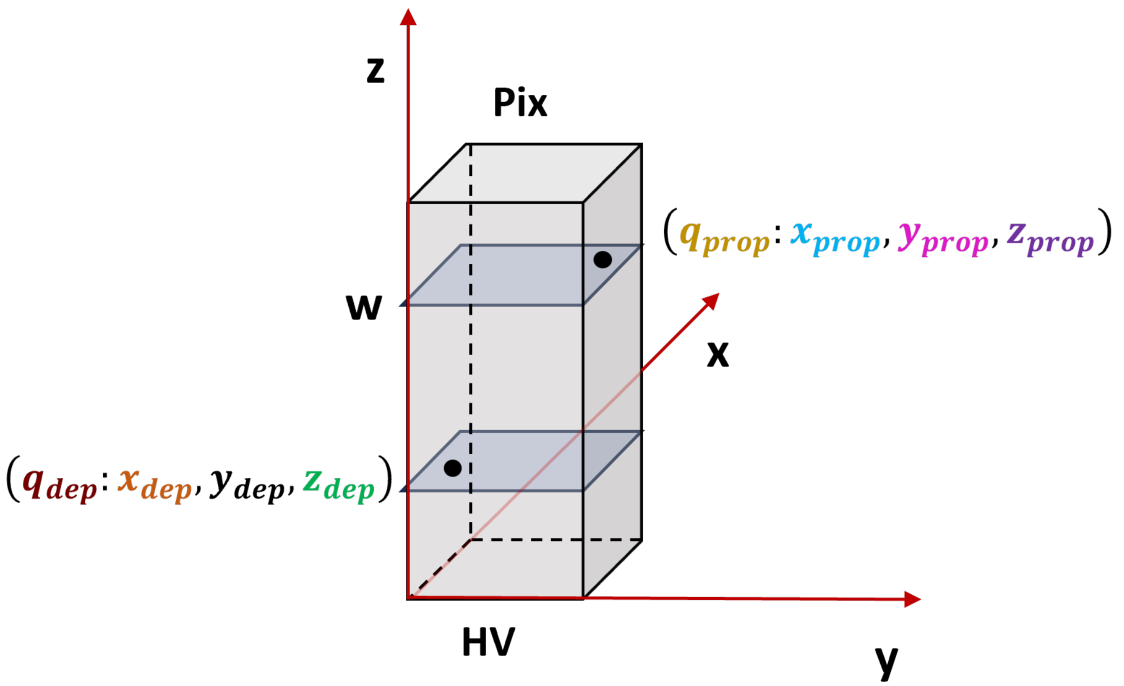
Beam Divergence X, Y (mrad)	Cluster Size X(pix)		
	FS	LUT	Rel err
0,0	1.224	1.428	17 %
10,0	1.344	1.449	8 %
0,10	1.547	1.551	0.2%
10,10	1.548	1.554	0.4%

- Excellent agreement btw FS and LUT observed with beam divergence increased by 10 mrad along the Y-axis

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, ΔZ vs Z LUTs from Allpix-squared
- Validated the approach using closure tests: point charge depositions, line charge deposition, 120GeV Pions, Pions with Pt = 100GeV, 10 GeV and 1GeV at eta = 0, 1, and 1.4
- Similar efforts in progress for 3D (see Jixing's talk) and strip detectors
- Next steps :
  - ✦ Repeat the studies at different fluences and operating voltages (1-3 x10^{15} n_{eq}/cm^2 , 300V - 500V)
  - ✦ Perform studies using planar sensors with pixel pitch of 25 µm x 100 µm , serving as further validation for the proposed technique
  - ✦ Anticipating the 2024 TB campaign for ITkPixV2 modules to validate our approach with the TB data

Thank you so much for your attention !! :)

Backup

ITk Pixel Radiation Damage Digitiser Speed Test

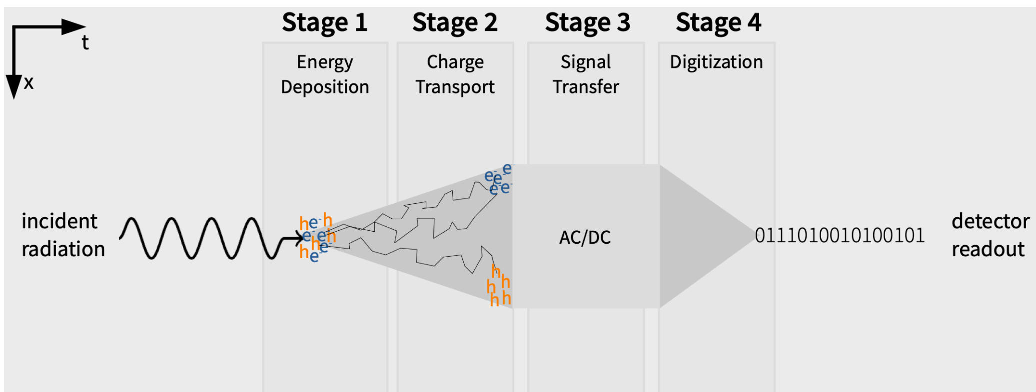
Comparison of Run2/3 strategy with the HL-LHC strategy

- Studies by Tomas Dado - Thanks!!
- Defining conventions :
  - D1 : Standard digitiser (no radiation damage)
  - D2 : Run 2/Run 3 radiation damage digitiser
  - D3 : ITk radiation damage digitiser with LUTs
- Tests showed : **t(D3) ~ t(D1)** -> ITk radiation damage digitiser is as fast as the standard digitiser
- Tests also showed : **t(D2) ~ 3 * t(D1)** -> Run 2/Run 3 digitiser is **3 times slower** than standard digitiser
- Tentative conclusion : **t(D2) ~ 3*t(D3)** -> ITk radiation damage digitiser with LUTs is **3 times faster** than Run 2/Run 3 digitiser :)

Allpix-squared framework

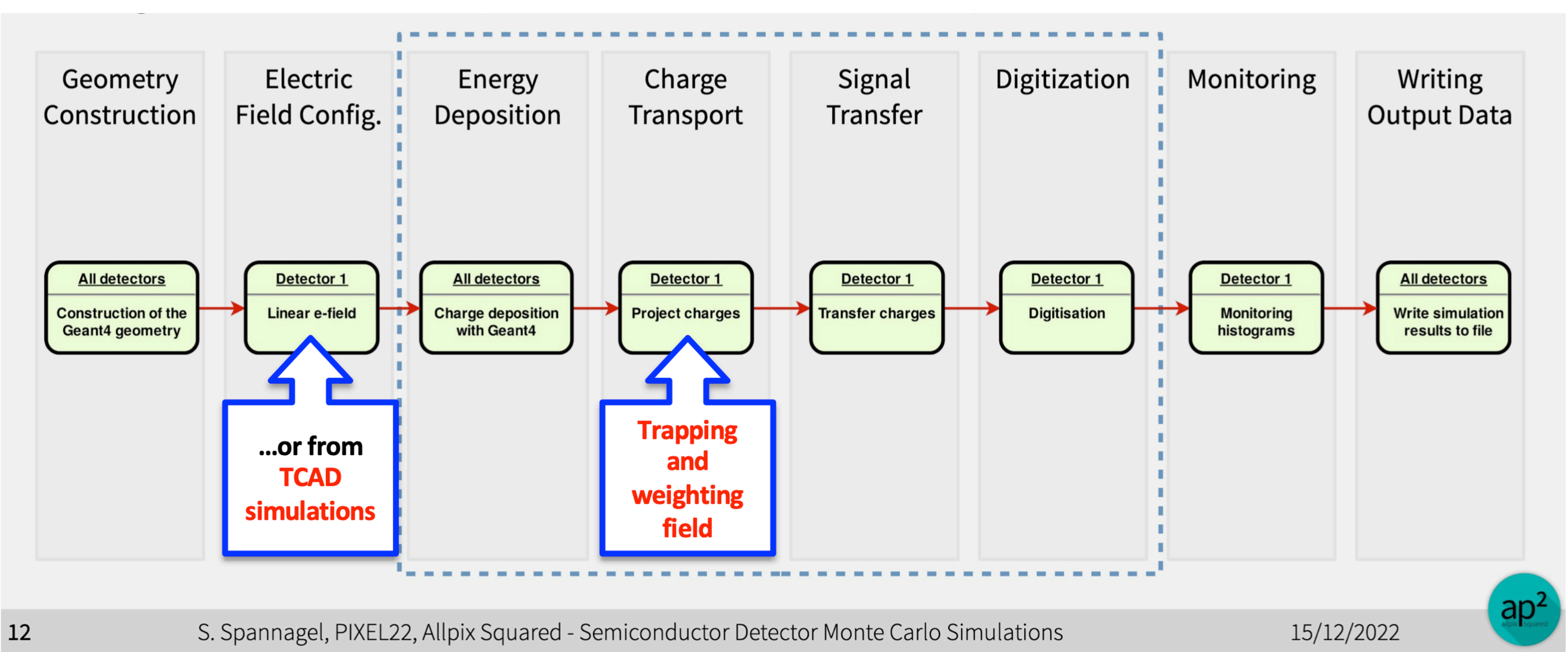
Simulation flow

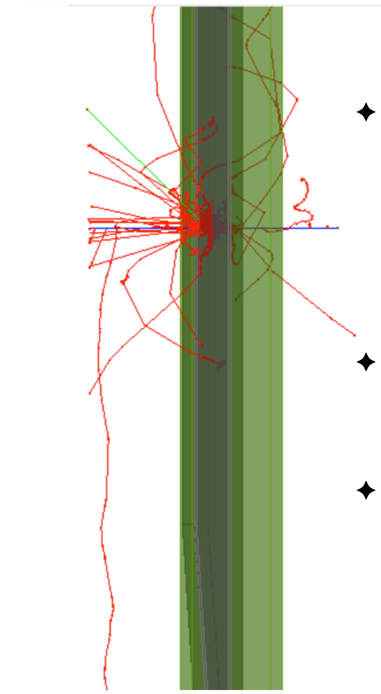
- Modular, generic simulation framework aiming at facilitating the different steps of the simulation of semiconductor detectors



- Building blocks follow individual steps of signal formation in detector

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





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

```
[Allpix]
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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]
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positedCharge"
```

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 ∝ 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

Results of Pt = 10 GeV

Understanding trends

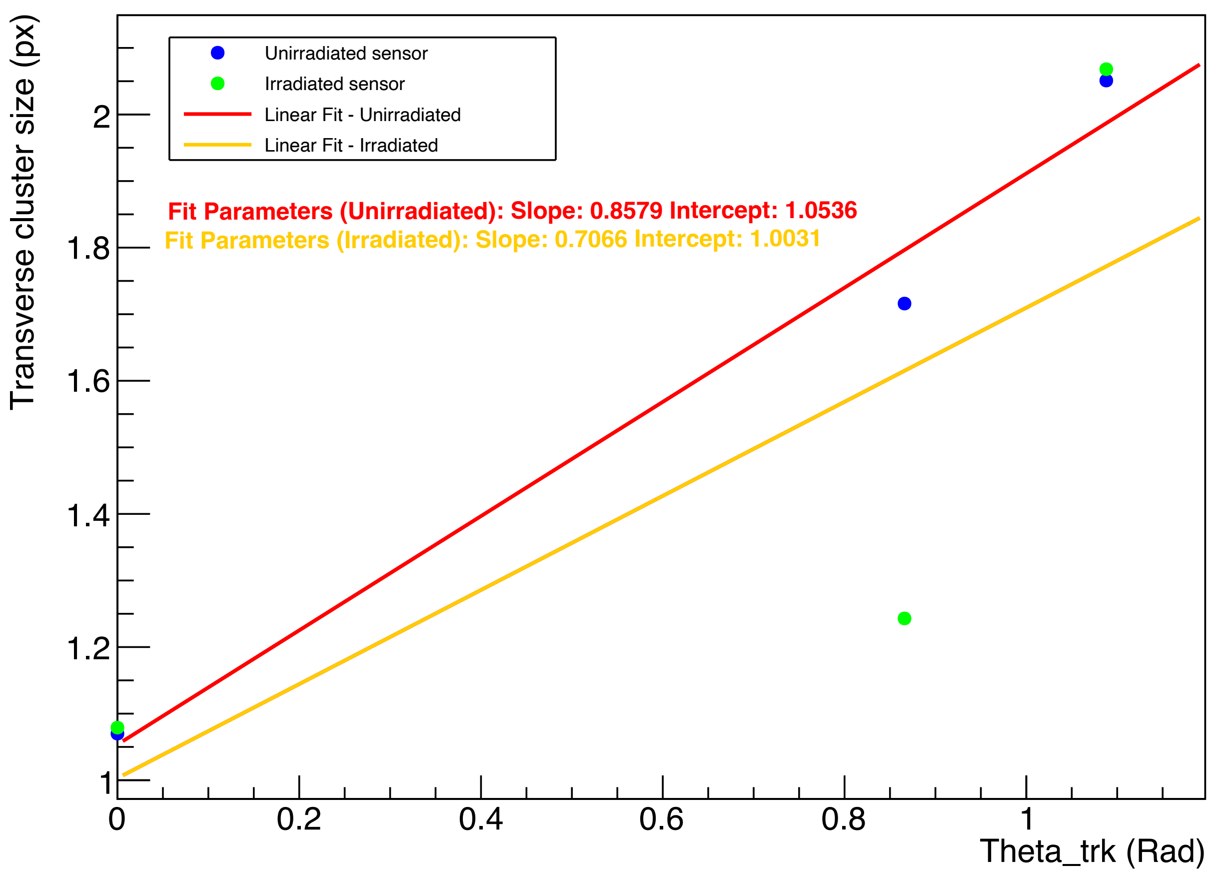
Eta	Propagated X Position (mm)			Cluster Size Y(pix)			Cluster Size X(pix)			Cluster Charge (ke)		
	FS	LUT	Diff/pitch	FS	LUT	Rel err	FS	LUT	Rel err	FS	LUT	Rel err
Normal incidence	10.0020	10.0063	8.6%	1.082	1.04	3.9%	1.097	1.055	3.8%	7.229	7.006	3.1%
1 (theta_trk = 0.866Rad)	10.0089	10.0155	4.6%	3.023	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 ∝ 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

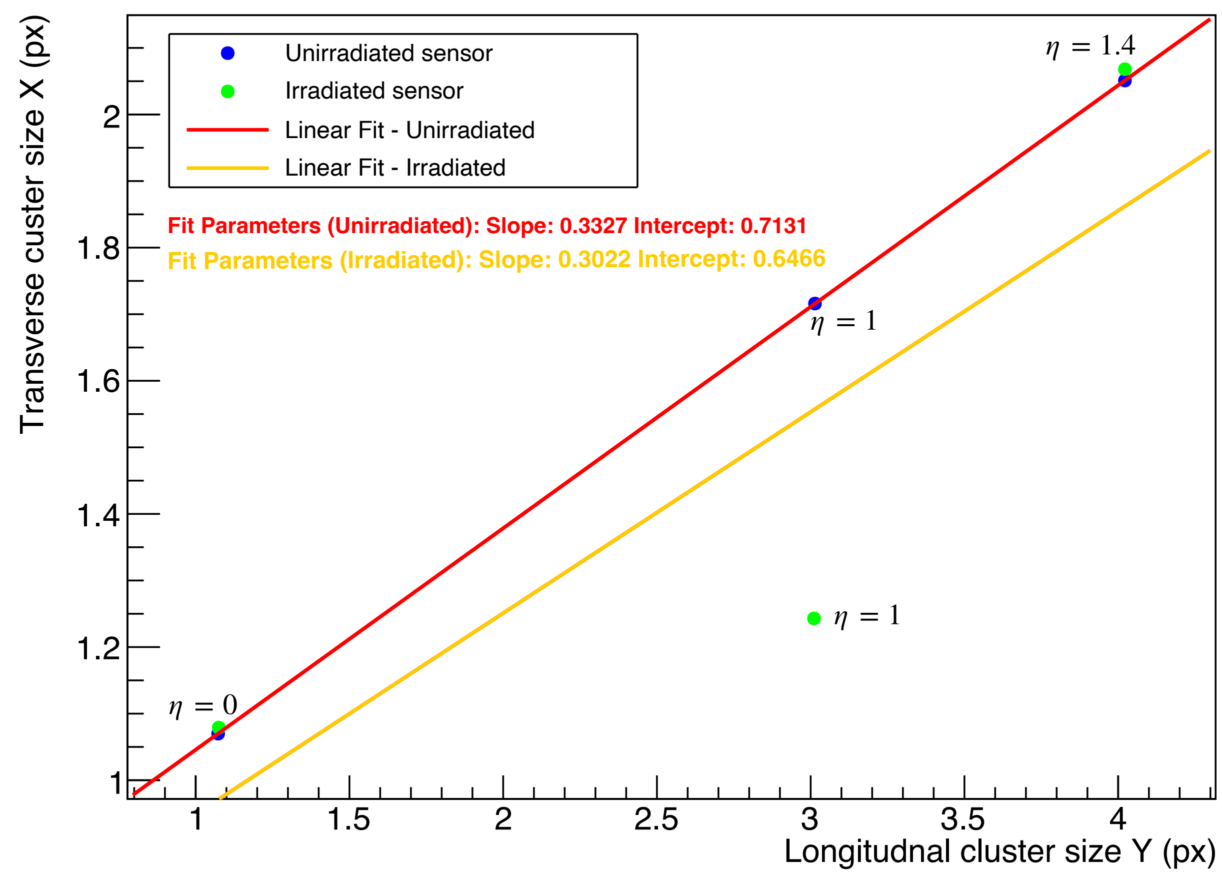
Understanding Transverse Cluster Size

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

Cluster size X vs θ_{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
- Nx ~ Ny * P_(sharing,x)!!!
- Probability of sharing in the transverse plane for unirradiated sensors = 0.33