4th Allpix-Squared User Workshop, 23/05/2023

Simulation of hybrid pixels using precise TCAD simulation

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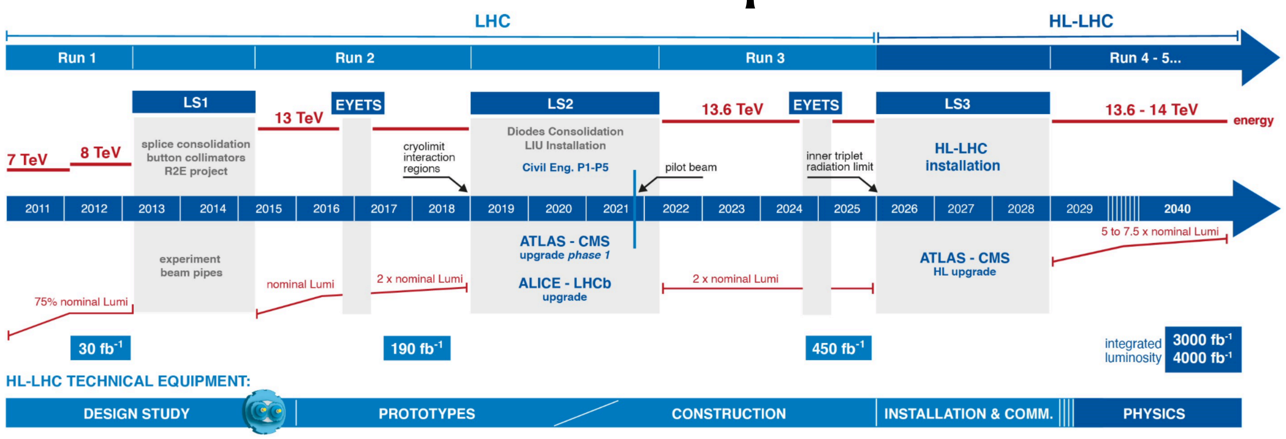
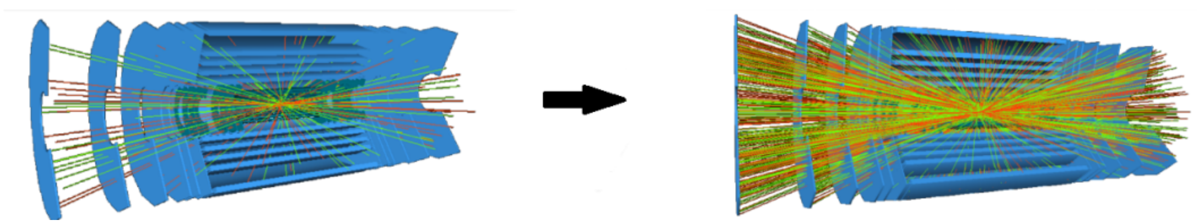
Radiation damage in silicon sensor bulk

Introduction

- The latest LHC roadmap:

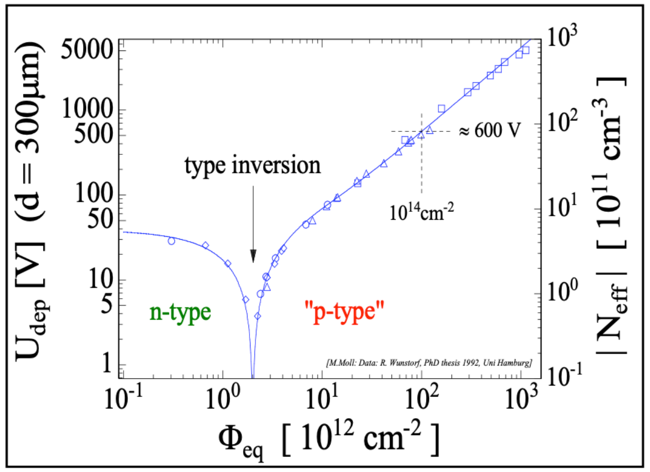




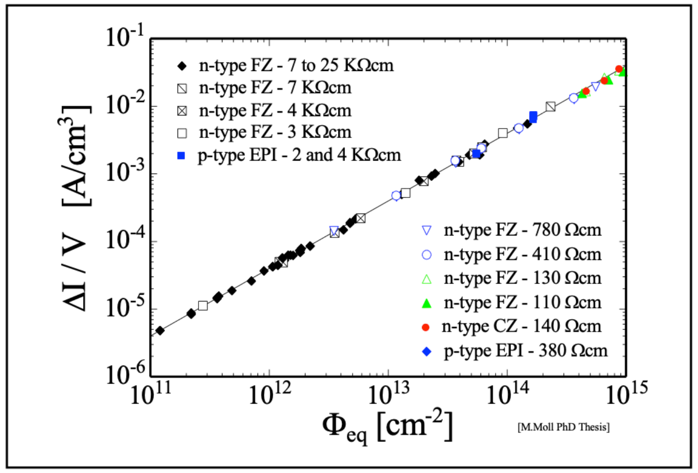
https://hilumilhc.web.cern.ch/content/hl-lhc-project

- **High Luminosity (HL) LHC:**
  - ✦ Peak luminosity: $1\text{x}10^{34} \rightarrow 5 - 7\text{x}10^{34}\text{cm}^{-2}\text{s}^{-1}$
  - ✦ Average collisions/BC: ~30→ ~200
  - ✦ Integrated luminosity: 350 → 4000
- **Increased radiation damage!**
  - ✦ ATLAS/CMS Pixel detectors - exposed to unprecedented amount of radiation
  - ✦ Crucial importance to model the impact of radiation damage -> accurate simulation of charged-particle interactions with the detector and the reconstruction of their trajectories

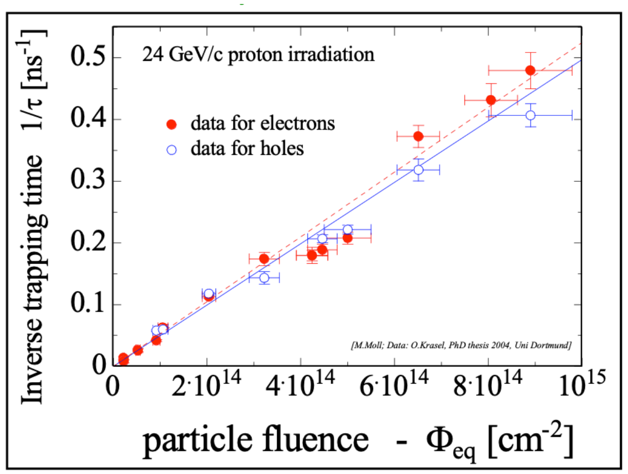
- **Impact of radiation damage on detector operations :**
  - ✦ Increase in depletion voltage, leakage current
  - ✦ Reduced charge collection efficiency due to trapping
    - ❖ **Smaller SNR -> bias in signal position reconstruction**



Depletion Voltage (N_{eff})



Leakage Current



Charge Trapping

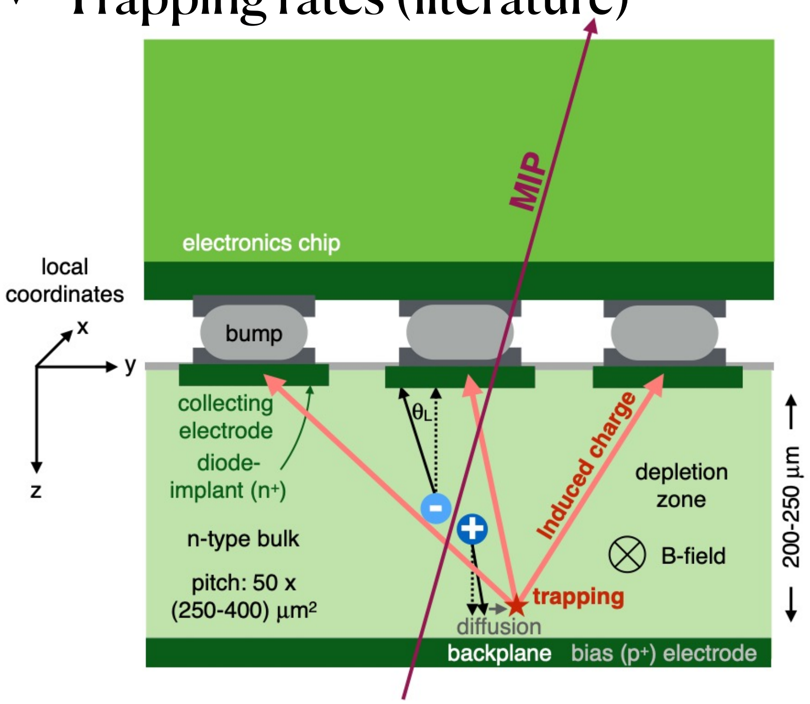
M. Moll, SIMDET 2018

Radiation damage modelling : ATLAS approach

Comparison of Run2,3 and HL-LHC strategy

Run 2 and Run 3

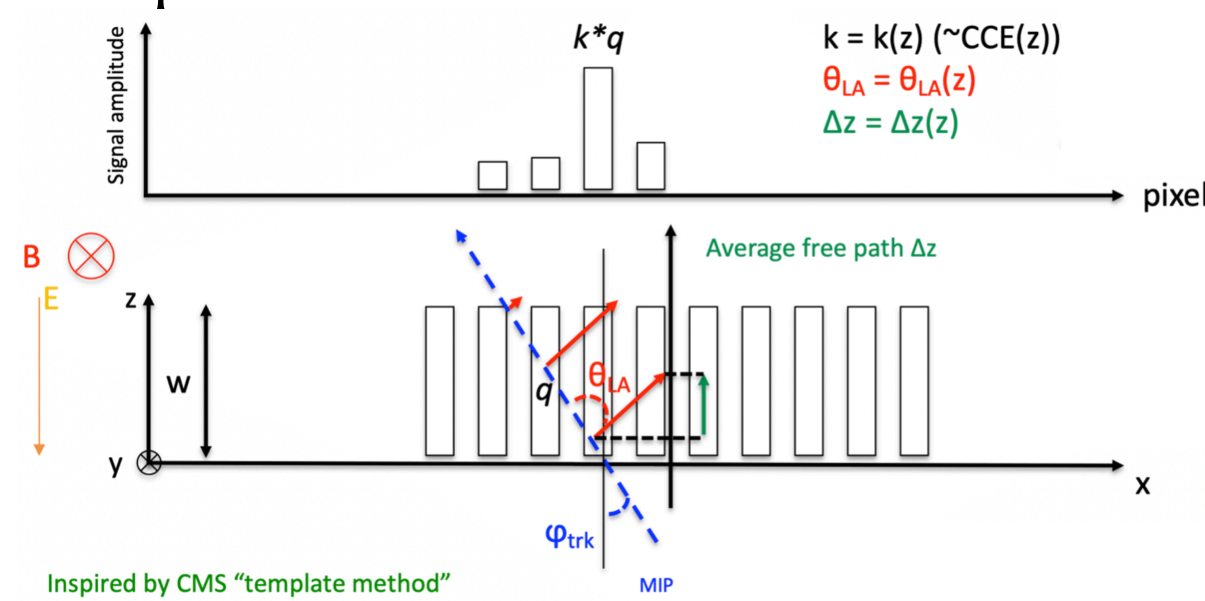
- Current strategy : Evaluate final position and induced signal of group of carriers in MC
- Inputs:
  - ✦ Precise electric field simulation (TCAD) to take into account radiation damage effects
  - ✦ Weighting potential (TCAD)
  - ✦ Trapping rates (literature)



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

HL-LHC

- 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

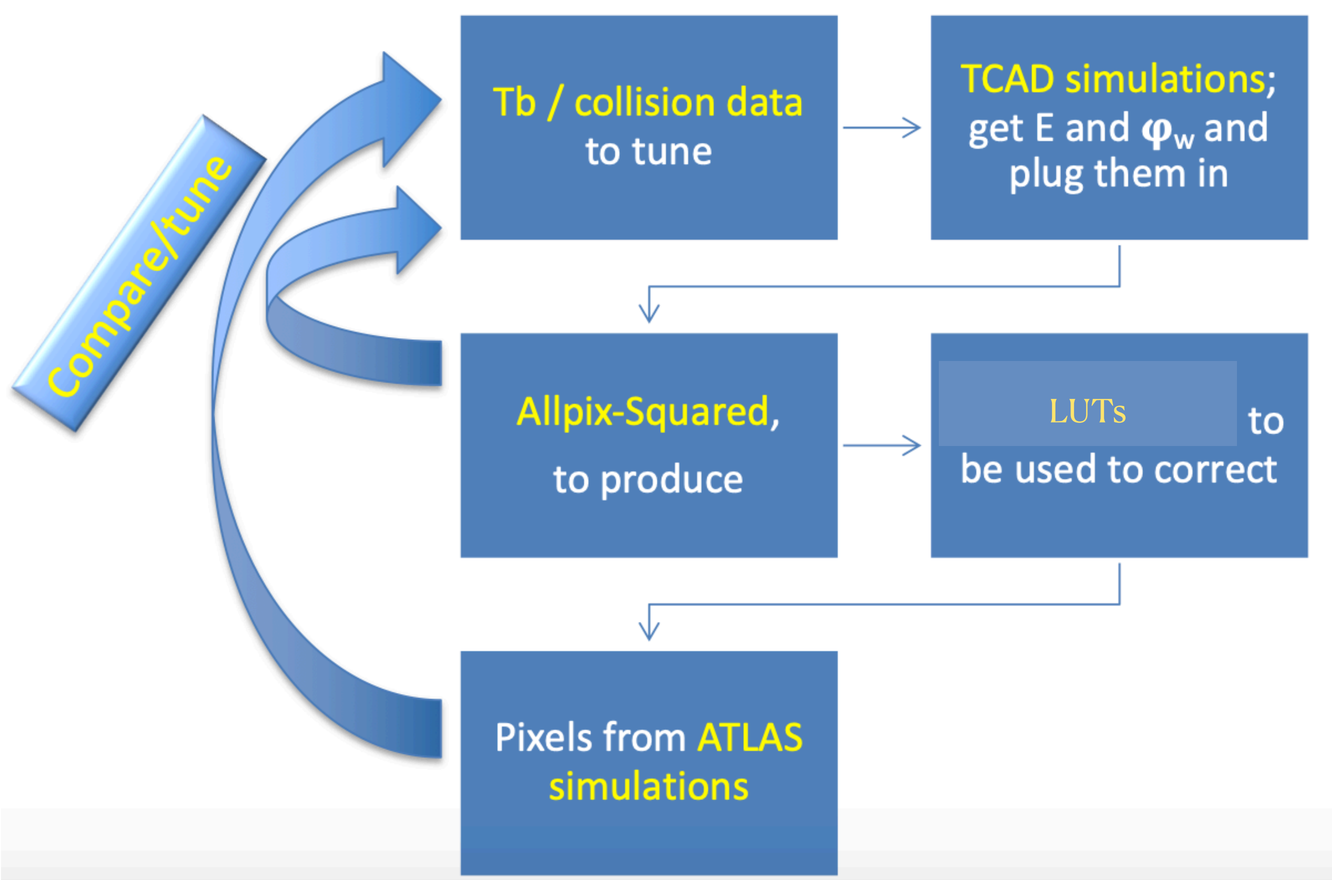


- Idea : For each simulated charge q at depth **z** find in which pixel it will end up, by how much ***(k)* the signal will be reduced**
  - ✦ Goal: Simulated pixels in MC is corrected using these information before digitisation -> correction scheme implemented using **Allpix-squared**

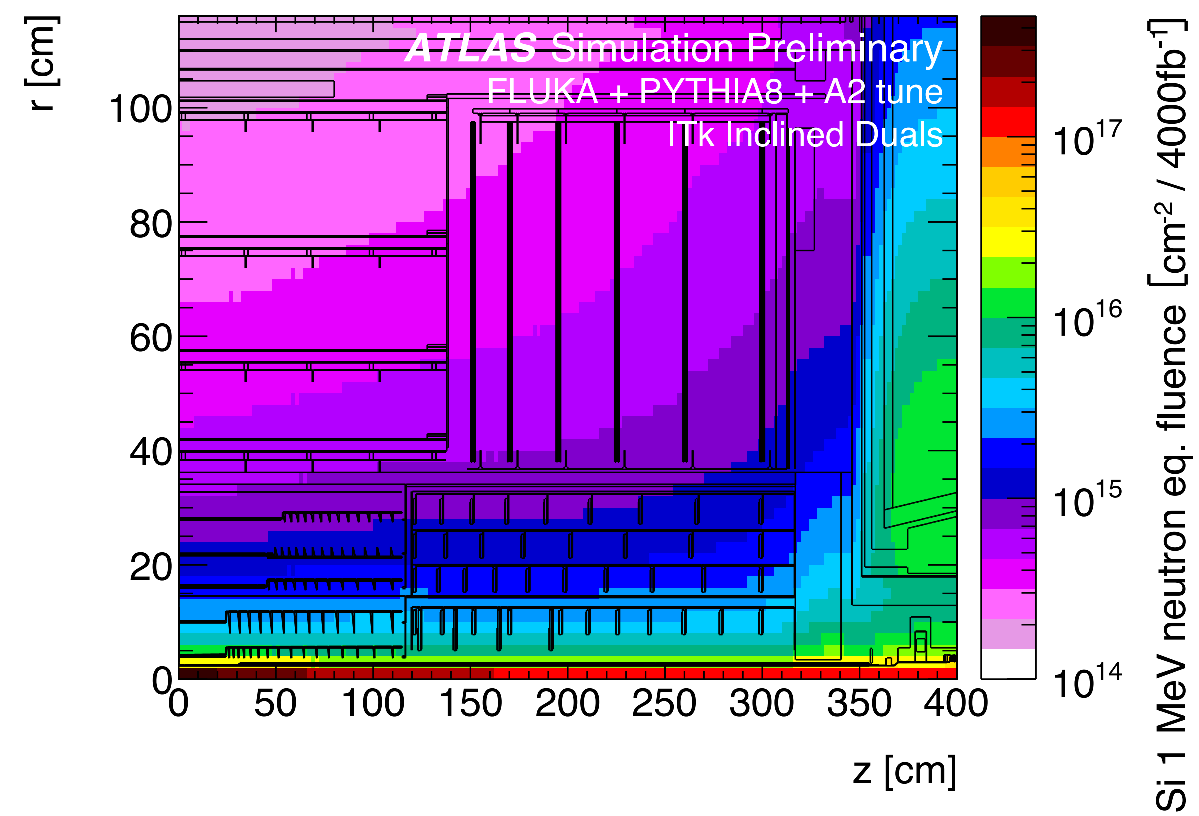
Allpix-squared for radiation damage digitiser

Implementation strategy

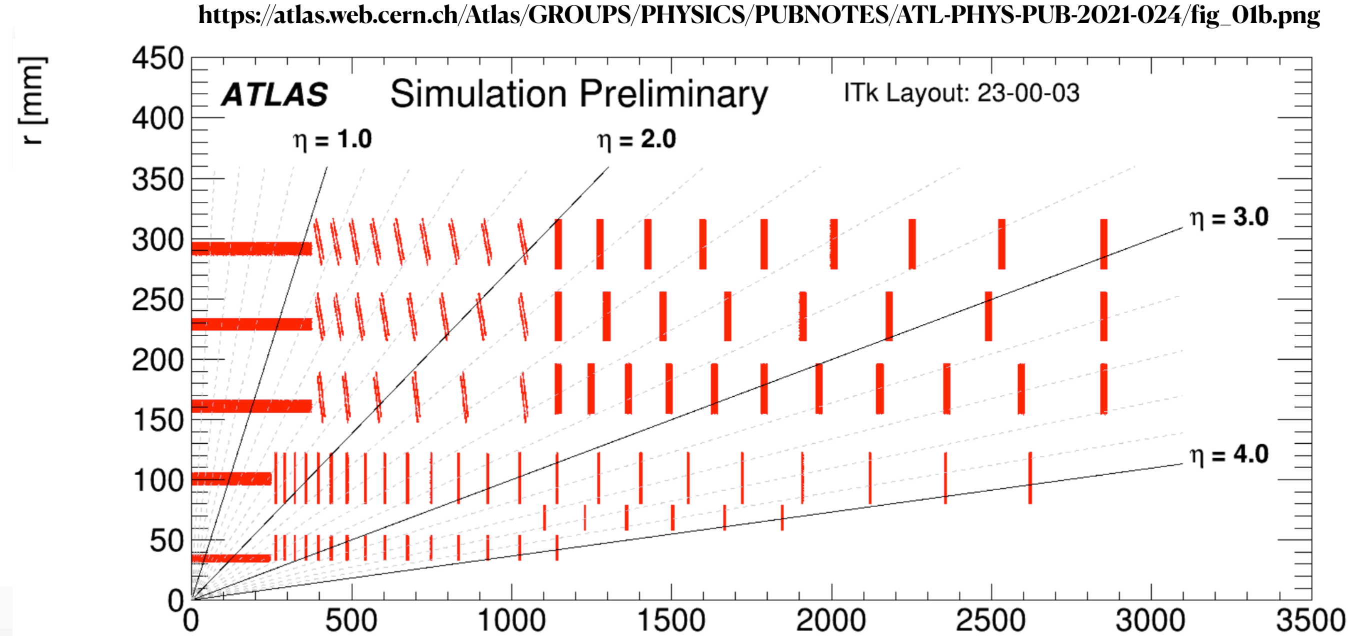
- Simulate sensors before and after irradiation, per geometry and per fluence
- Save k factor = collected charge after/before irradiation for a pixel struck at a certain Z position
- Evaluate Lorentz angle deflection as a function of Z position
- Average free path as a function of Z



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



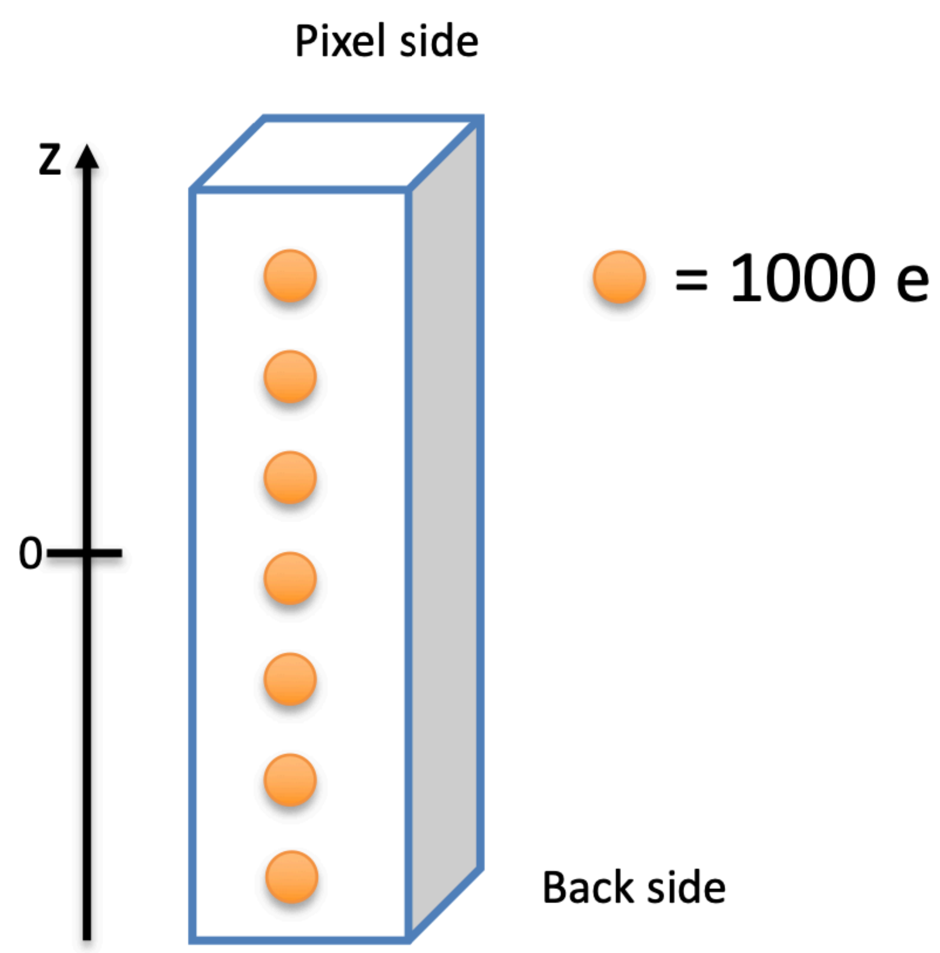
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-024/fig_01b.png



LUT #1 : CCE vs Z

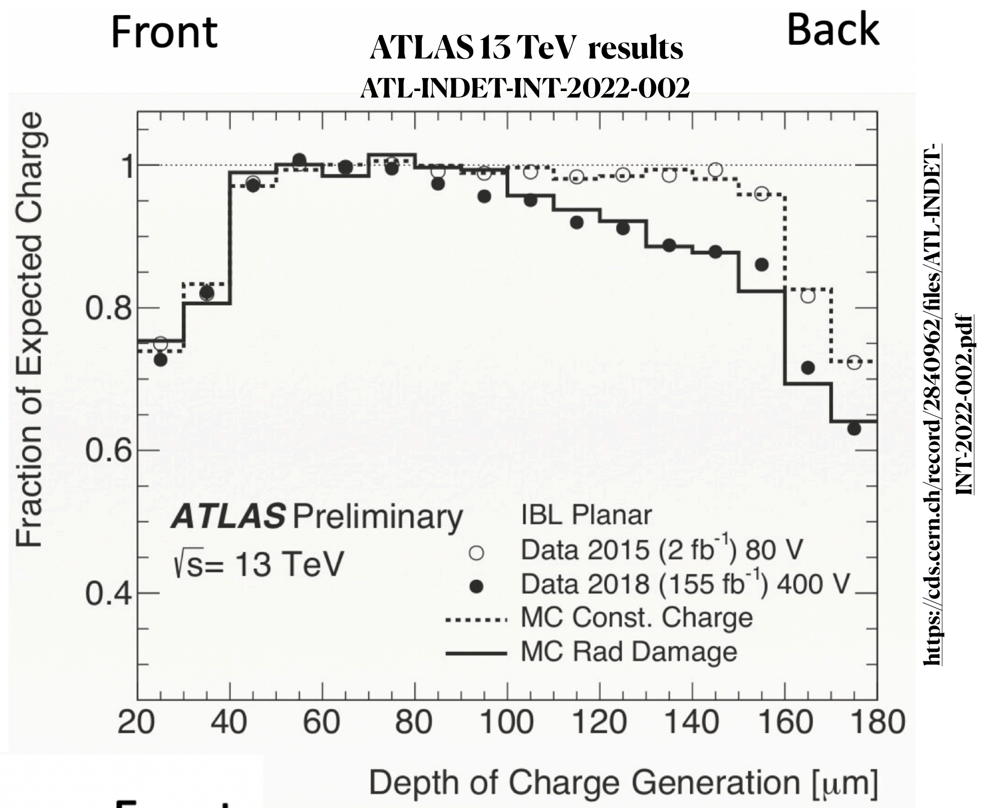
How is CCE estimated?

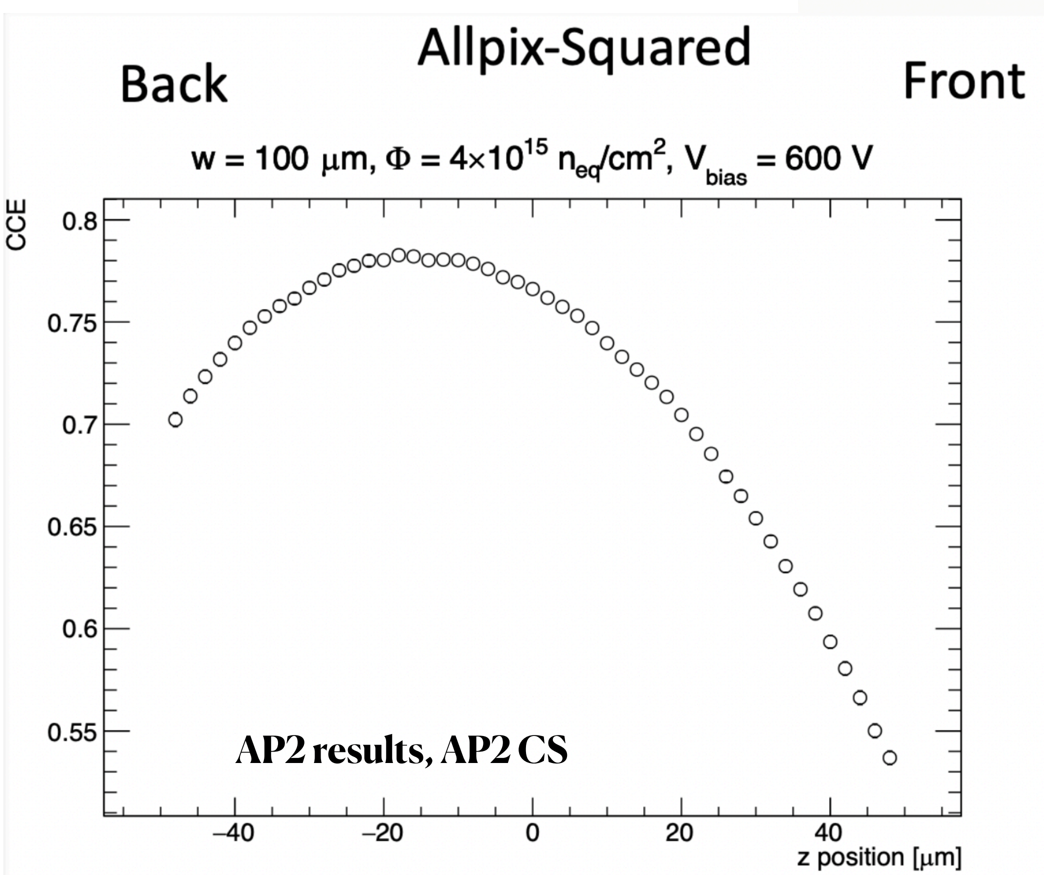
- Simulate point deposition ([DepositionPointCharge]) at different z position
    - ✦ 1 simulation per Z position
- Get the fraction of induced charge
- Plot CCE vs Z
    - ✦ CCE = (total pix charge/ deposited charge)
- Simulation details:
    - ✦ 100 events per Z position
    - ✦ 1000e deposited per event
    - ✦ Scan performed every 2 um
    - ✦ Simulation for 100 µm thick sensor at **$4x10^{15}$ n_{eq}/cm^2** and **600 V**

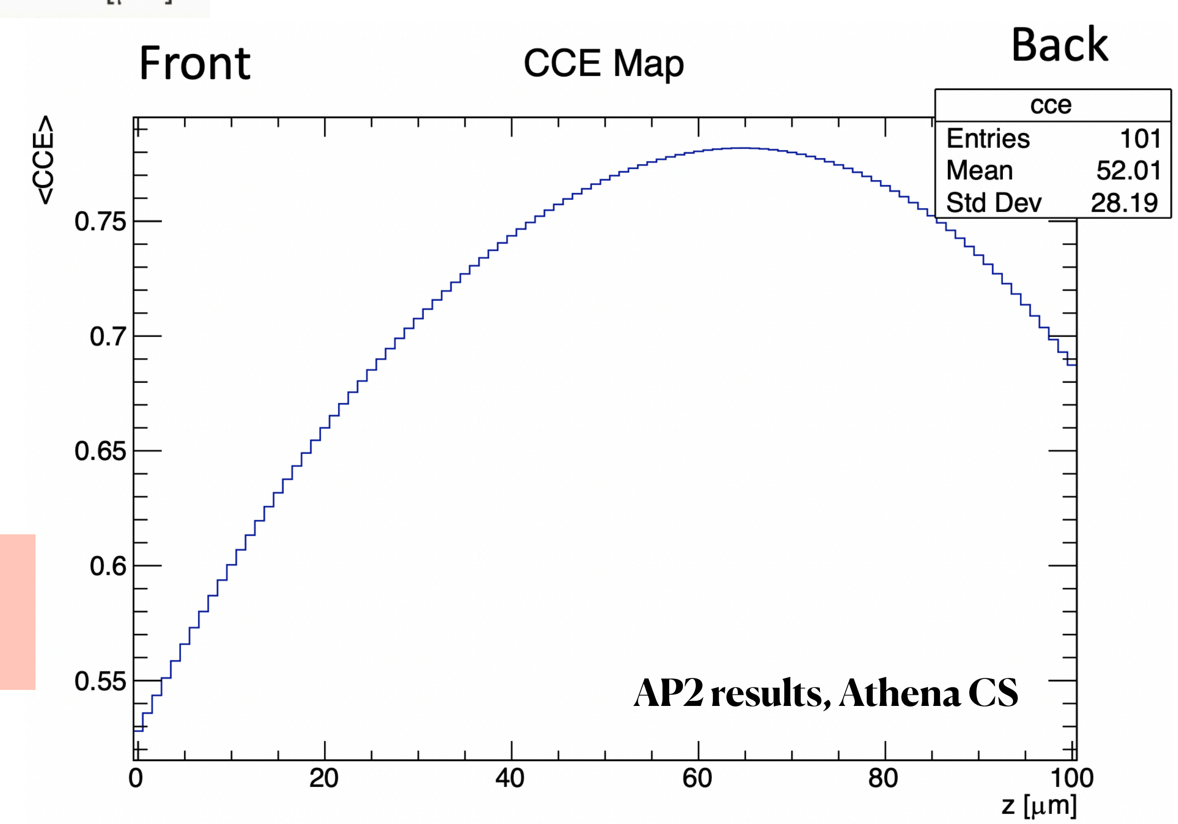


CCE vs Z profile : Data and AP2 simulation

CCE = (Pixel total charge)/(Deposited charge)







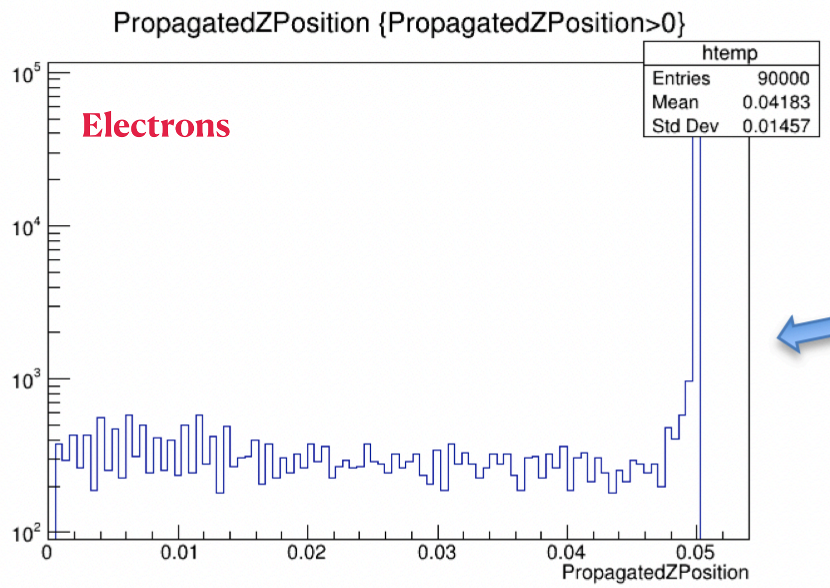
Opposite trend in AP2 : CCE is smaller at the pixel front side than the HV side

CCE vs Z profile

Workaround estimation of CCE using Ramo potential

Charge injection : 0um (mid-sensor plane)

Back Front



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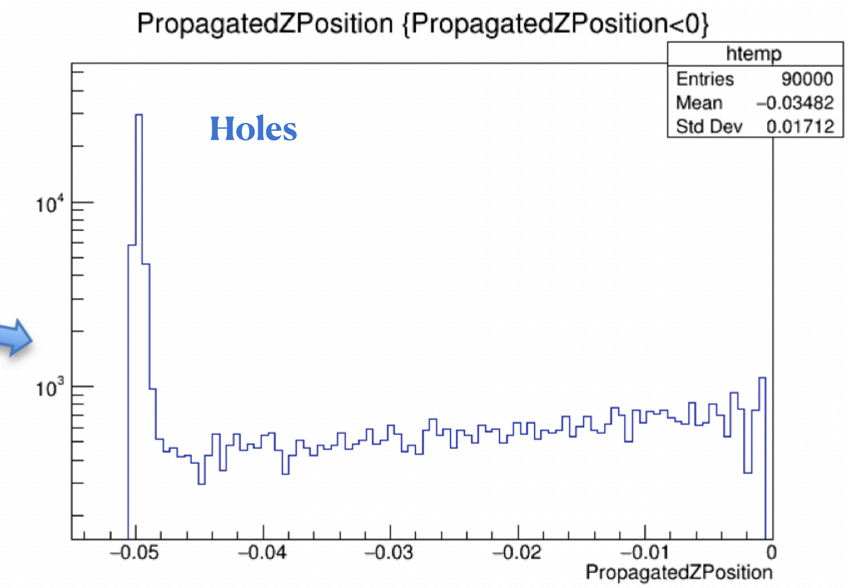
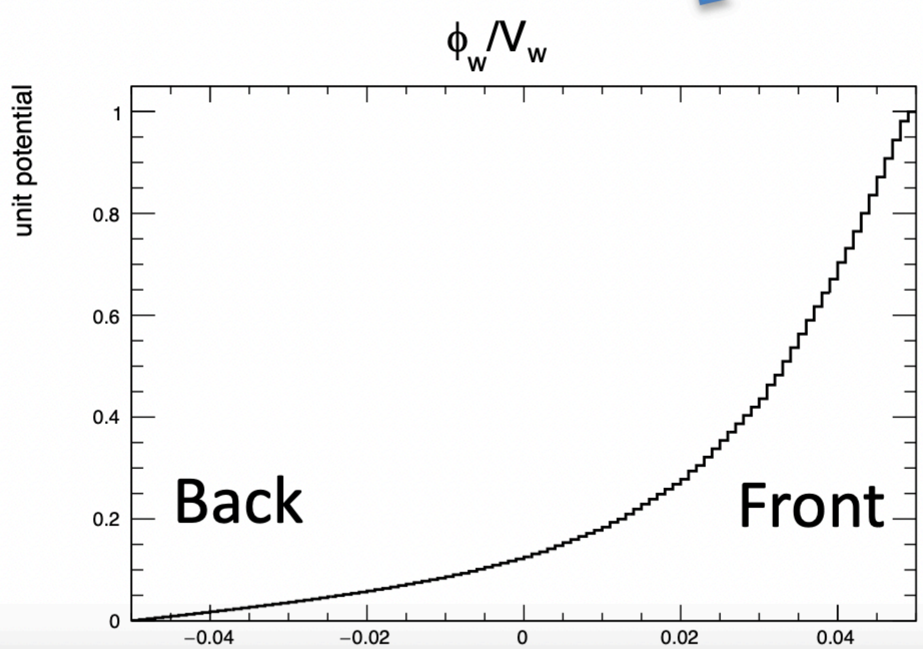


Reweight each bin with the Ramo potential



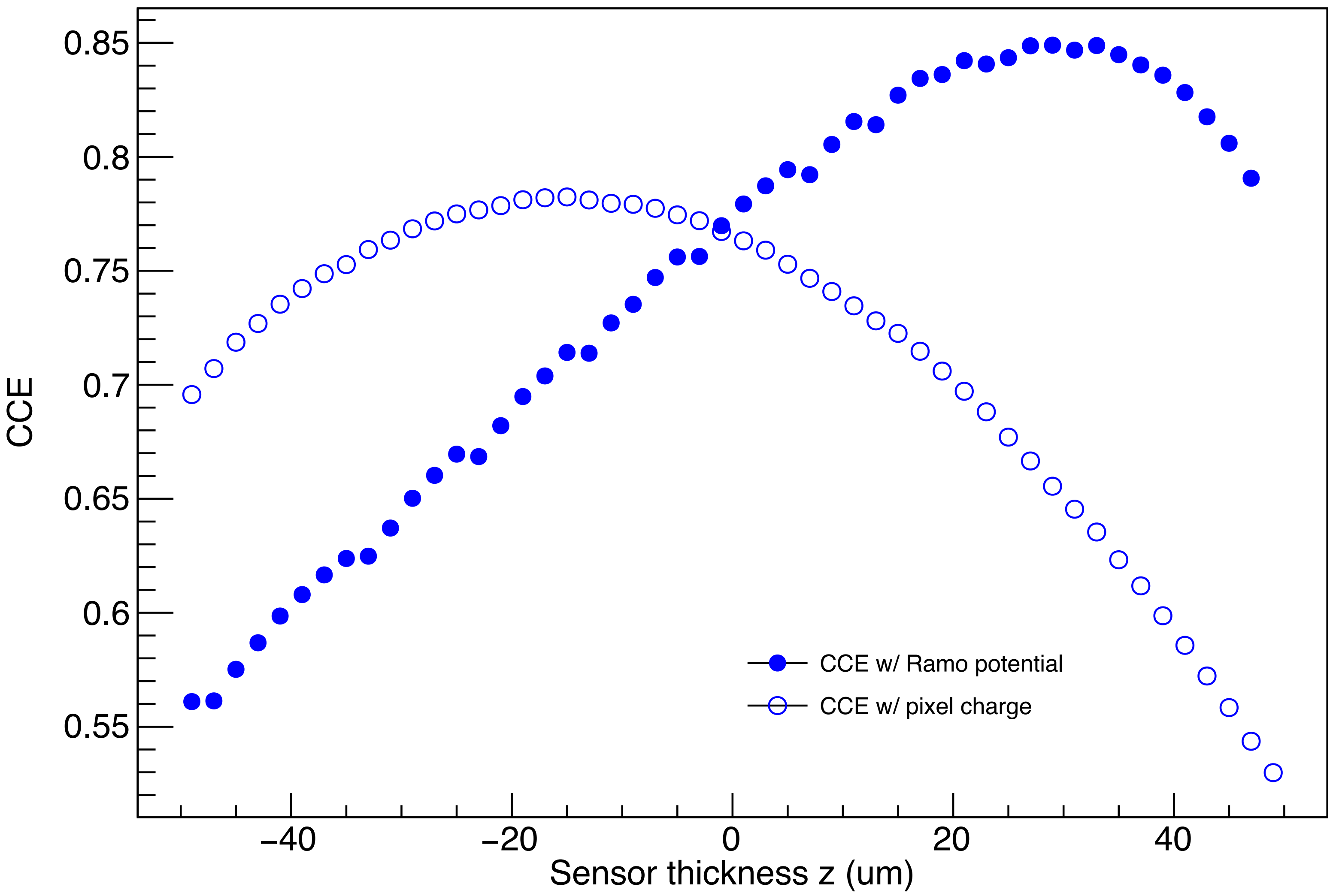
Calculate induced charge:

$$Q(z_{inj}) = \sum_{carriers} -q(\phi_w(z_{fin}) - \phi_w(z_{inj}))$$

Repeat for all z_{inj} injection positions

CCE vs Z profile

CCE estimated using Ramo potential



- **Computing charge using Ramo gives a profile which is consistent with expectations**
- So, what is not working as expected?
  - Thanks to AP2 developers -> better understanding of what is happening
- Full thread here

Understanding CCE vs Z plots

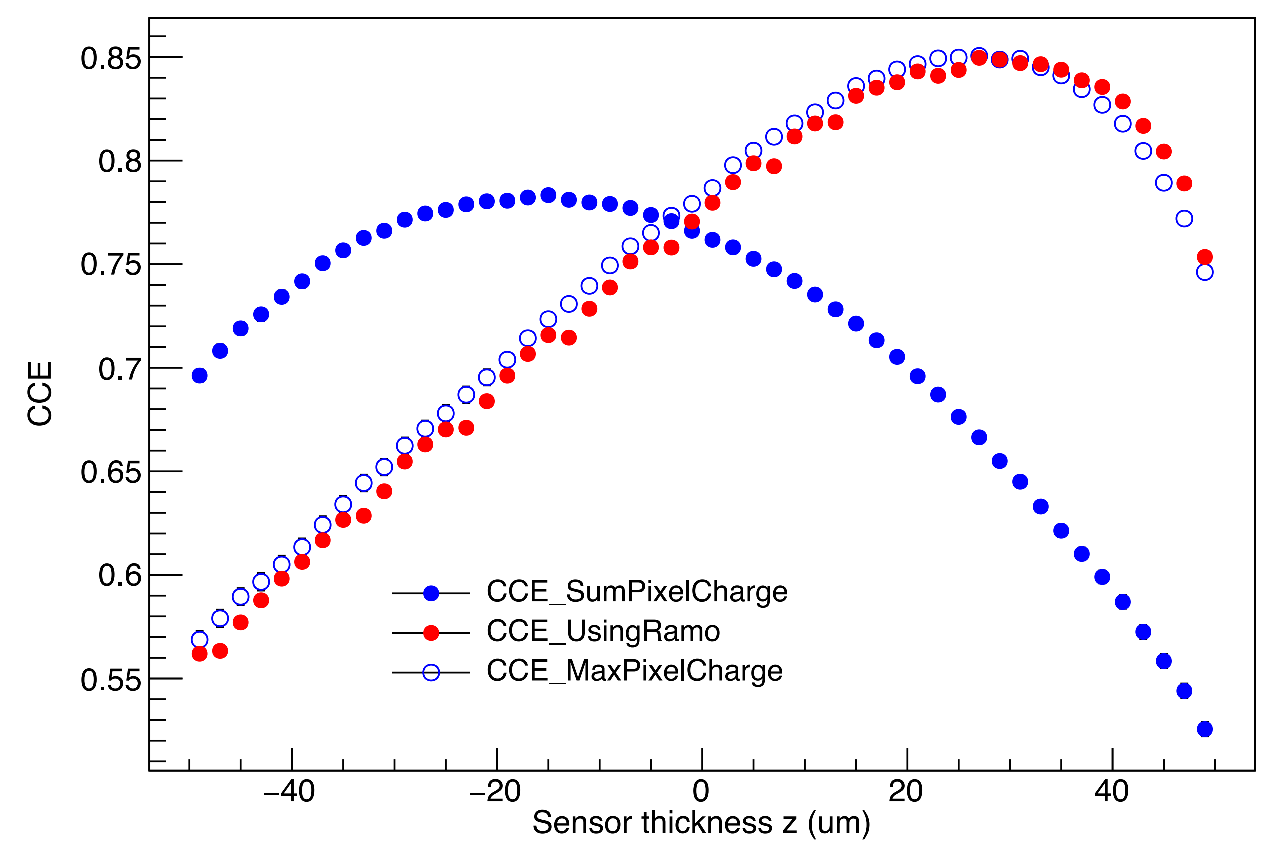
Thanks to AP2 developers

- Charge injection = centre of pixel (200,96), pixel charge for one event :

```
Event: 10 Pixel charge: 5 deposited in Pixel (199,95 )
Event: 10 Pixel charge: 4 deposited in Pixel (199,96 )
Event: 10 Pixel charge: 5 deposited in Pixel (199,97 )
Event: 10 Pixel charge: 3 deposited in Pixel (200,95 )
Event: 10 Pixel charge: -814 deposited in Pixel (200,96 )
Event: 10 Pixel charge: 3 deposited in Pixel (200,97 )
Event: 10 Pixel charge: 5 deposited in Pixel (201,95 )
Event: 10 Pixel charge: 3 deposited in Pixel (201,96 )
Event: 10 Pixel charge: 5 deposited in Pixel (201,97 )
 maximum pixel charge: -814
```

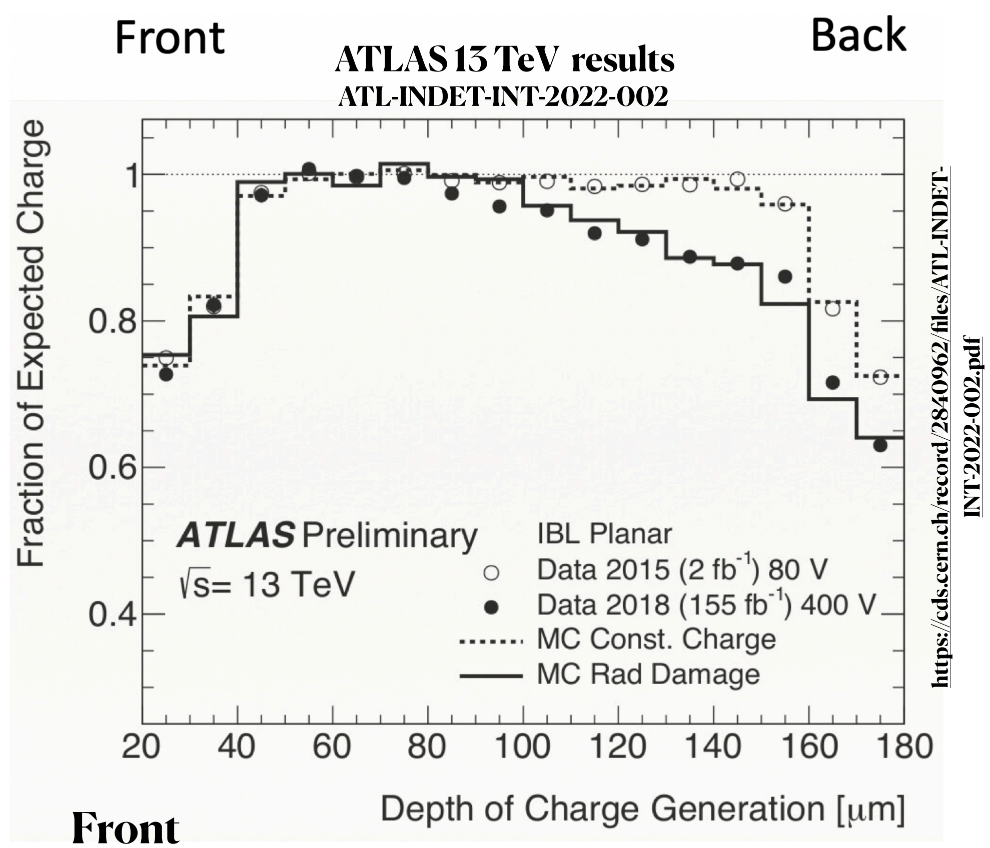
- Central pixel (200,96) sees the largest charge
- Neighbours see a non-zero (+ve) charge induced -> imbalance between electrons and holes introduced by the trapping

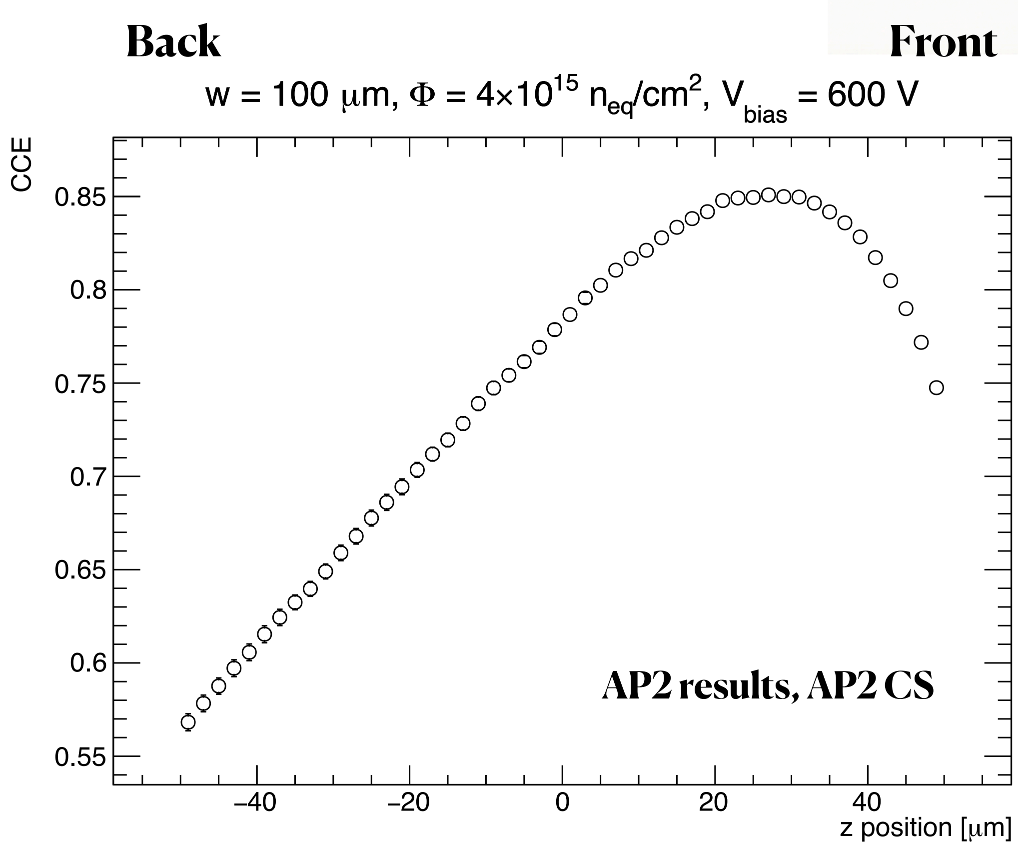
- Modified analysis script -> largest pixel charge contribution (**blue open dots**)
- Ignored the contribution from the neighbours to calculate the induced charge
  - ✦ Small positive charges are below threshold



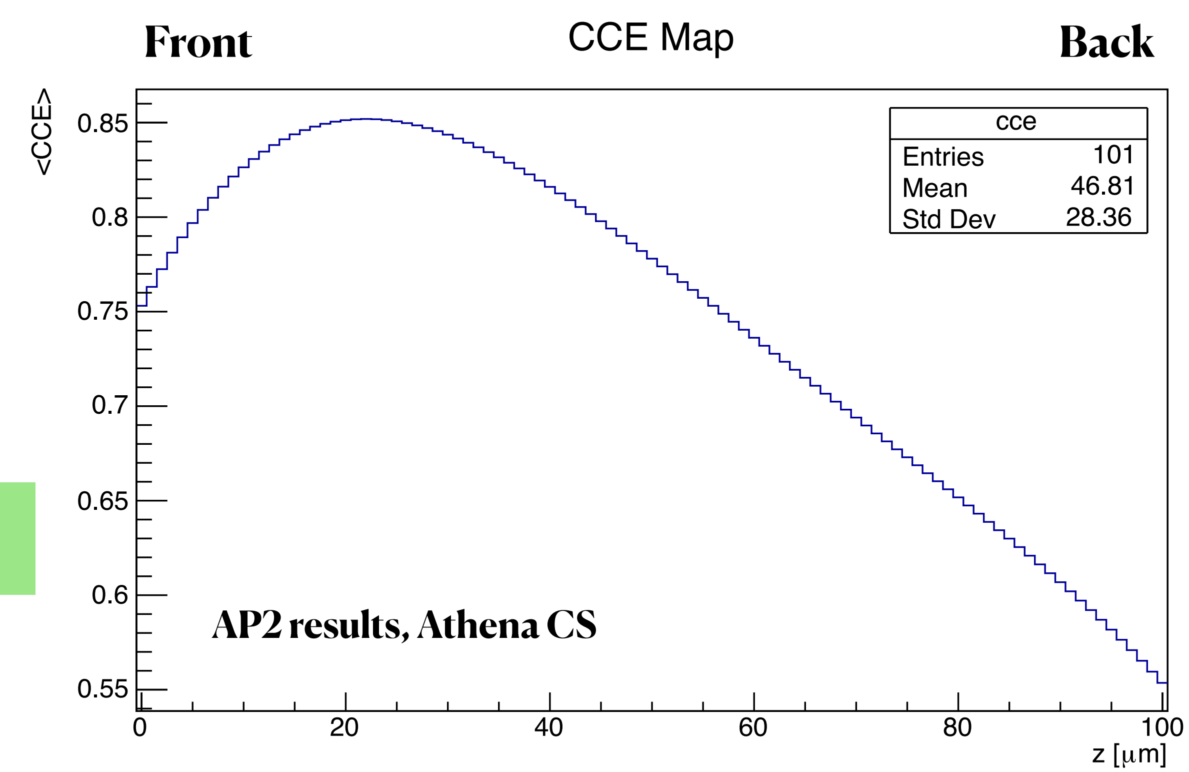
LUT #1 : CCE vs Z

CCE estimated using highest pixel charge



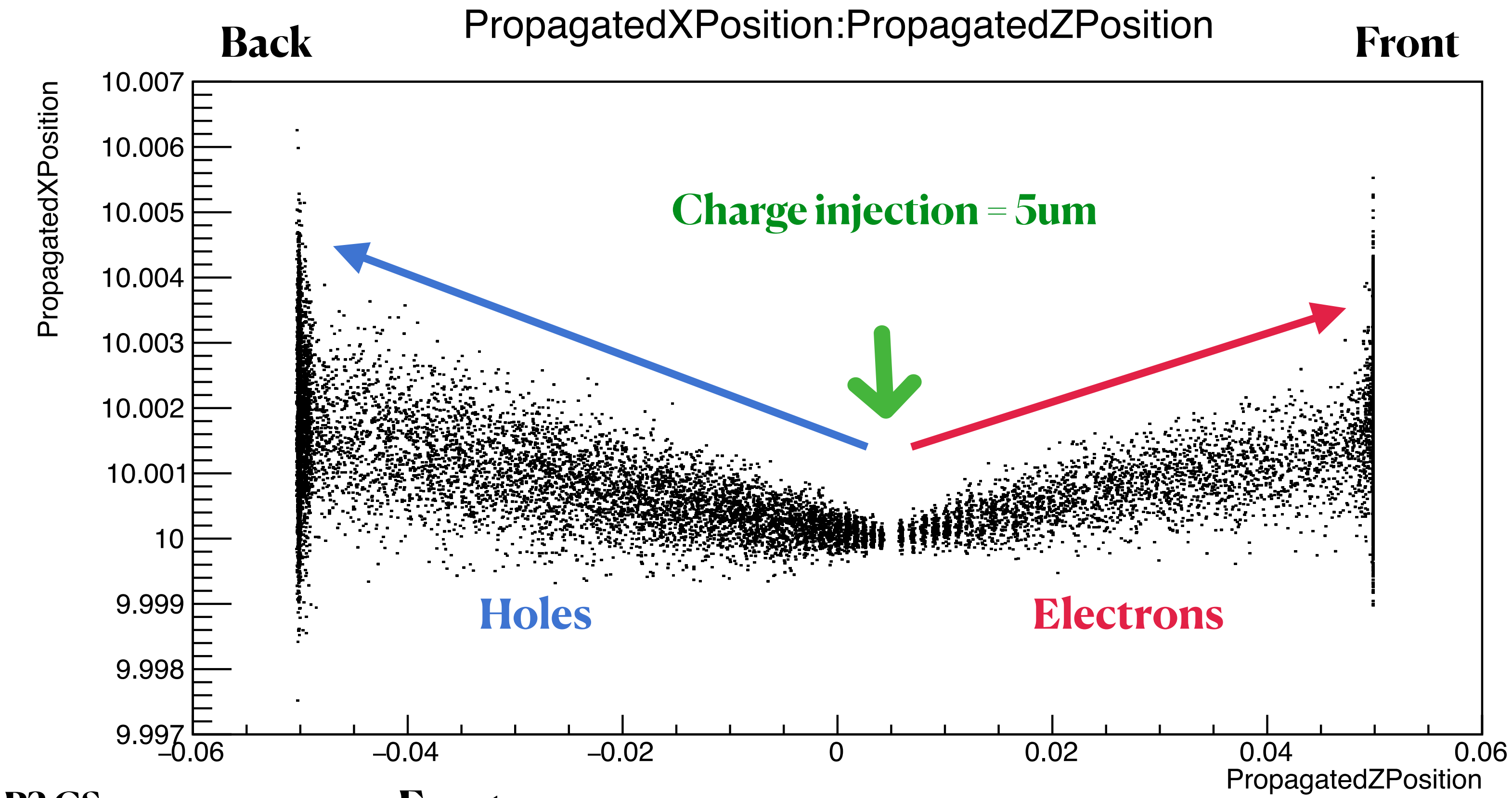


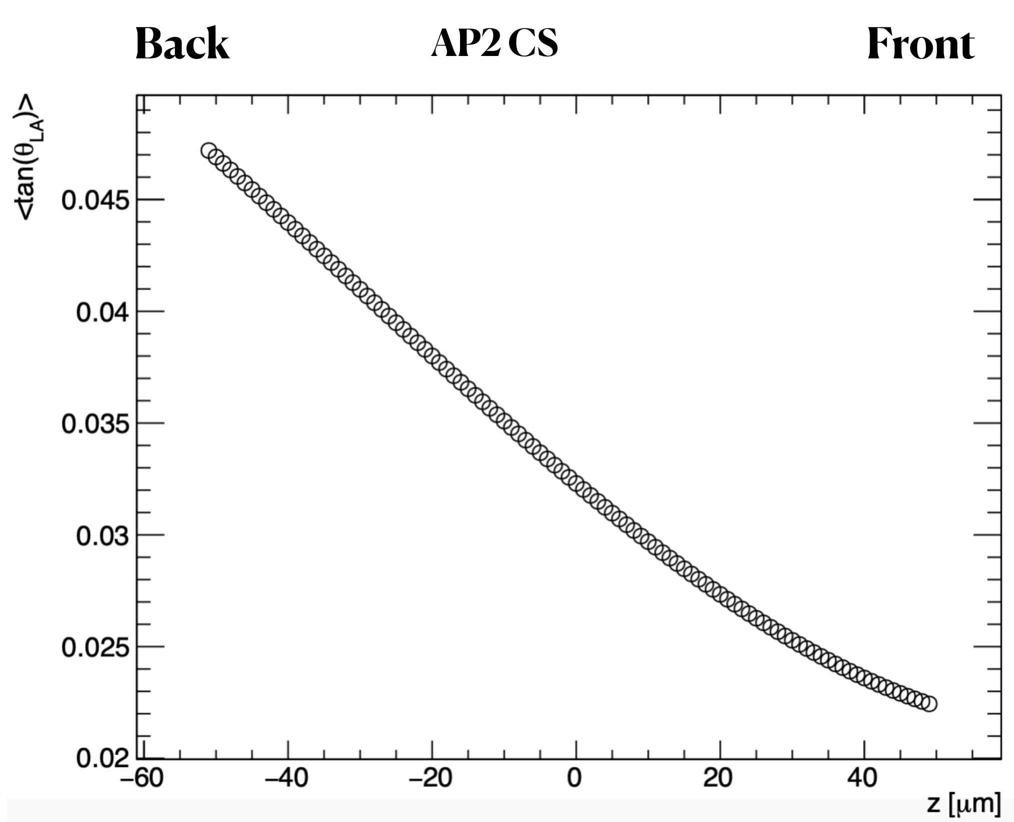
CCE profiles consistent with data

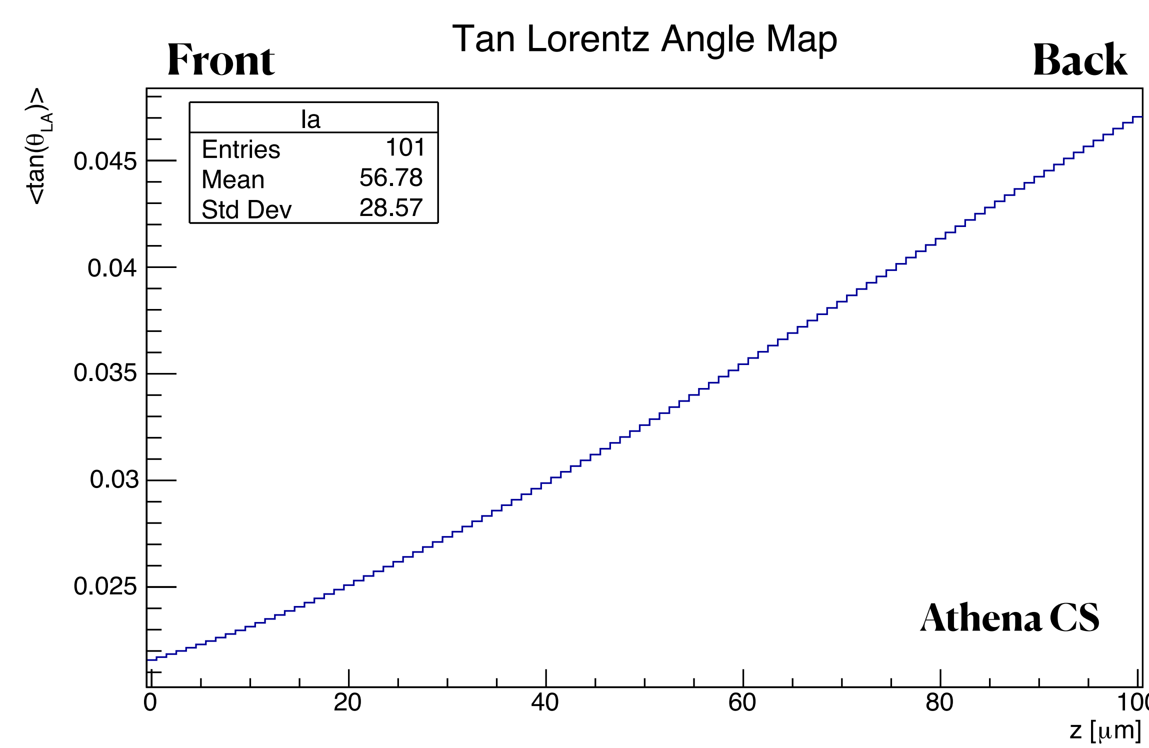


LUT #2 : $\tan(\theta_L)$ vs Z

From Allpix-squared



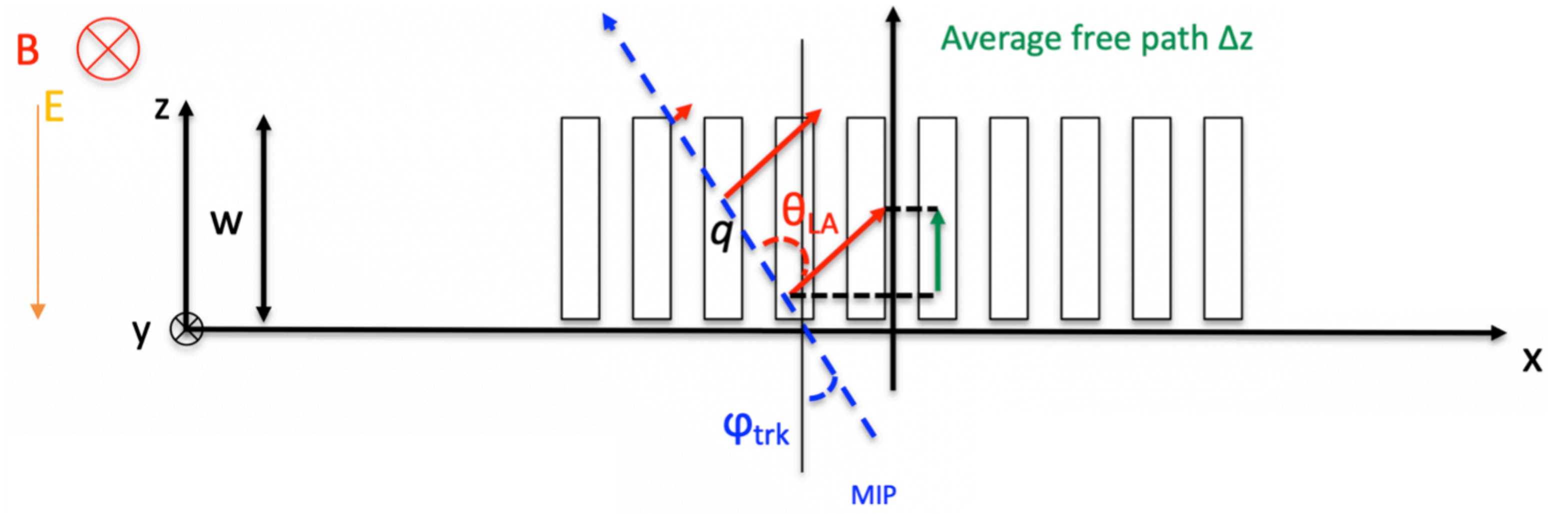




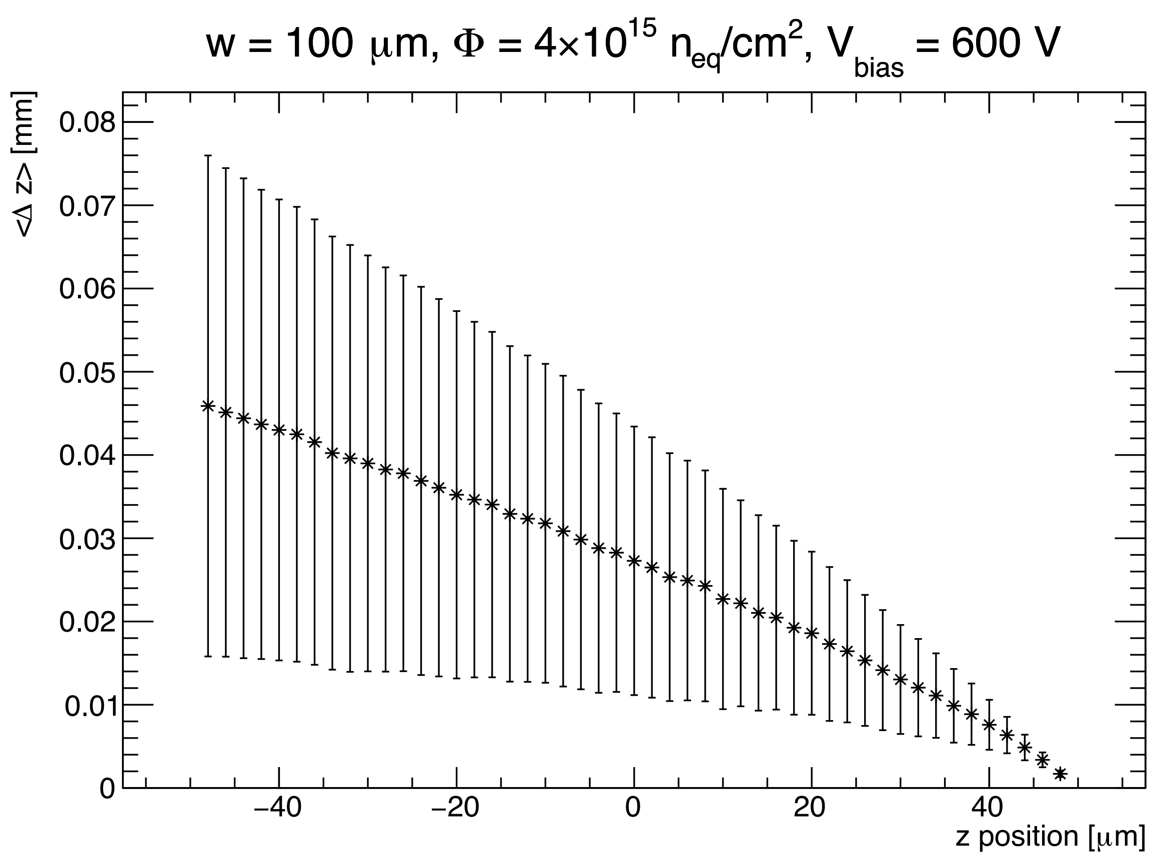
LUT #3 : ΔZ vs Z

From Allpix-squared

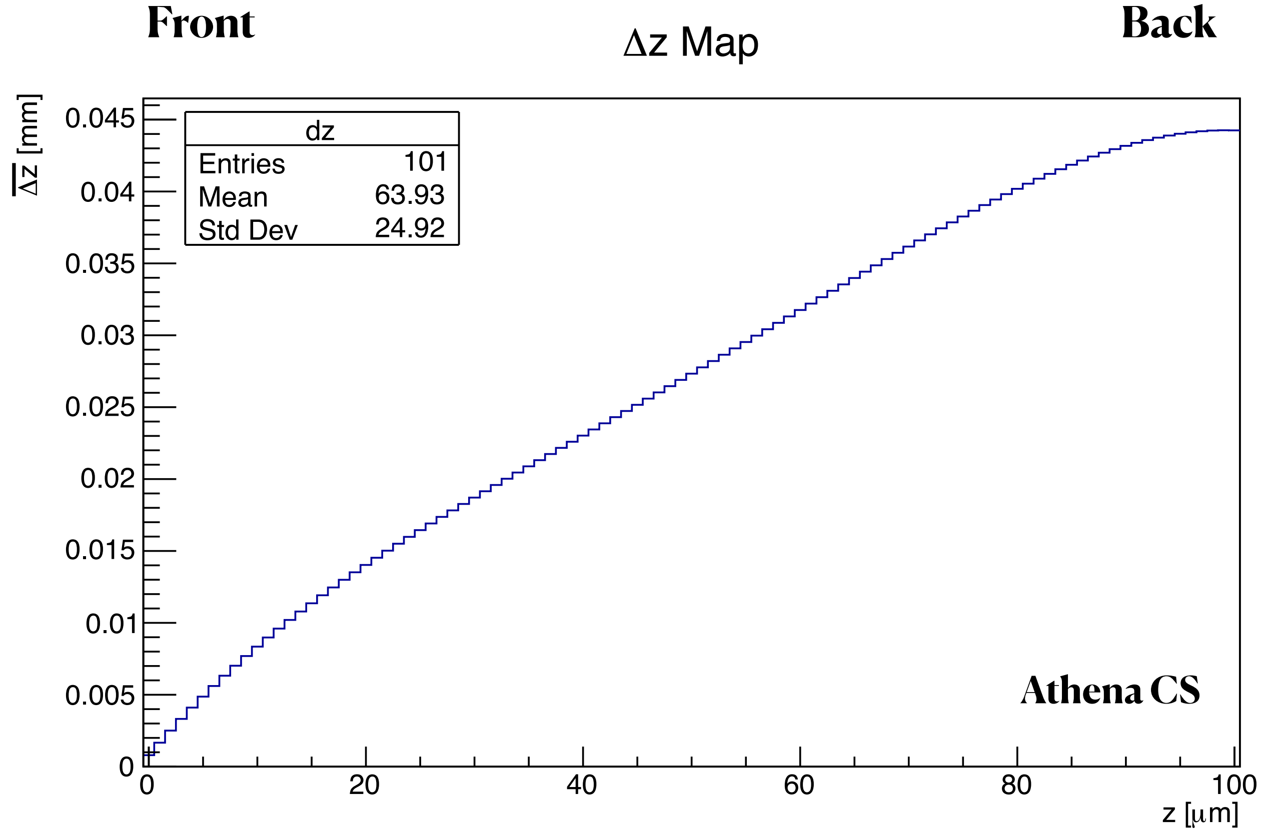
- Deflection in x is proportional to the distance covered in z
- In the radiation damage digitiser for Run2 and 3 -> is computed using a random generated value, which is not planned for HL-LHC -> need an average distance in z



Back **AP2 CS** **Front**



Front **Back**

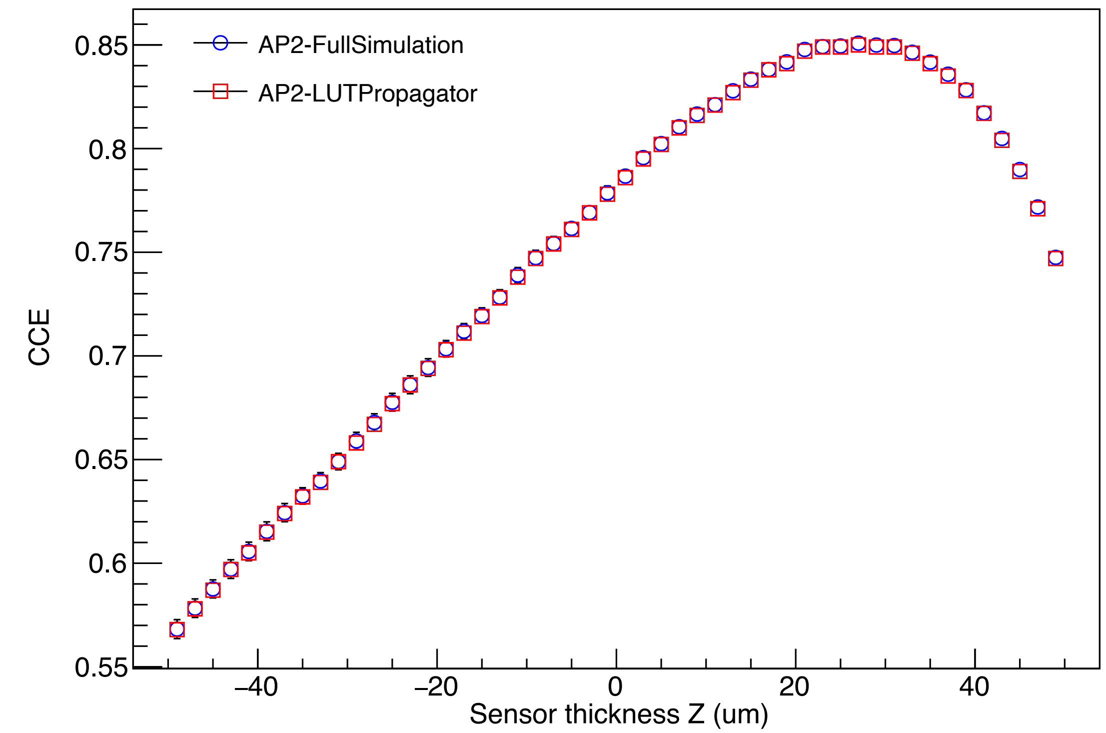


Closure test

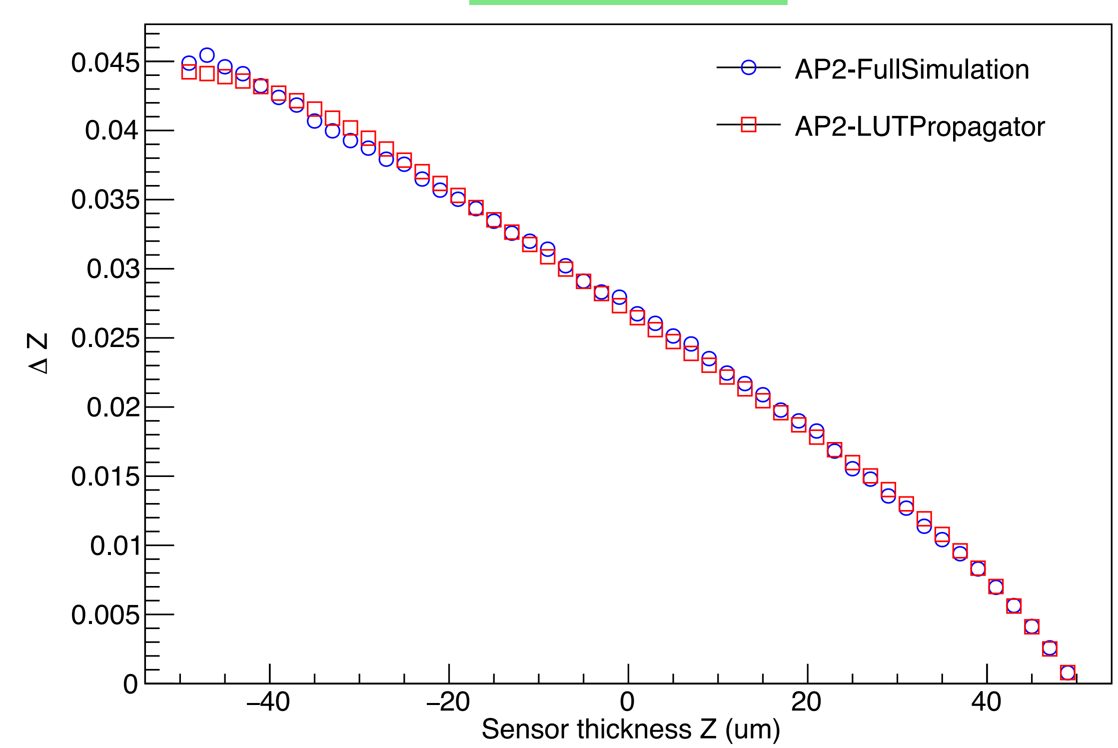
LUT propagator

- 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:
    - ❖ CCE(Z) = k(Z_deposited)*q(Z_deposited)
    - ❖ Z_propagated = Z_deposited + $\Delta Z(Z_{depsoied})$
    - ❖ 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

LUT propagator codes : https://gitlab.cern.ch/knakkali/allpix-squared/-/tree/308e1c9fa22590125f798d21199d72fb8fcfeec2/src/modules/LUTPropagator



Excellent agreement !!



Conclusion and outlook

- 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

✦ **Huge shoutout to AP2 developers for their help at various stages of this work**

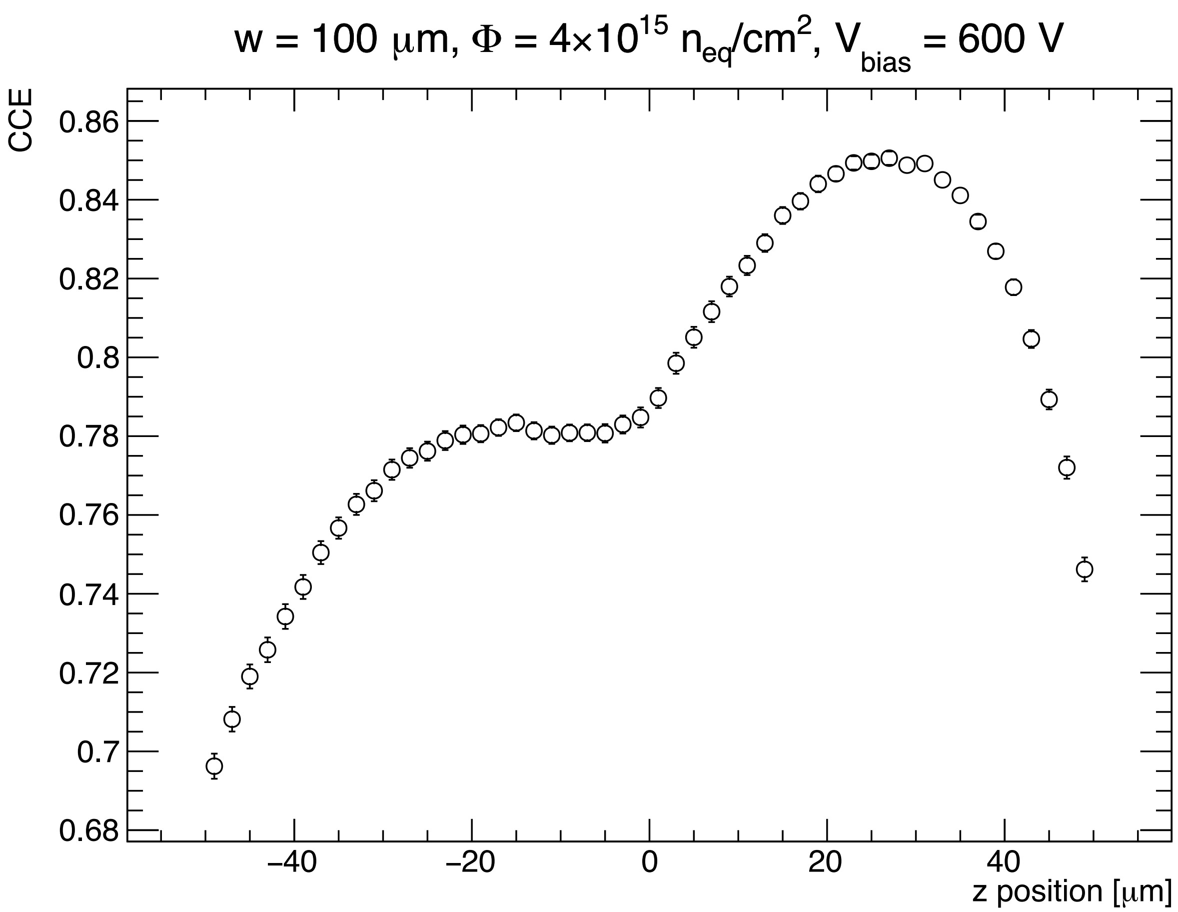
- Redo the studies using MIP
- Simulation of ITk 3D sensors with University of Trento and FBK

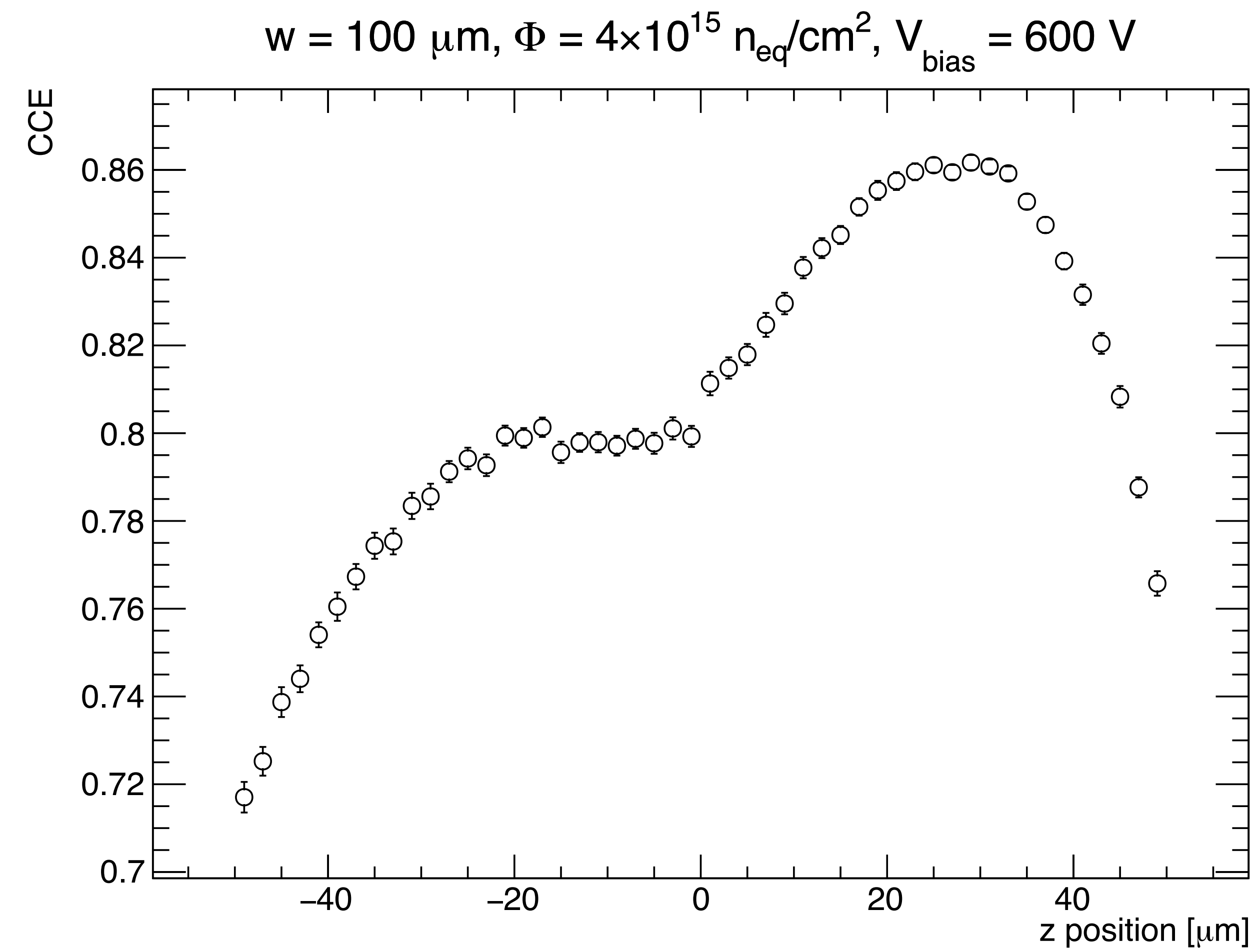
Thank you so much for your attention !! :)

Backup

CCE vs Z profiles

- Running AP2 on latest, modified RadDamVarTree to sum over all -ve charges
- TP + PT GP+IT





Pixel charges in each event

10 events at different z values

- Test: look at the pixel charges in each event for Qinj at different z

Z = 47um (close to front side)

```
Event: 10 Pixel charge: 20
Event: 10 Pixel charge: 36
Event: 10 Pixel charge: 20
Event: 10 Pixel charge: 37
Event: 10 Pixel charge: -794
Event: 10 Pixel charge: 37
Event: 10 Pixel charge: 20
Event: 10 Pixel charge: 38
Event: 10 Pixel charge: 20
 maximum pixel charge: -794
 Pix total charge: -794
```

Z = 0um (sensor center)

```
Event: 10 Pixel charge: 5
Event: 10 Pixel charge: 4
Event: 10 Pixel charge: 5
Event: 10 Pixel charge: 3
Event: 10 Pixel charge: -814
Event: 10 Pixel charge: 3
Event: 10 Pixel charge: 5
Event: 10 Pixel charge: 3
Event: 10 Pixel charge: 5
 maximum pixel charge: -814
 Pix total charge: -814
```

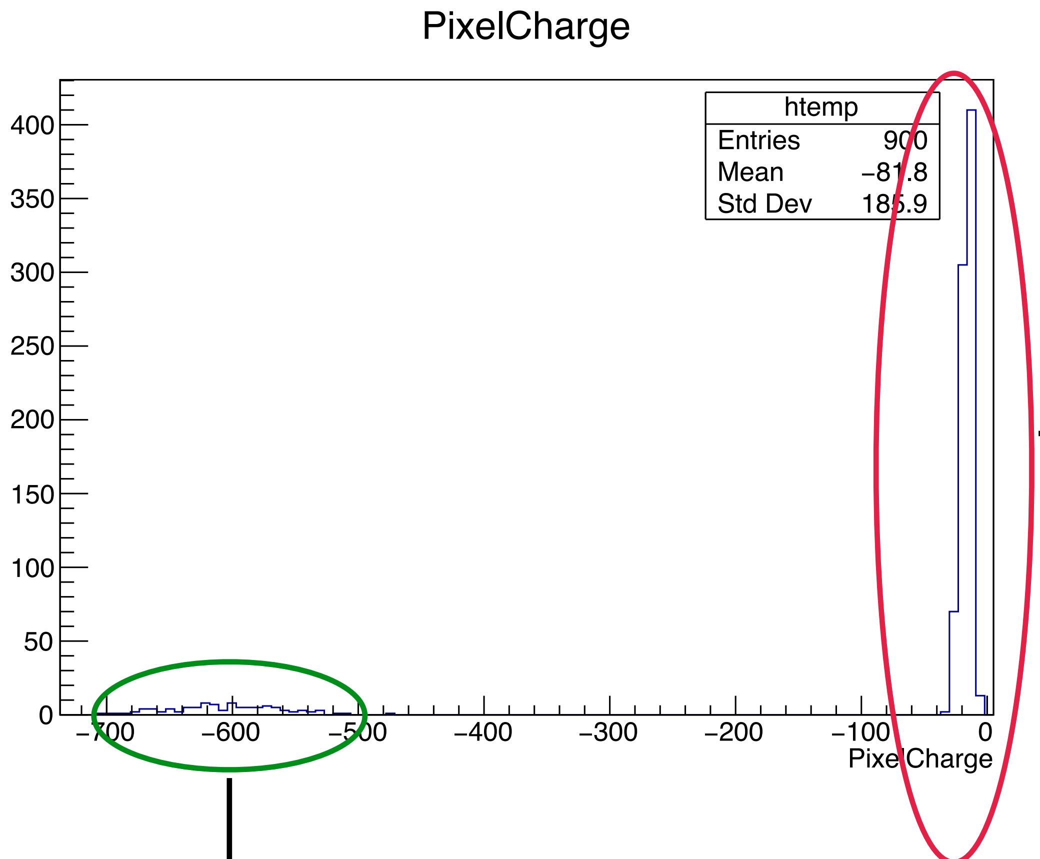
Z = -47um (close to back side)

```
Event: 10 Pixel charge: -11
Event: 10 Pixel charge: -18
Event: 10 Pixel charge: -11
Event: 10 Pixel charge: -20
Event: 10 Pixel charge: -640
Event: 10 Pixel charge: -20
Event: 10 Pixel charge: -12
Event: 10 Pixel charge: -23
Event: 10 Pixel charge: -12
 maximum pixel charge: -640
 Pix total charge: -640
```

- Z > -15um -> positive charges are induced on neighbours
- The small positive charges when injection is close to the front are due to holes that got trapped on the way back to the HV side. On the contrary when we inject close to the back there are electrons that travel quite some distance and get diffused and or drifted (a bit) by Lorentz force. So they end up in a region in which they can induce some charge also on the neighbours
- The above hypothesis can be verified by looking PropagatedX and PropagatedY for z = -40

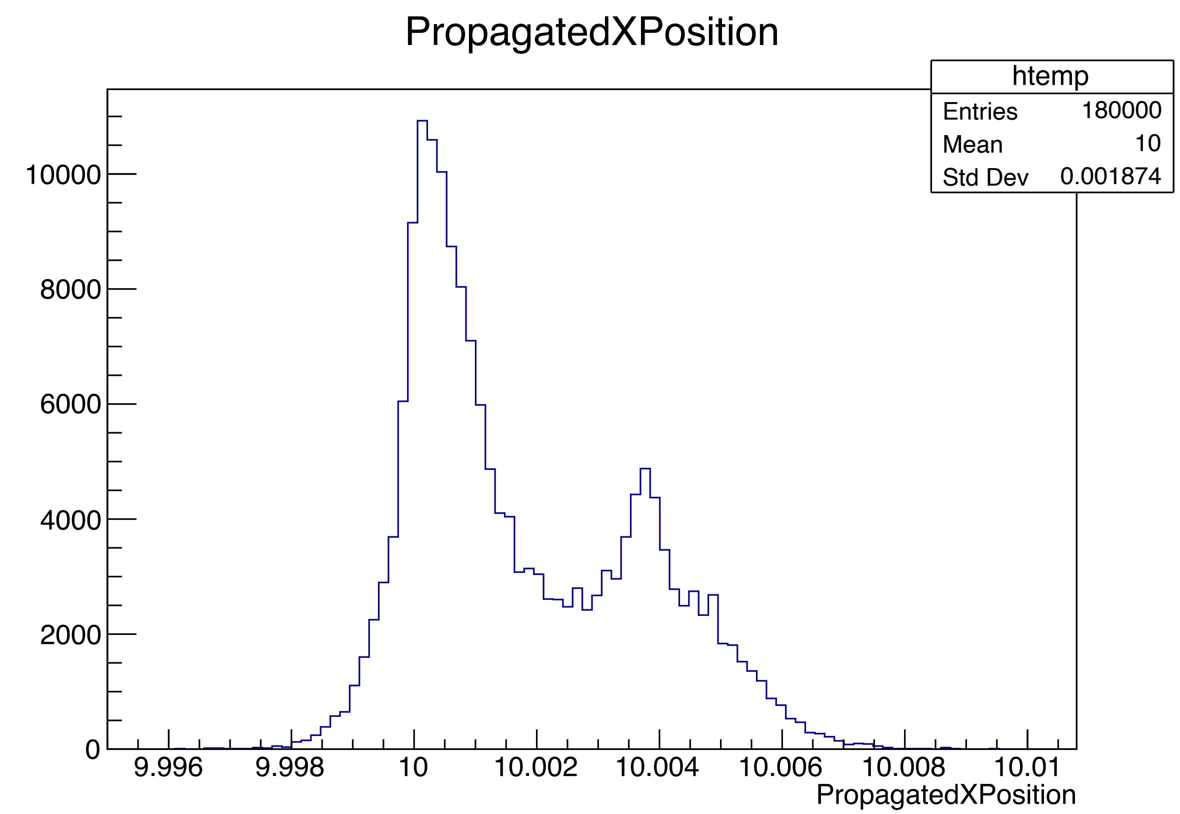
PropagatedX and PropagatedY distributions

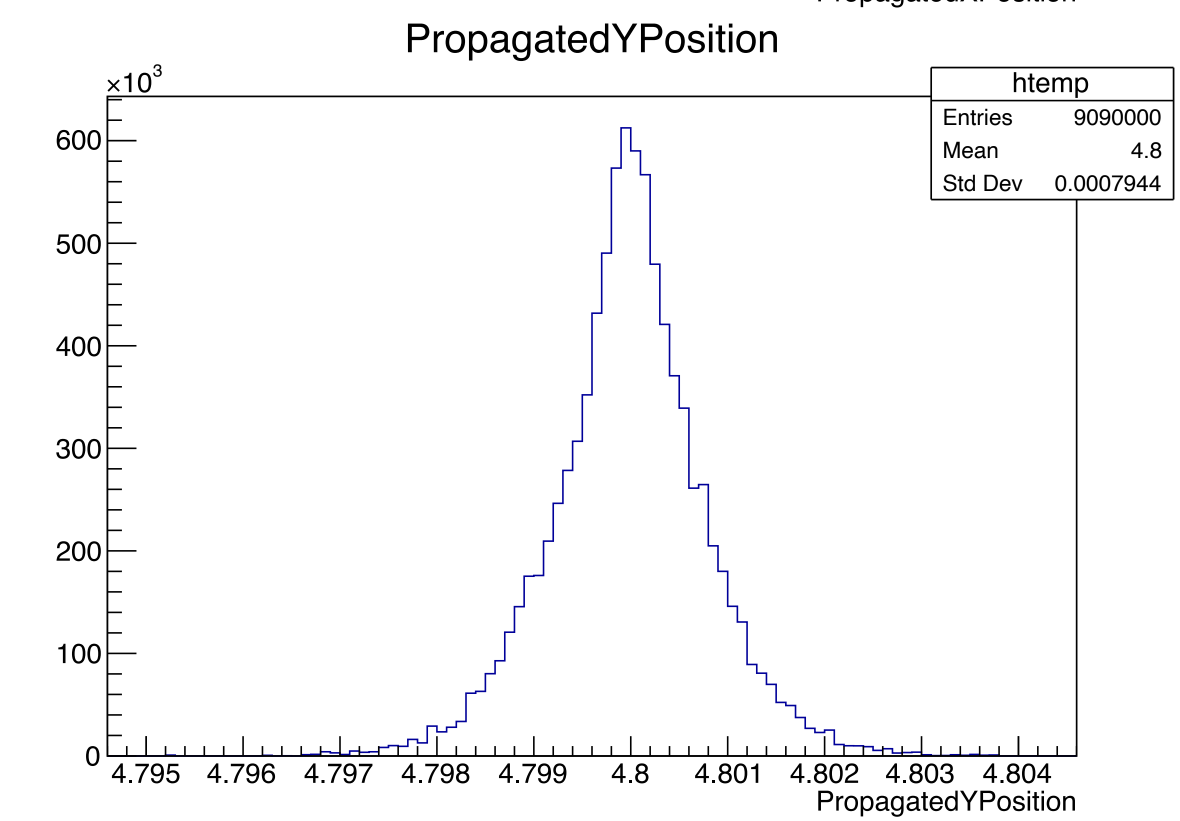
Z = -41um -> close to HV side



Induced negative charges on the neighbours

Induced negative charges on central pixel (200,96)



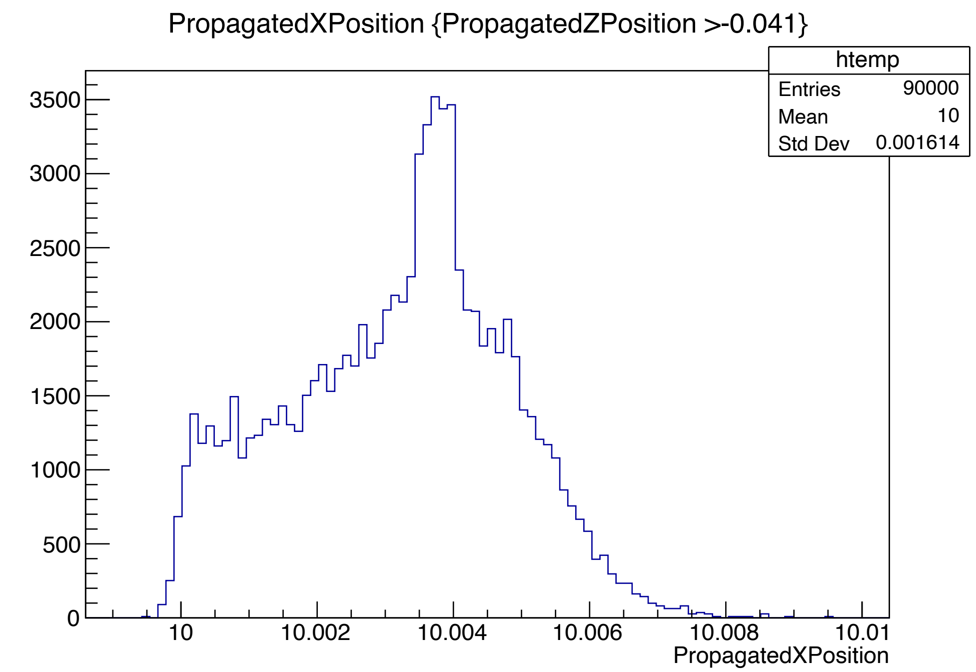


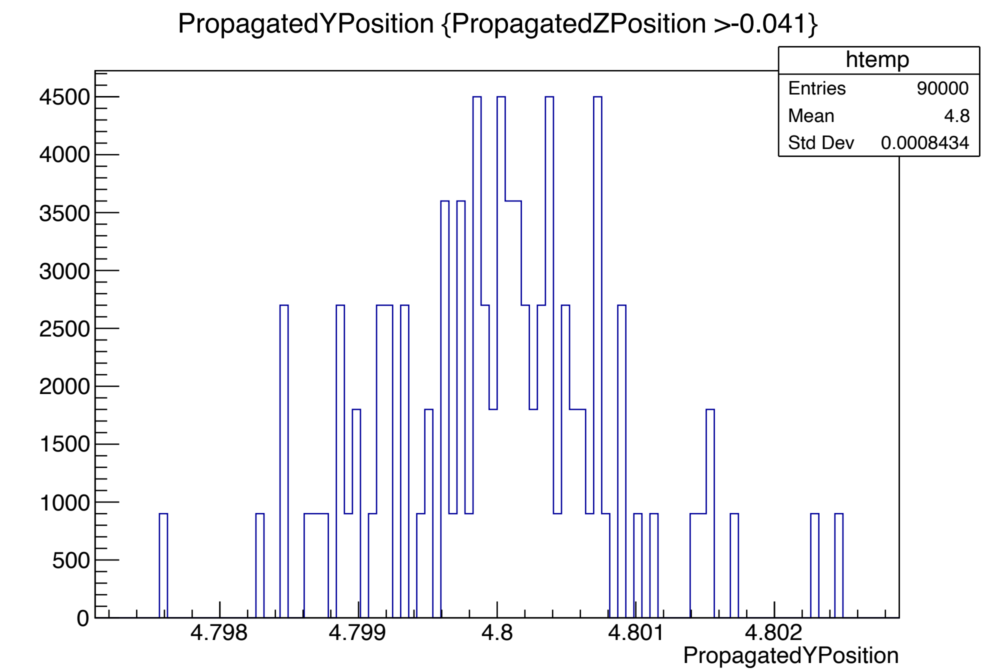
- If the small negative charges are coming from the electrons migrated into the neighbouring pixels, we should observe some events at :
    - PropagatedXPosition > 10.025 or propagatedXpositions < 9.975
    - PropagatedYPosition > 4.825 or propagatedYpositions < 4.775
- This is not what we see in the plots on the right
- How do we explain what we see?

PropagatedX and PropagatedY

Z = -41um, for electrons and holes

Electrons





Holes