CDD-2024, 26-29 March 2024

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

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Playing with Particles

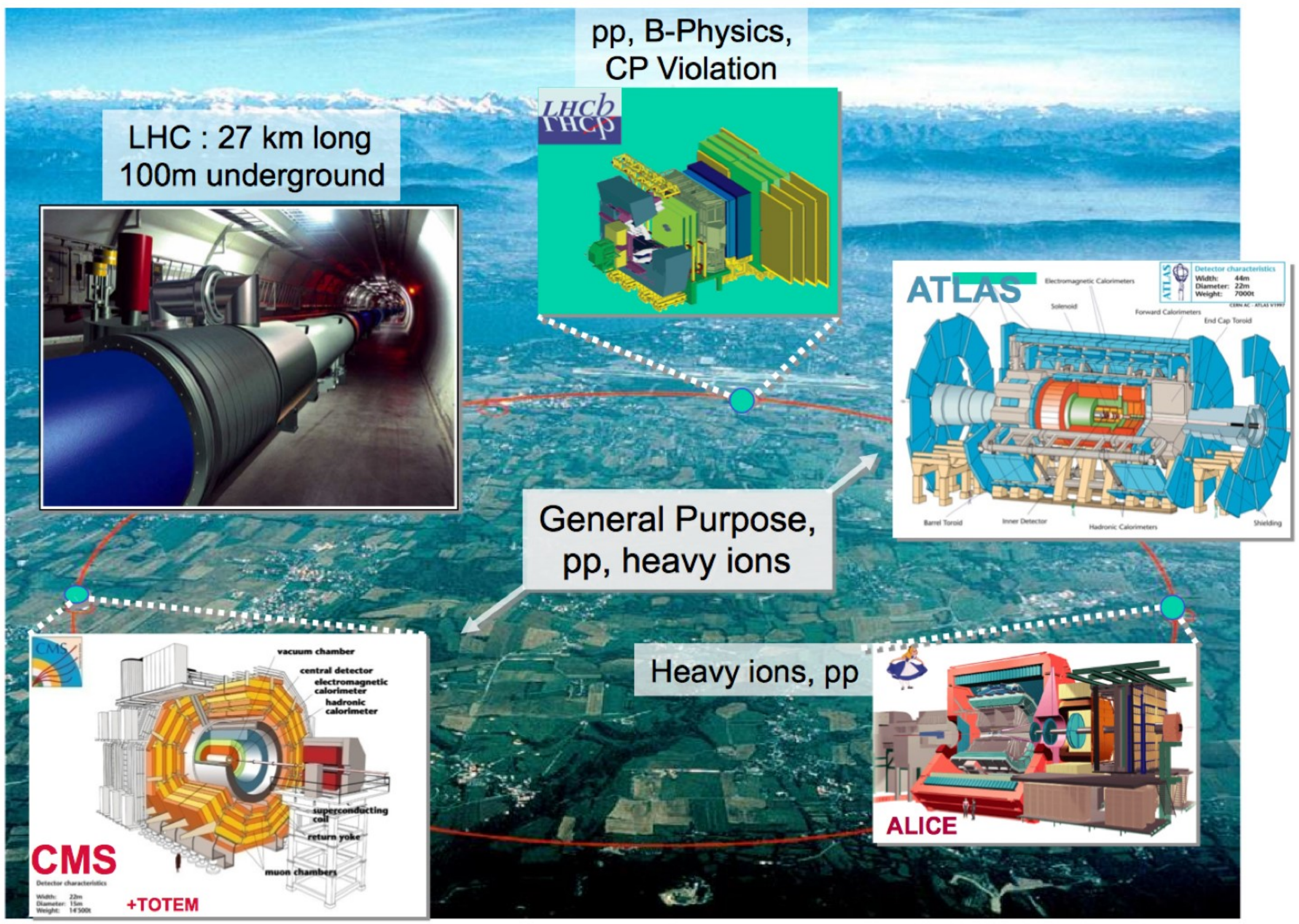
Standard model of particle physics ~ the theory of almost everything!

- Best theoretical framework for particle physics
- Description of the interaction of fundamental particles via exchange of force carriers
- All the particles in SM have been discovered (except for graviton)
- SM is incomplete
  - ✦ Matter-antimatter asymmetry , dark matter , existence of 3 generation of quarks and leptons with different mass scale , gravity

: discovered at colliders

The Large Hadron Collider (LHC)

World's largest and most powerful accelerator



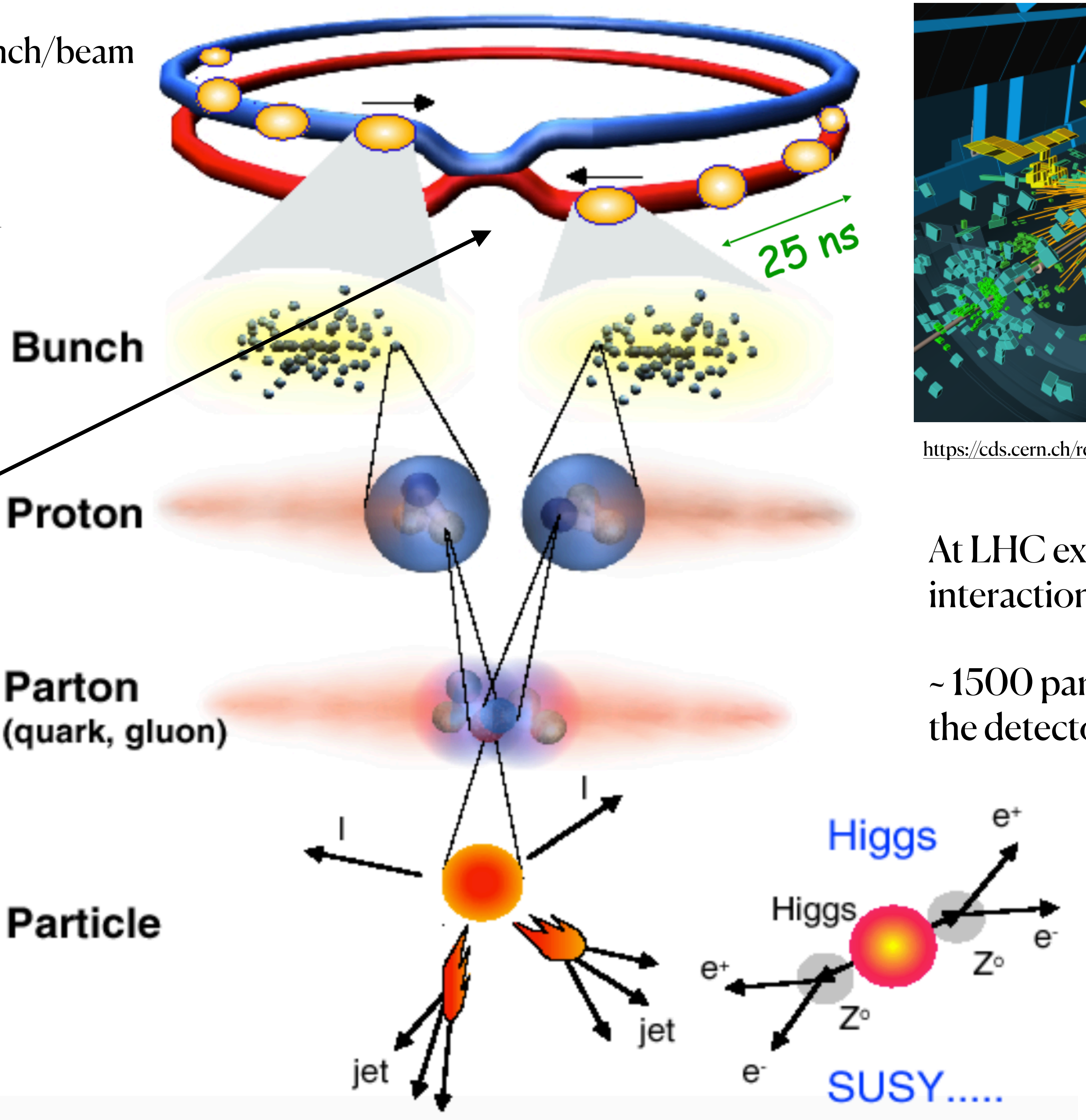
- Situated 100m beneath the France–Switzerland border in a 27km circumference tunnel near Geneva
- 1232 dipole magnets, B = 8.3T
- Accelerates and collides two counter-circulating particle beams (protons or ions)
    - 2012 : Run 1 at 2 x 4 TeV , 2013-2015 : LS1
    - 2015: Run 2 at 2 x 6.5TeV , 2018 -2022: LS2
    - 2022 : Run3 at 2 x 6.8TeV , 2025 - 2027 : LS3
    - 2027: HL-LHC
- Houses 4 main experiments : ATLAS, CMS, ALICE, LHCb
- ~ 4000MCHF (machine R&D and injectors, tests and pre-operation)

Collisions at LHC

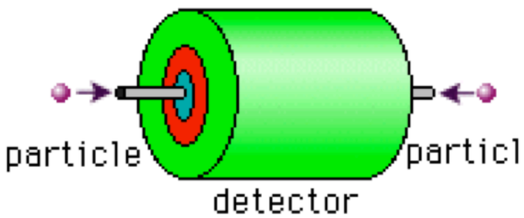
Taking a closer look

Proton-Proton : 2835 bunch/beam
Protons/bunch : 10^{11}

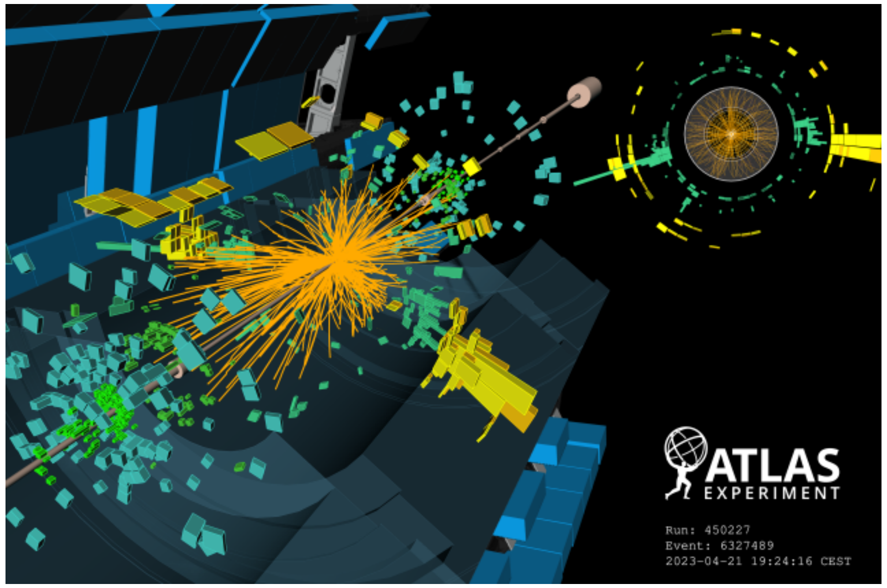
Beam energy : 6.8 TeV
Luminosity : $10^{34}\ cm^{-2}s^{-1}$



Build your detector here



Event display. 6.8TeV



https://cds.cern.ch/record/2856820

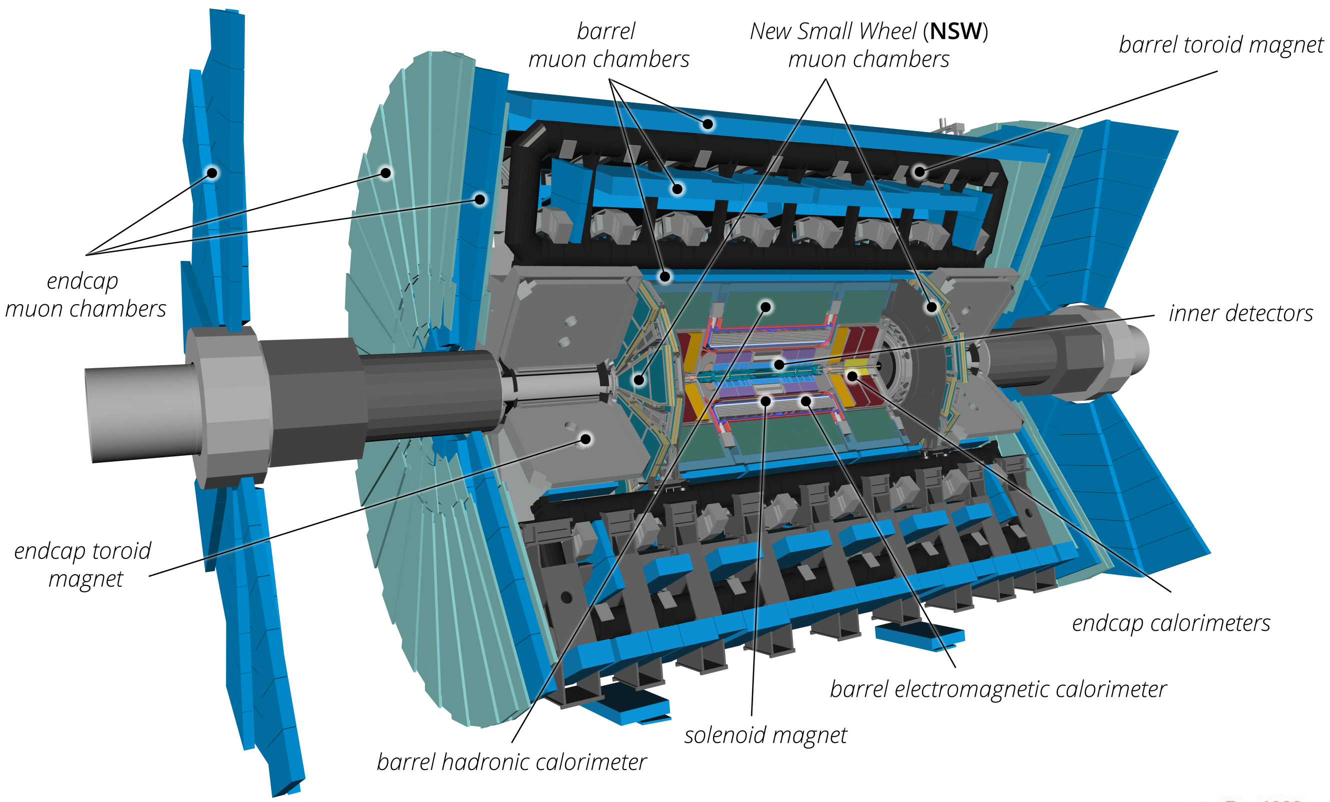
At LHC experiments : 10^9 pp interactions per second

~ 1500 particles (p, n, π) produced in the detectors at each bunch -crossing

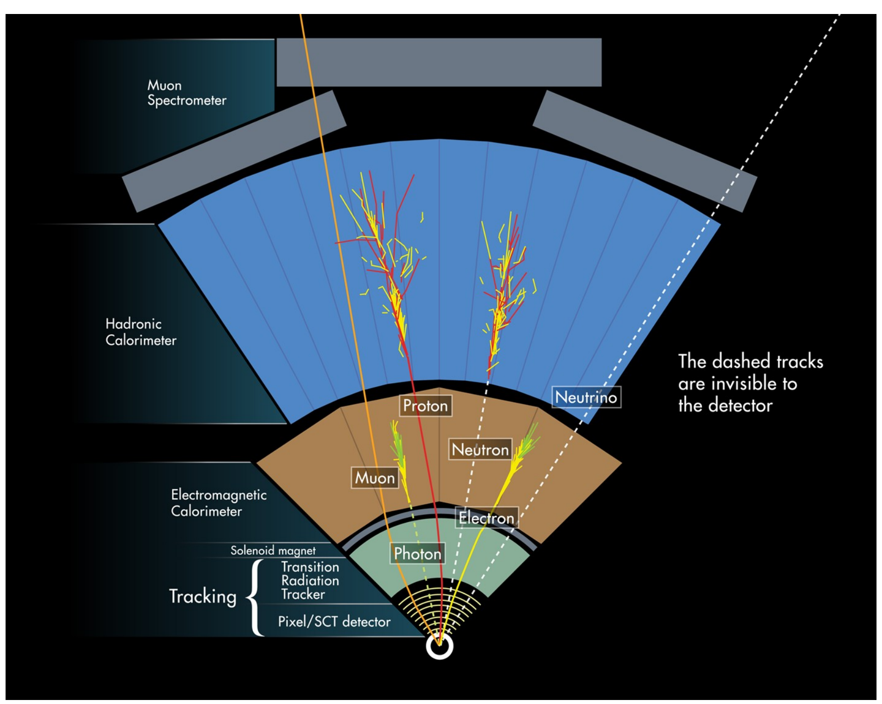
Selection of **1** in
10,000,000,000,000
events

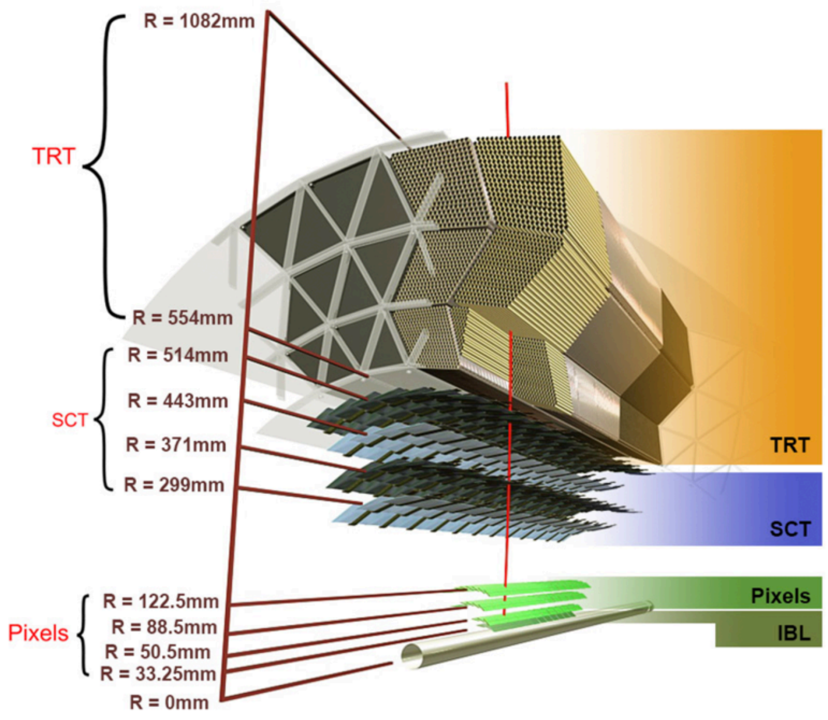
A Toroidal LHC Apparatus (ATLAS)

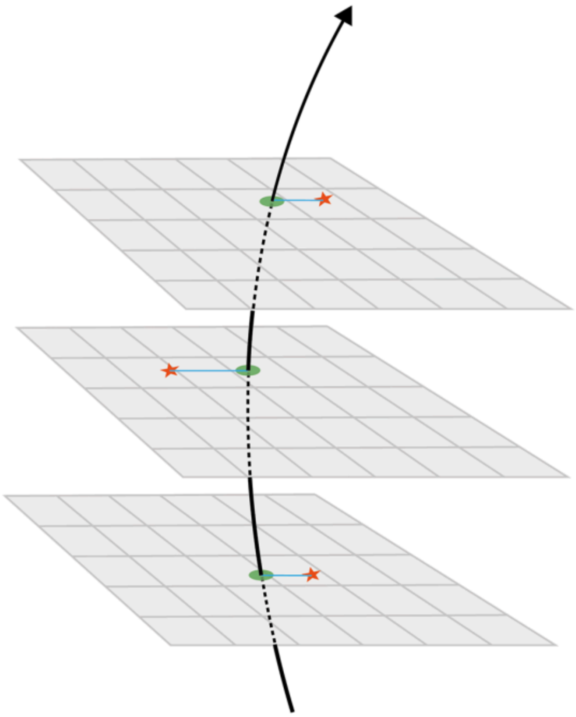
As Heavy as the Eiffel Tower!



- Largest volume detector ever constructed for particle collider
    - Dimensions : 46m long, 25m diameter, 7000 tonnes
- 6 concentric subsystems around the interaction point (IP) for precise particle trajectory, momentum, and energy measurement
- Inner detector (ID) submerged in 2T magnetic field for precise measurement of charged particle momenta

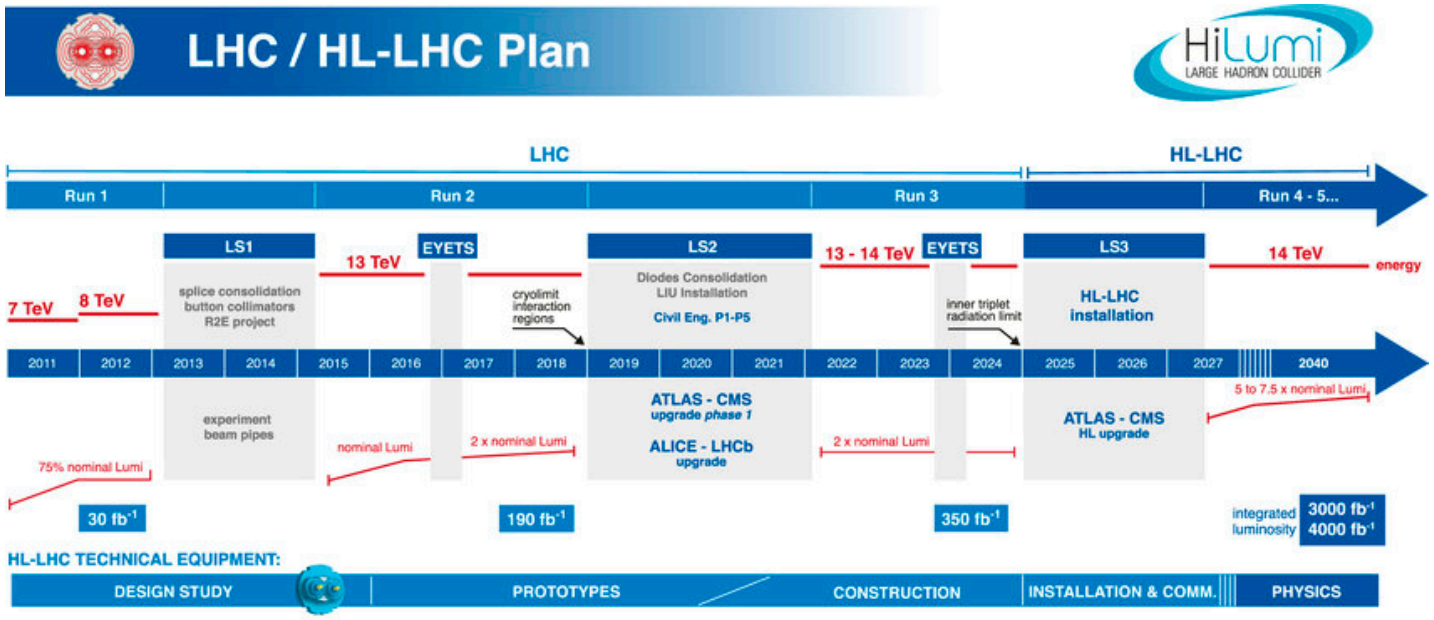






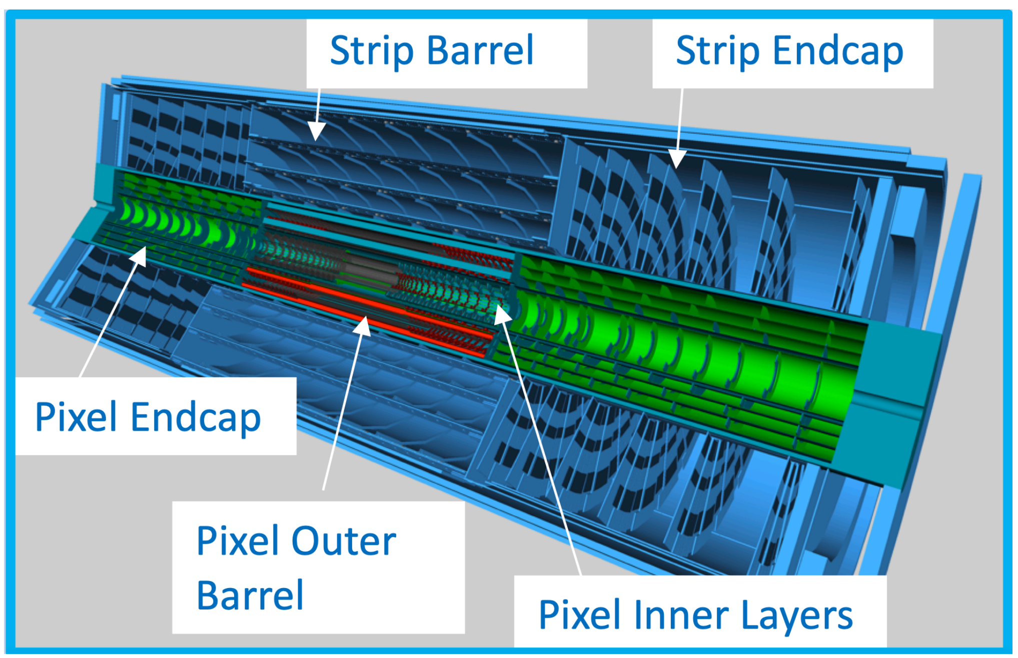
High Luminosity LHC (HL-LHC)

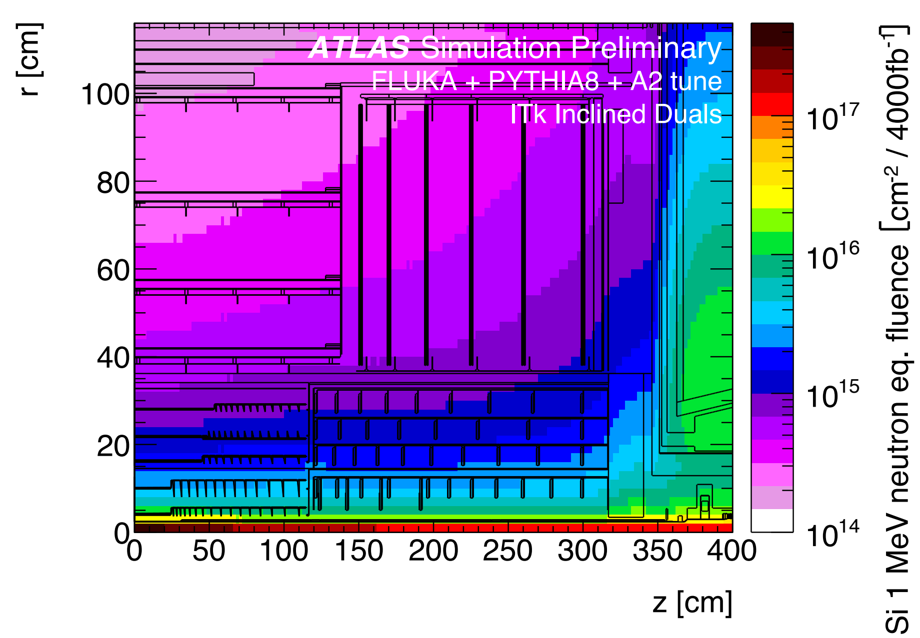
At least 15 million Higgs boson per year!!



- **High Luminosity (HL) LHC:**
  - Peak luminosity: $1x10^{34} \rightarrow 5 - 7x10^{34} cm^{-2}s^{-1}$
  - 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

- Replacement of the current Inner Detector system with a full silicon Inner Tracker (ITk)



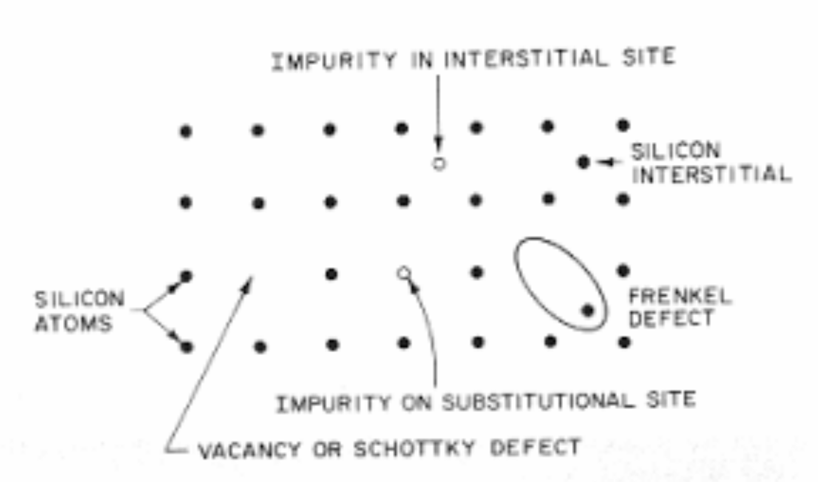


- **New Inner Tracker (ITk)**
  - High granularity
  - Reduced material
  - Radiation hardness
  - Faster readout
  - Goal: new tracker to have better performance compared to current ID

Radiation damage in Silicon Sensors

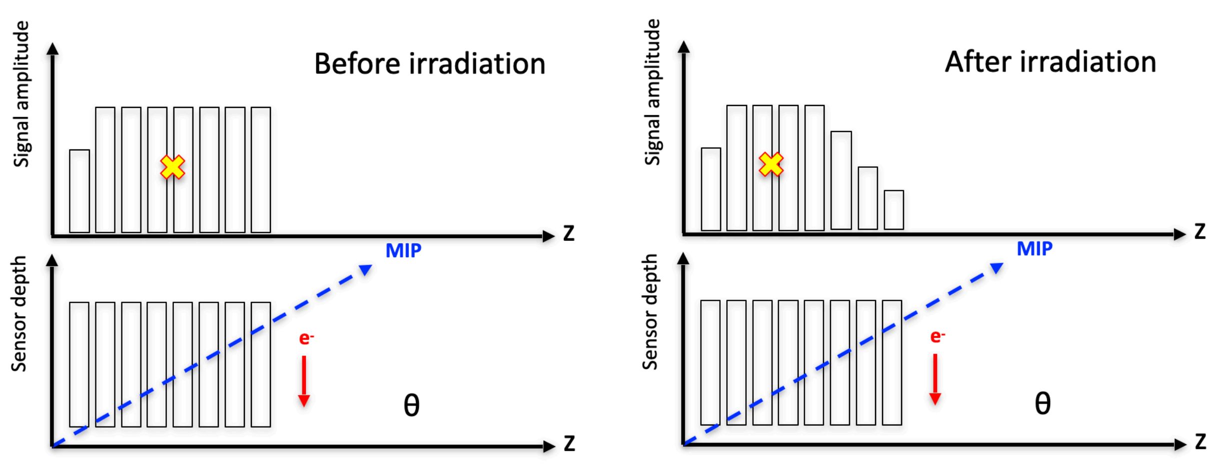
In a nutshell.

- Radiation damage to detector materials : 2 types
  - ✦ Surface damage due to ionising energy loss (IEL)
    - ✦ Accumulation of positives in the oxide (SiO_2) and the Si/SiO_2 interface -> affects inter-strip capacitance, breakdown behaviour ..
  - ✦ **Bulk (crystal) damage** due to non-ionising energy loss (NIEL)
    - ❖ Inelastic collision btw incident particle and silicon lattice -> displacement of an atom from its lattice
    - ❖ Creates Interstitial site + vacancy -> Frenkel defects



    - ❖ Unstable point defects can create stable secondary defects -> energy levels in the band-gap -> acts as trapping centers

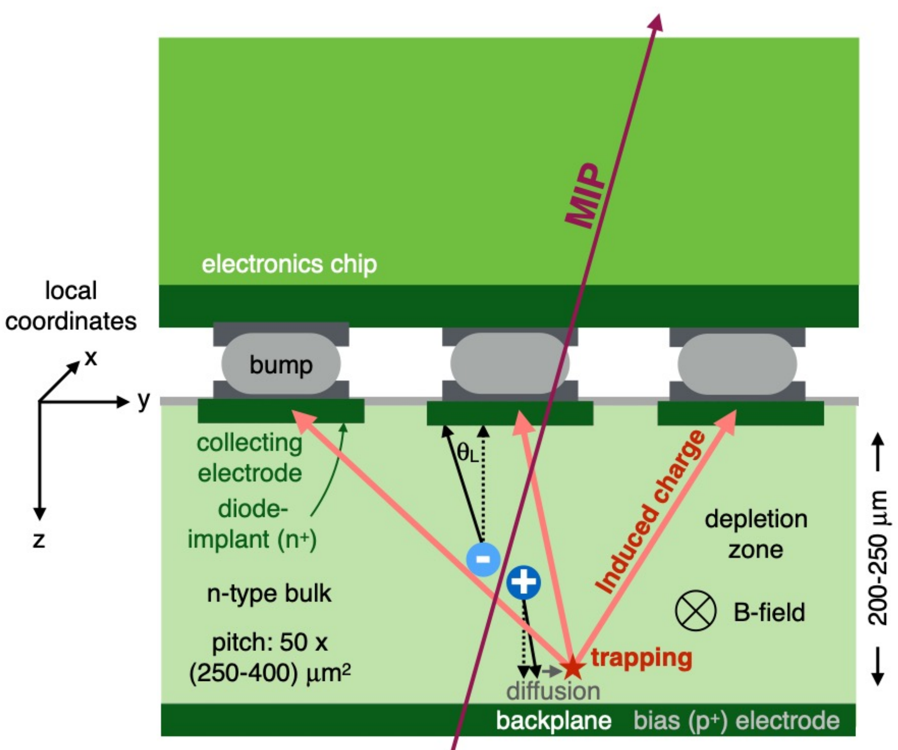
- Macroscopic effects of bulk radiation damage on detector operations :
  - ✦ Increase in depletion voltage
  - ✦ Increase in Leakage currents
  - ✦ **Decrease in charge collection efficiency -> signal loss**
    - ❖ Smaller signal-to-noise ratio
    - ❖ Induce bias in signal position reconstruction



Radiation damage modelling : ATLAS approach

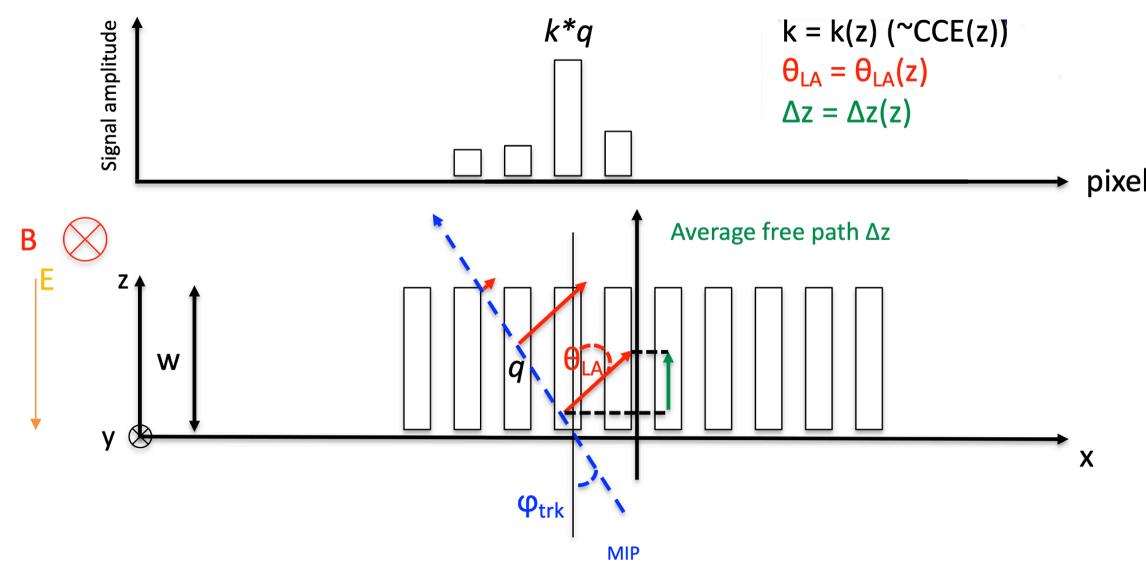
Run2 /Run3 vs. HL-LHC strategy

- 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

- HL-LHC : ATLAS/CMS pixel detectors exposed to unprecedented levels of radiation damage
- 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)

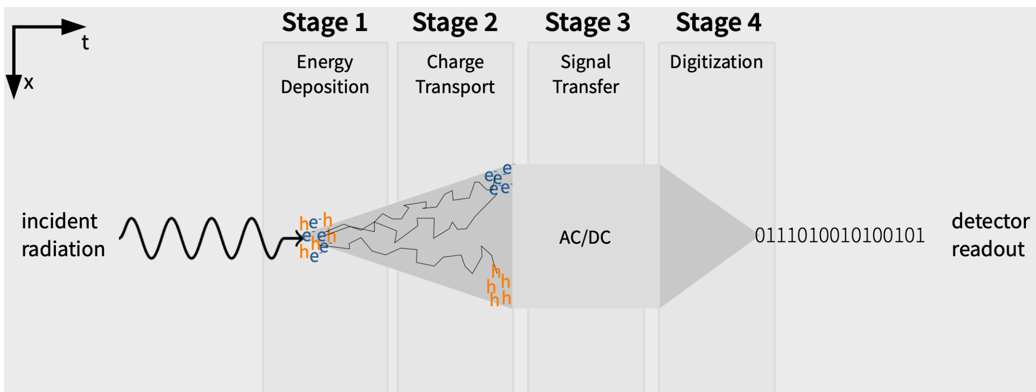


- Idea : For each simulated charge q at depth **z** find in which pixel it will end up, by how much ***(k)*** **the signal will be reduced**
  - ✦ Goal: Simulated pixels in MC is corrected using these information before digitisation -> correction scheme implemented using **Allpix-squared** (doi:10.1016/j.nima.2018.06.020)

Allpix-squared framework

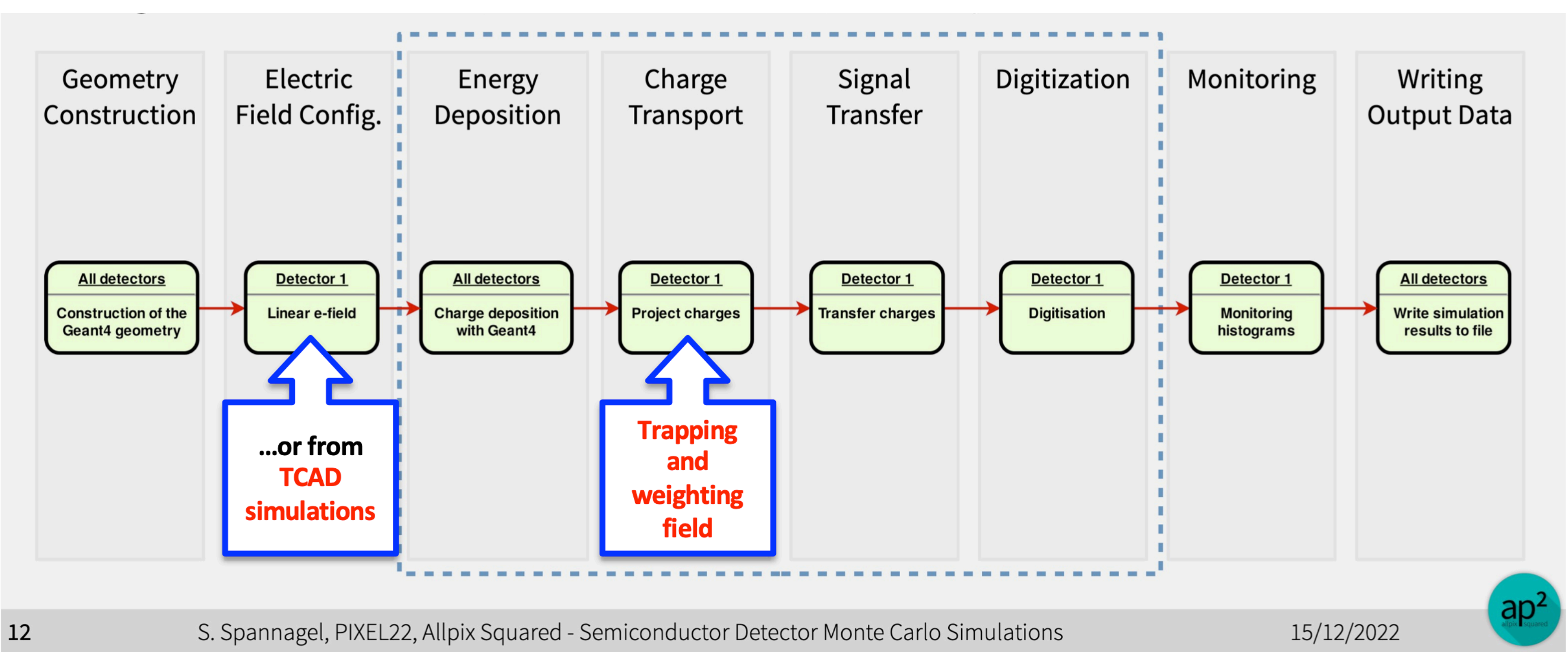
Simulation flow

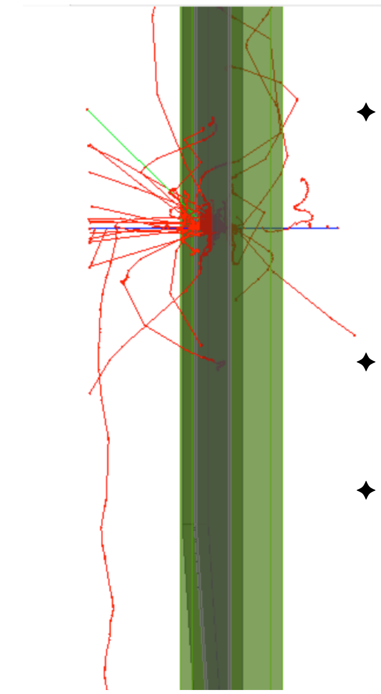
- Modular, generic simulation framework aiming at facilitating the different steps of the simulation of semiconductor detectors



- 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

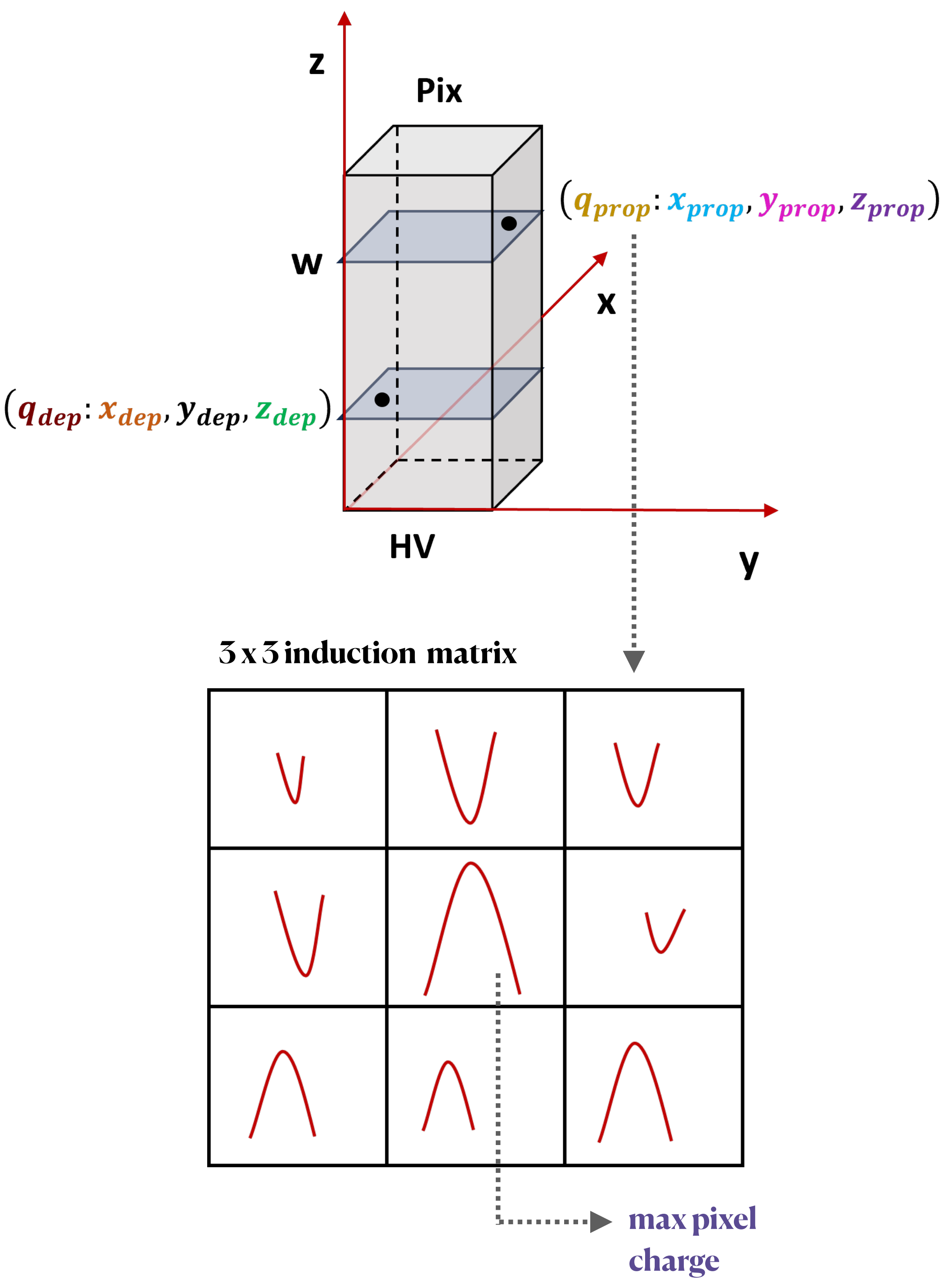
```
[Allpix]
log_level = "INFO"
log_format = "DEFAULT"
detectors_file = "planar_detector.conf"
number_of_events = 125000
root_file = "histos_125kEvents_100um_4e15_600V"
random_seed = 0

[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"
```

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 **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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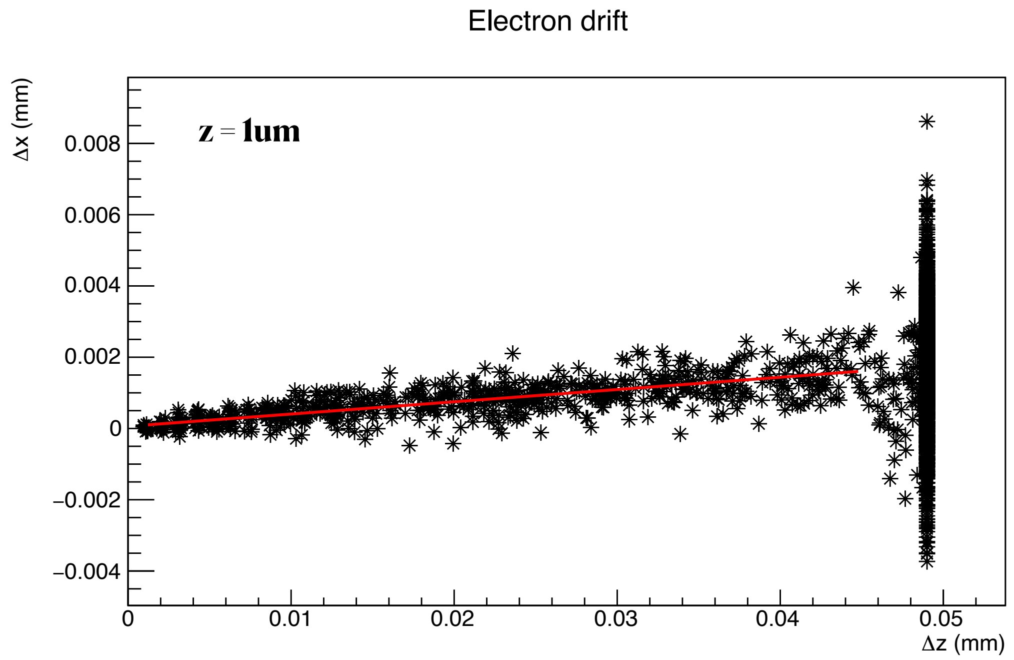

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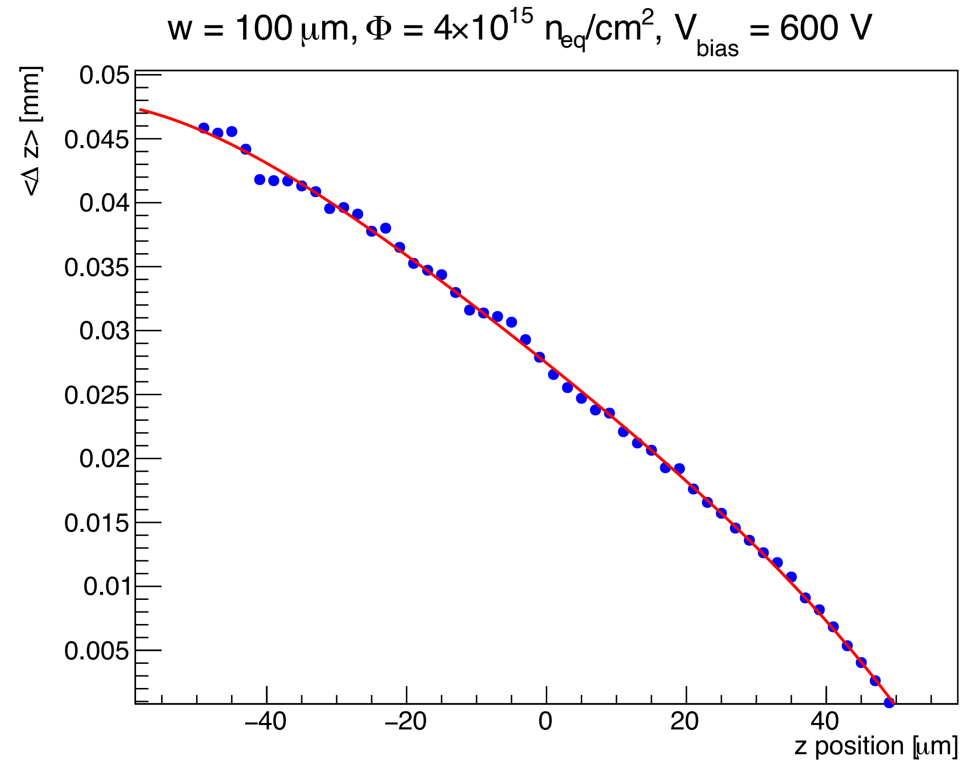
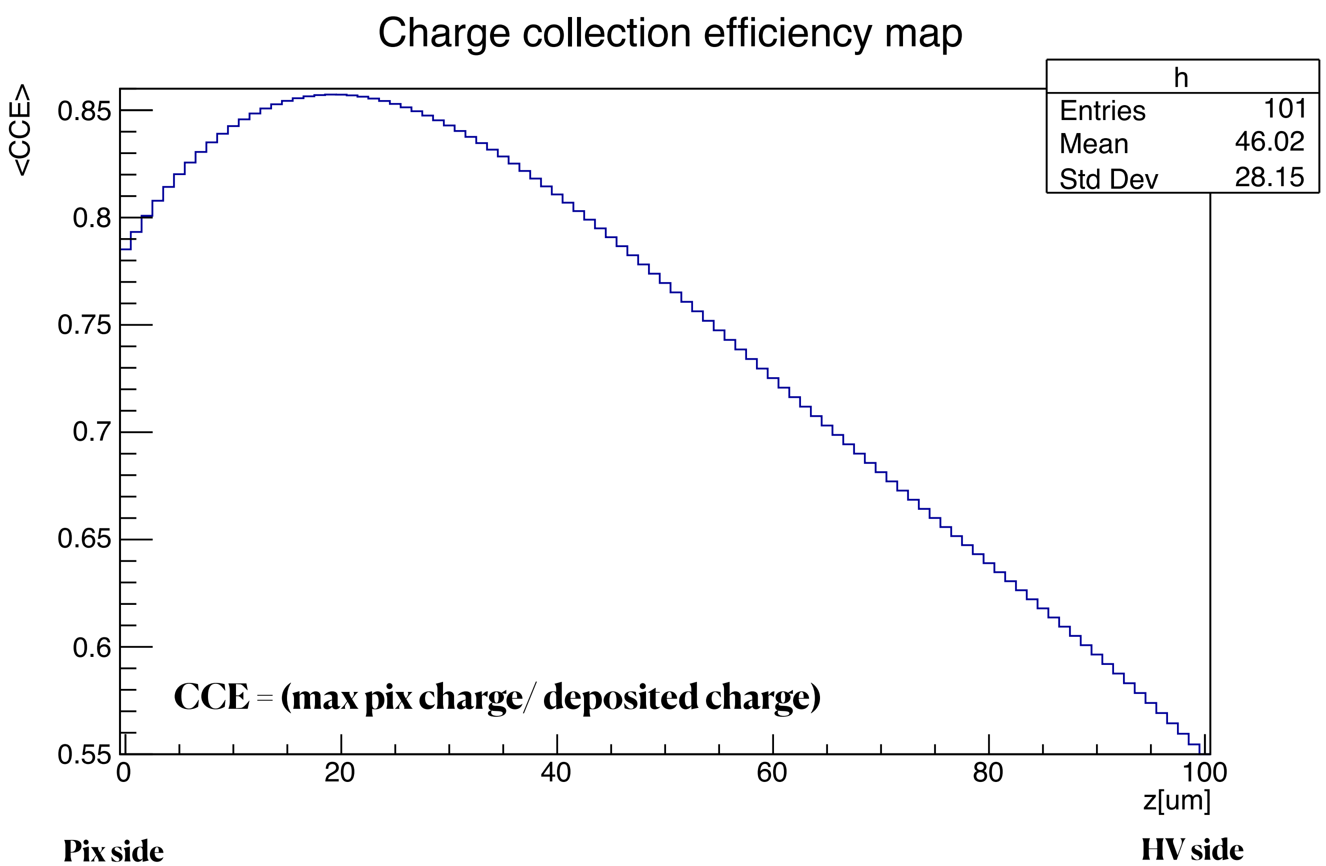
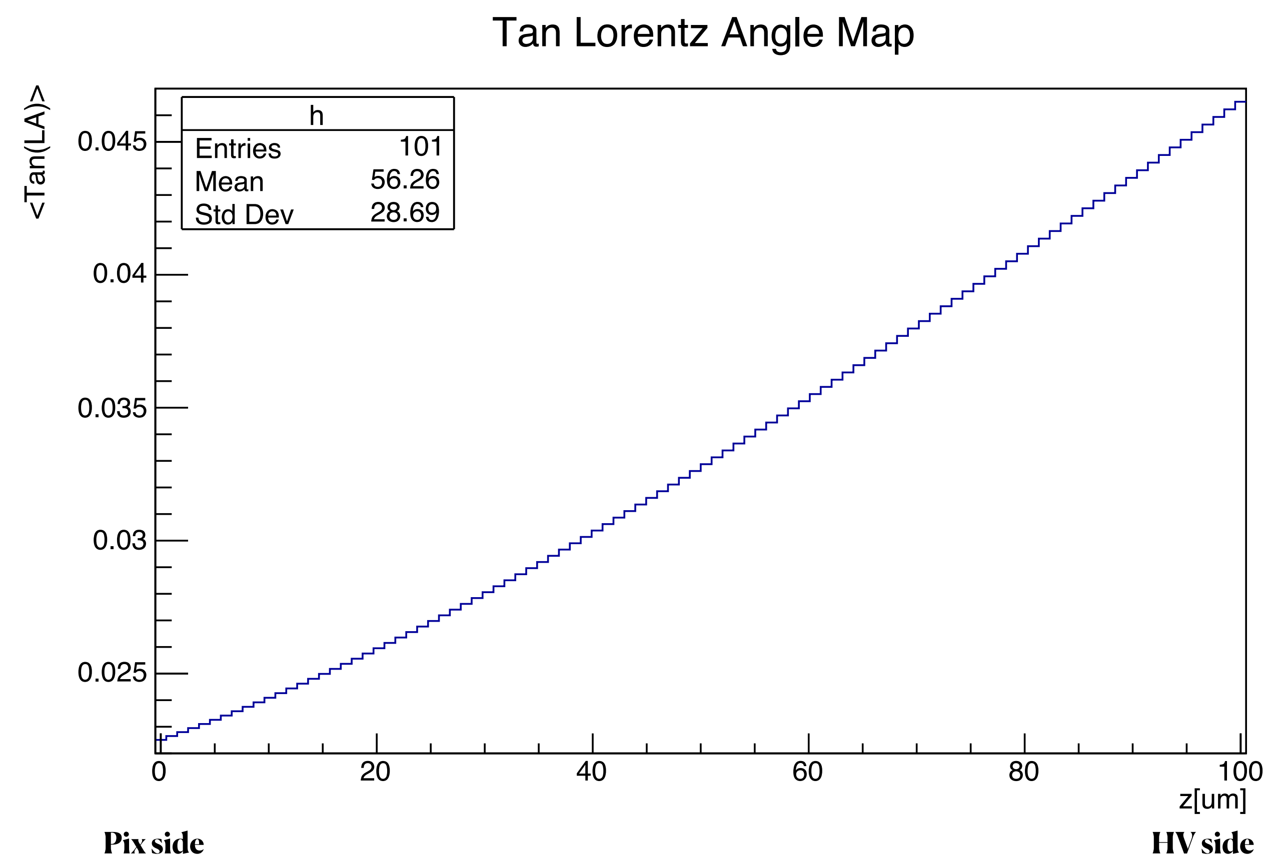
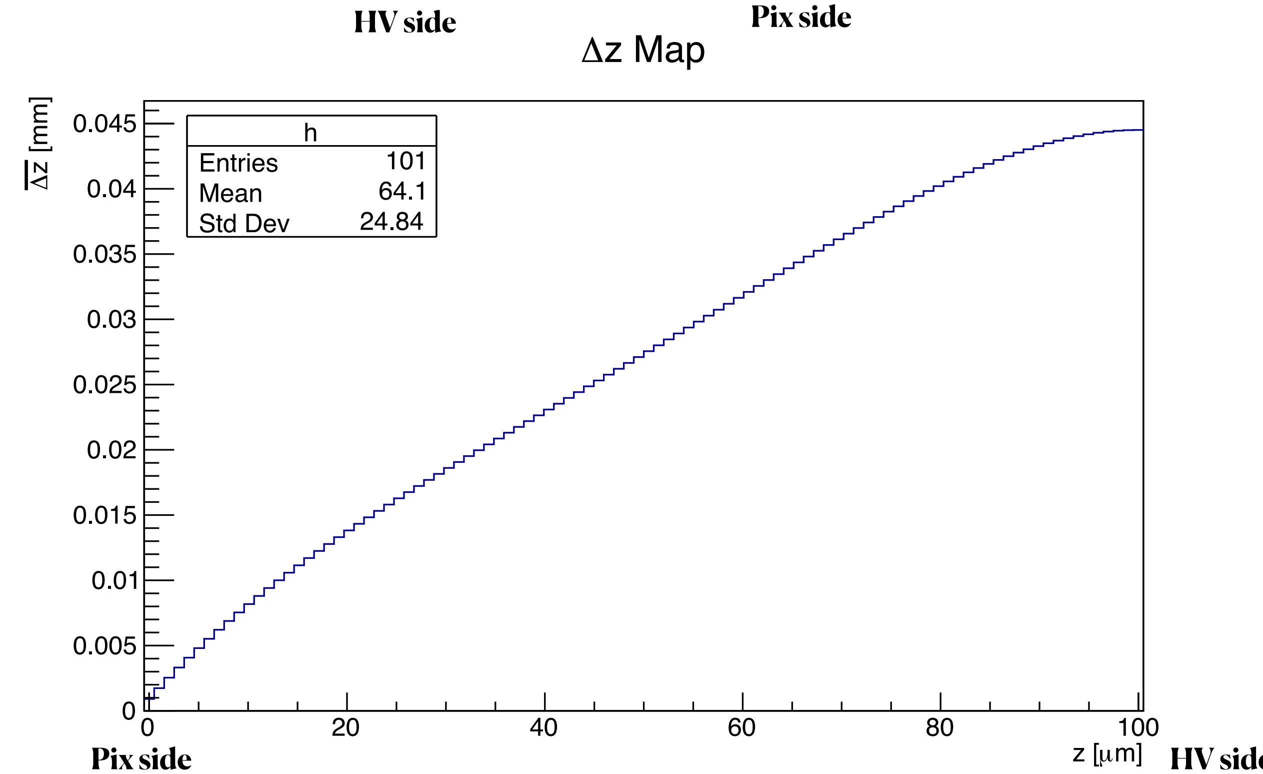


LUTs from Allpix-Squared

LUTs



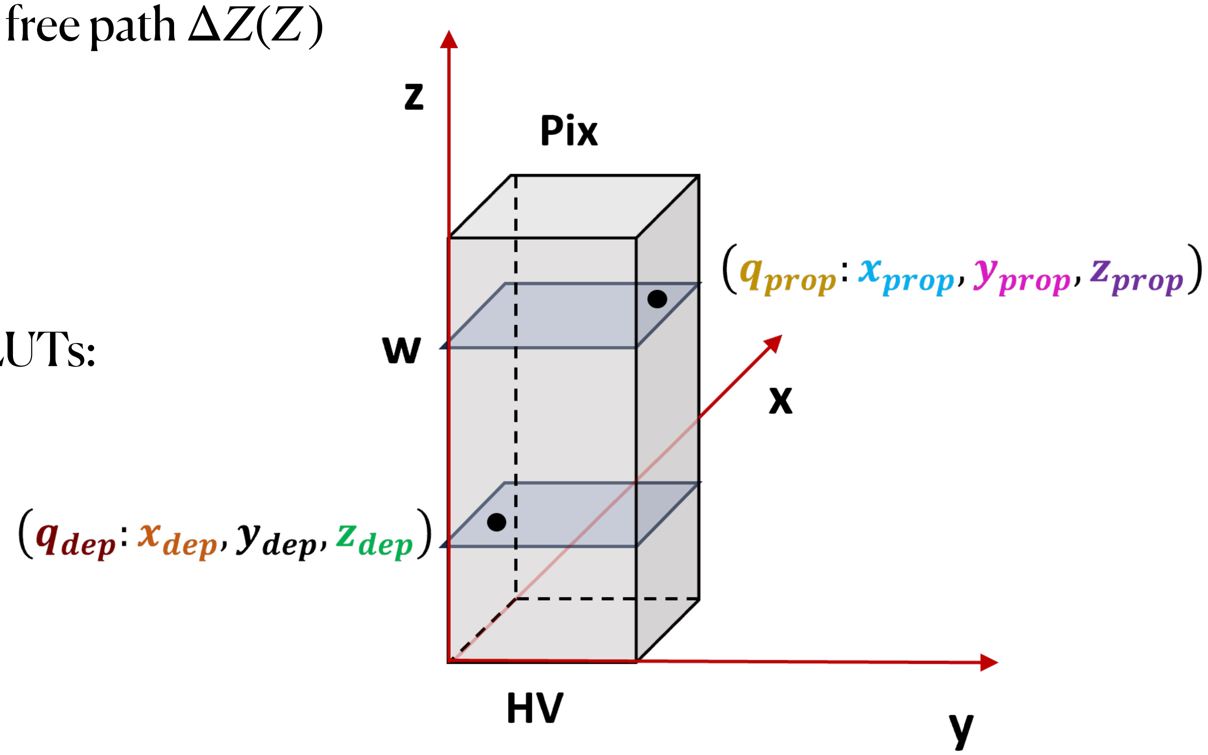




- Fluence = $4\text{x}10^{15}\ n_{eq}/cm^2$
- Voltage = 600V
- Thickness = 100 μm
- Pitch = 50 μm x 50 μm

Closure test

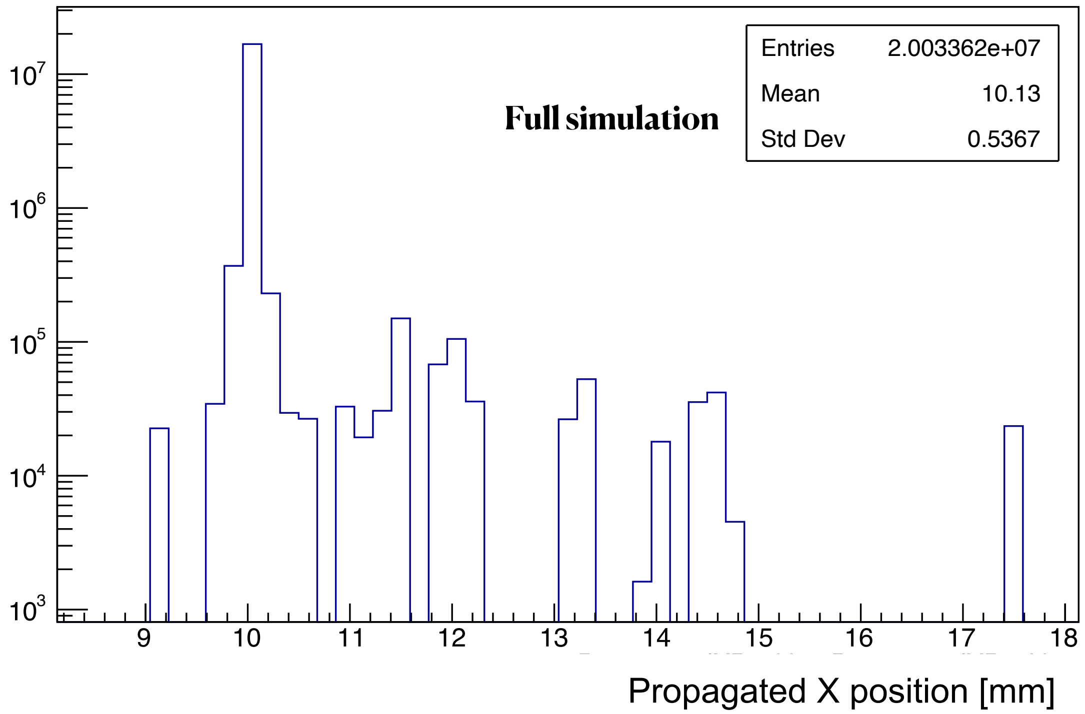
- Using AP2, we've estimated :
  - CCE (Z), average Lorentz angle deflection as a function Z , average free path $\Delta Z(Z)$
- Closure test to validate our approach :
  - Simulate charge deposition
  - Determine final position and fraction of induced charge using our LUTs:
    - $q_{prop} = CCE(z_{dep}) * q_{dep}(z_{dep})$
    - $z_{prop} = z_{dep} + \Delta z(z_{dep})$
    - $x_{prop} = x_{dep} + tan(\theta_L)(z_{dep}) * \Delta z(z_{dep})$
  - 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



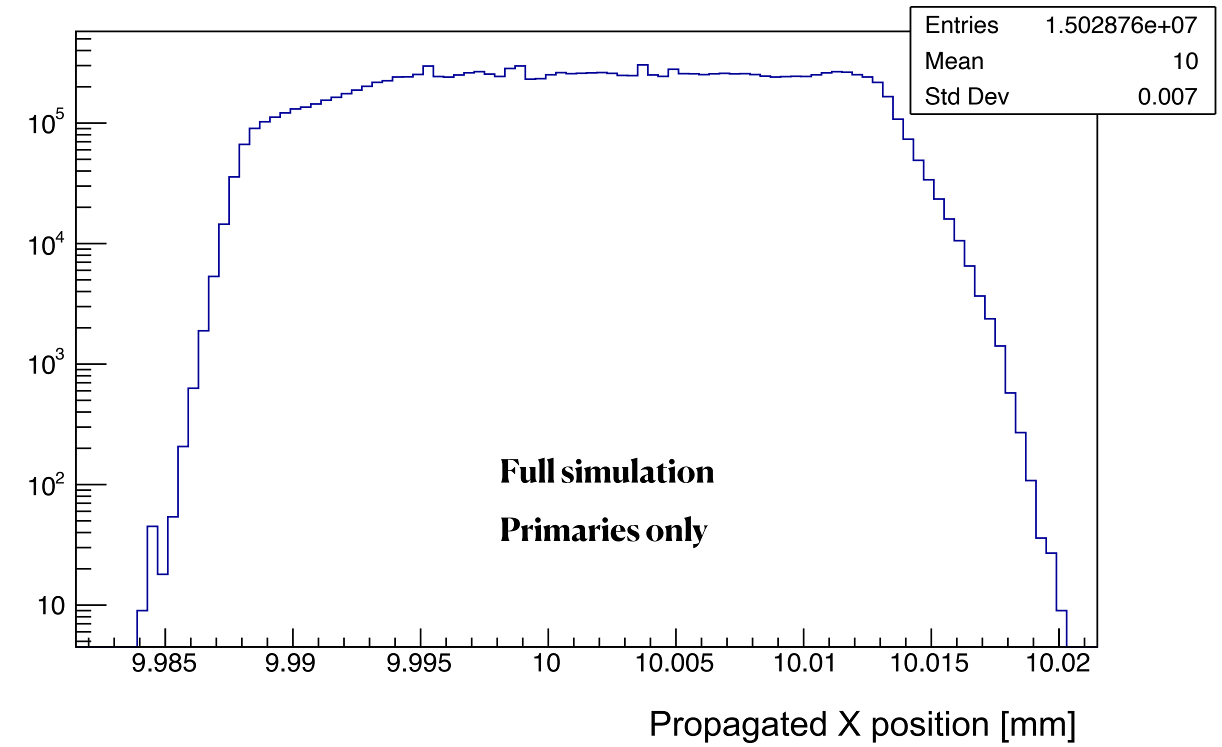
- Developed a new module in Allpix-squared : LUTPropagator
- Performed closure tests with: point charge deposition, line charge deposition, **120 GeV Pions** using LUTs generated with the "scan" model of charge deposition
  - RD50 Dec'23 : slides
  - Allpix-Squared user workshop May23 : slides

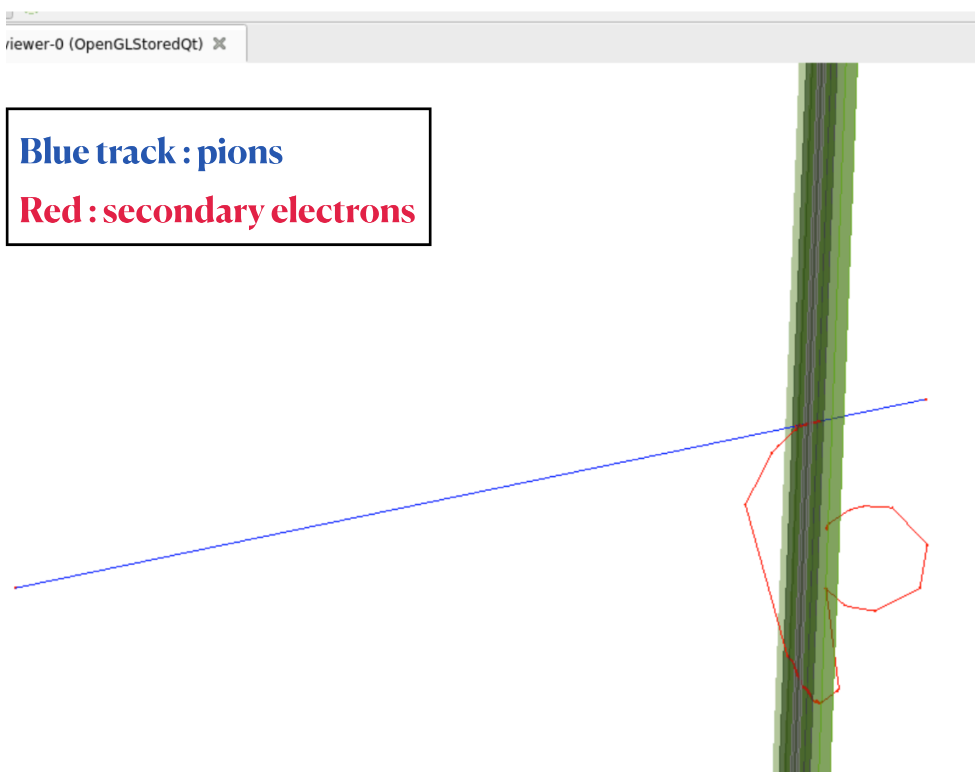
Propagated X Position

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

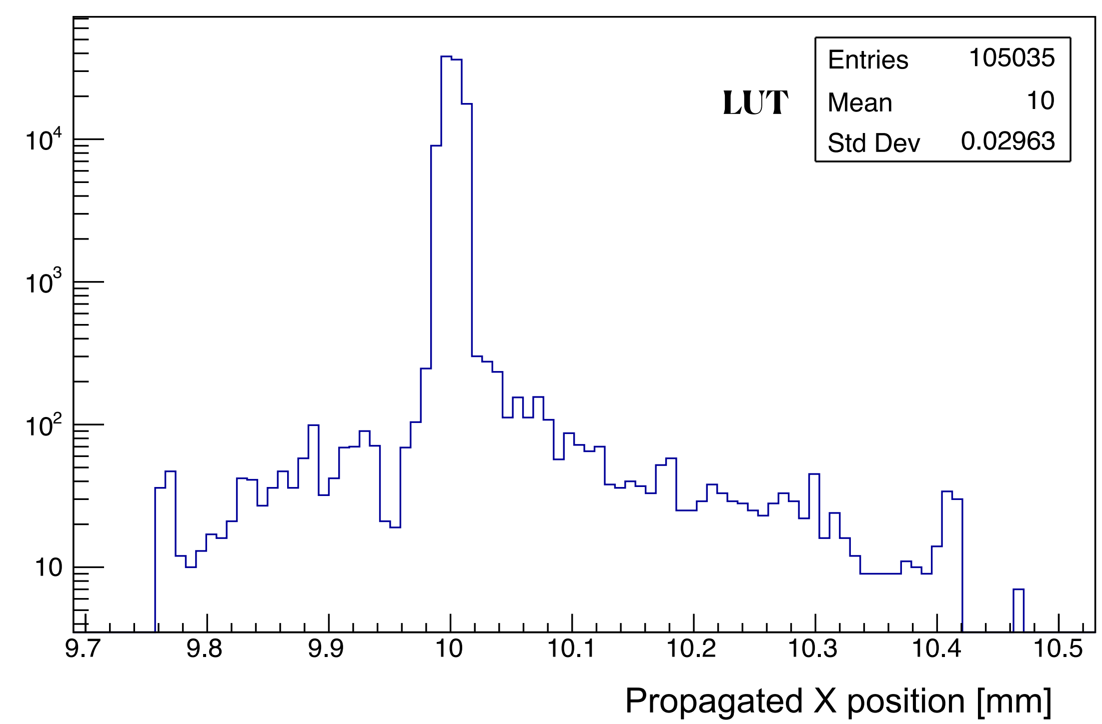


Filtering secondaries



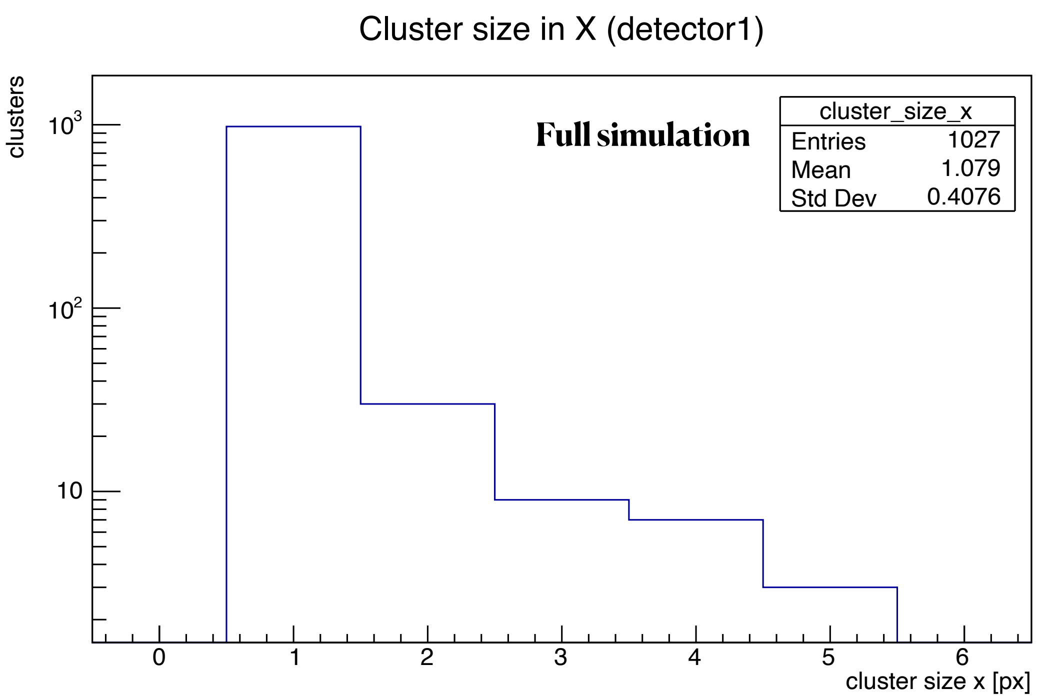


Diff = 0um

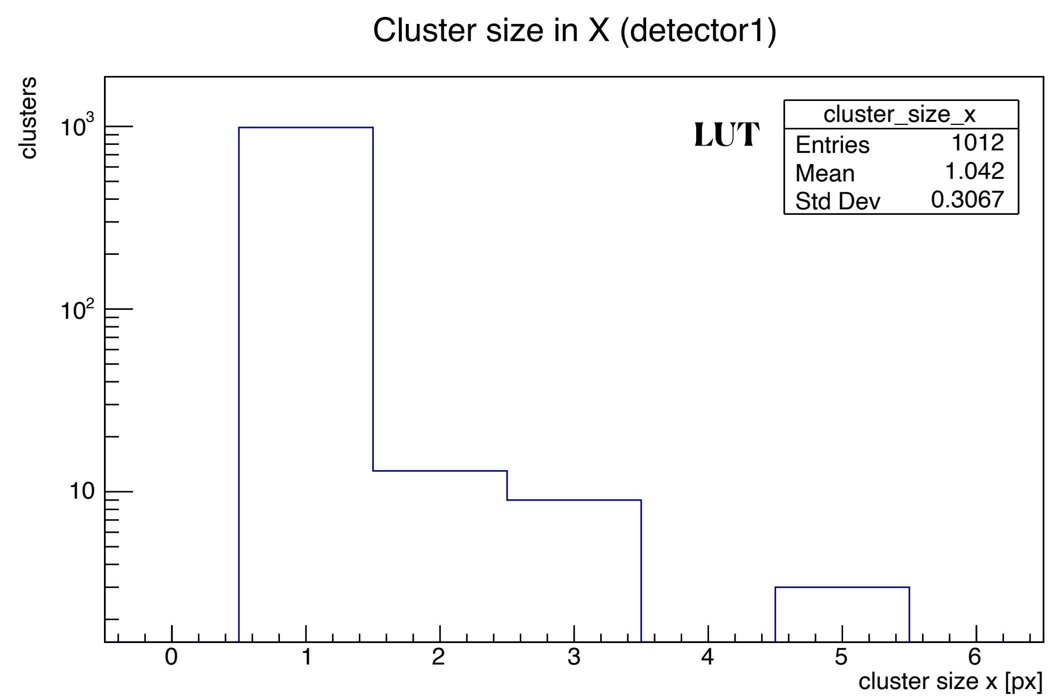


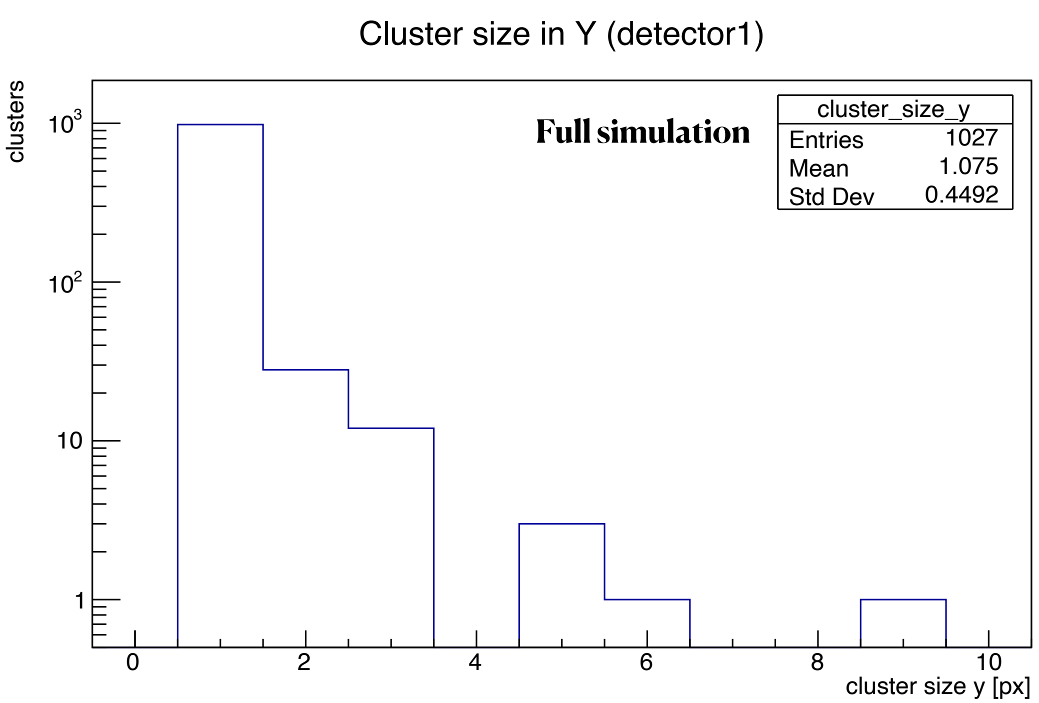
Cluster size X & Y

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

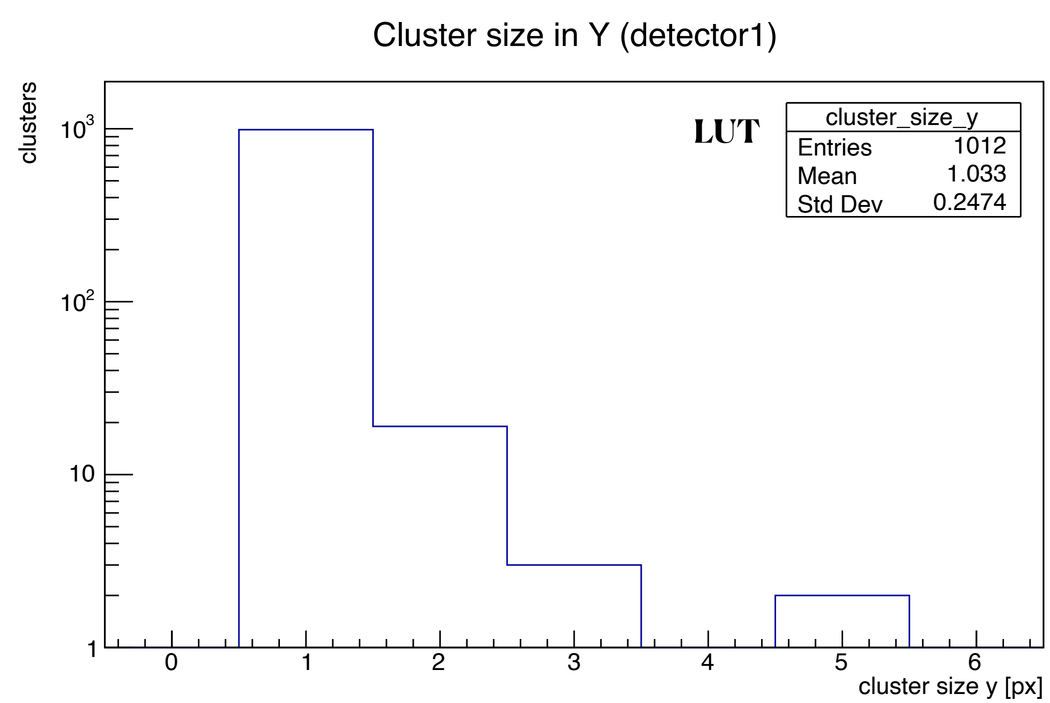


Rel err mean: 3.4%



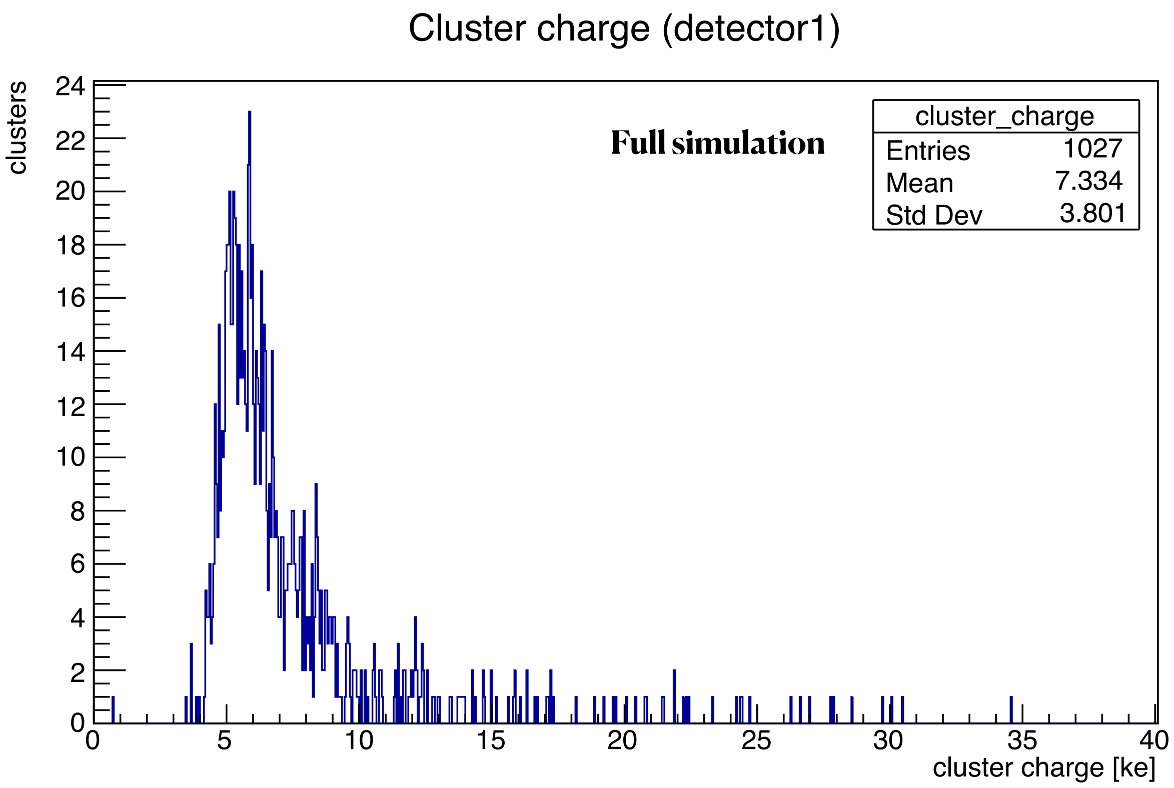


Rel err mean: 3.9%

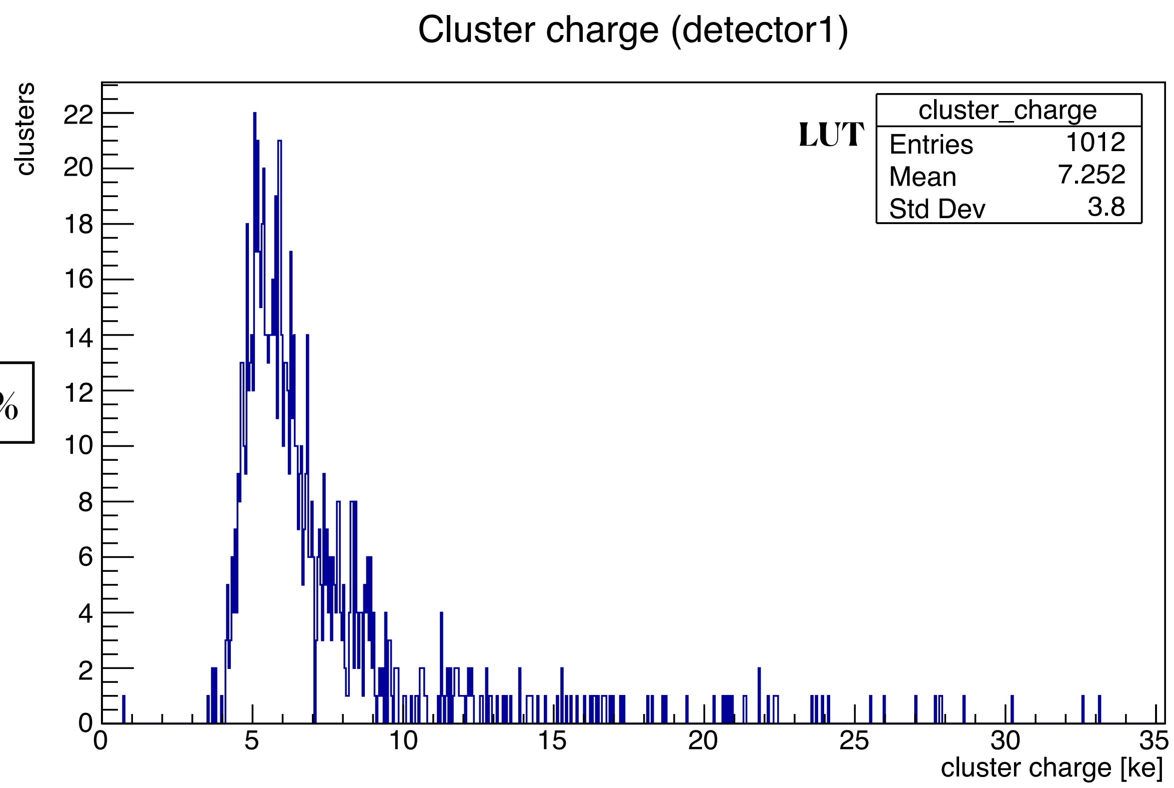


Cluster charge

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



Rel err mean: 1.1%



Excellent closure between FS and LUT-based simulations for all the 4 observables!!!

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 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

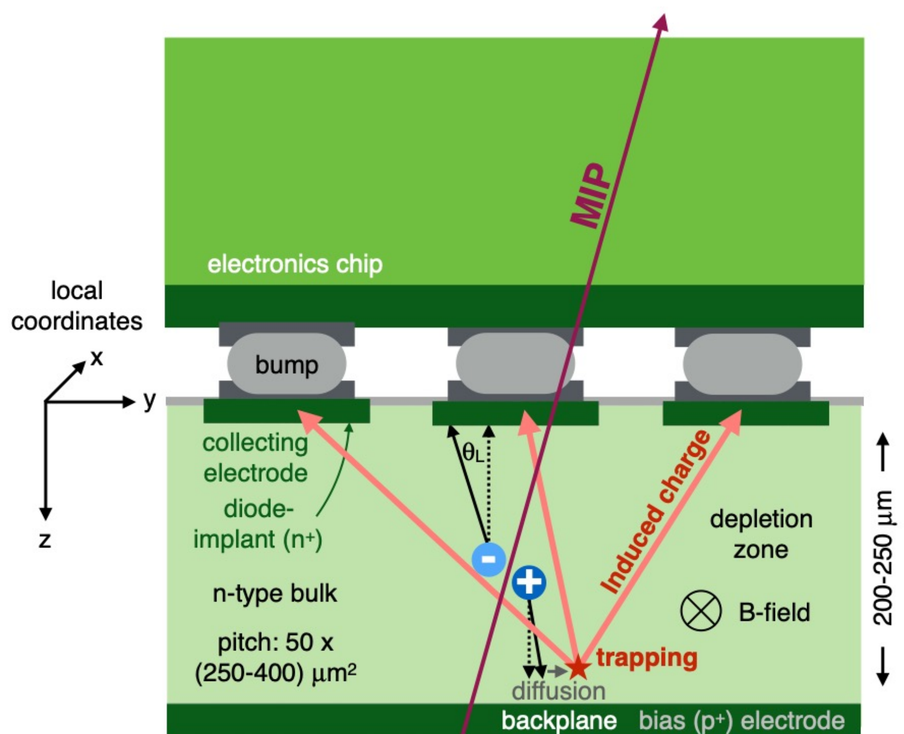
Thank you so much for your attention !! :)

Backup

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)



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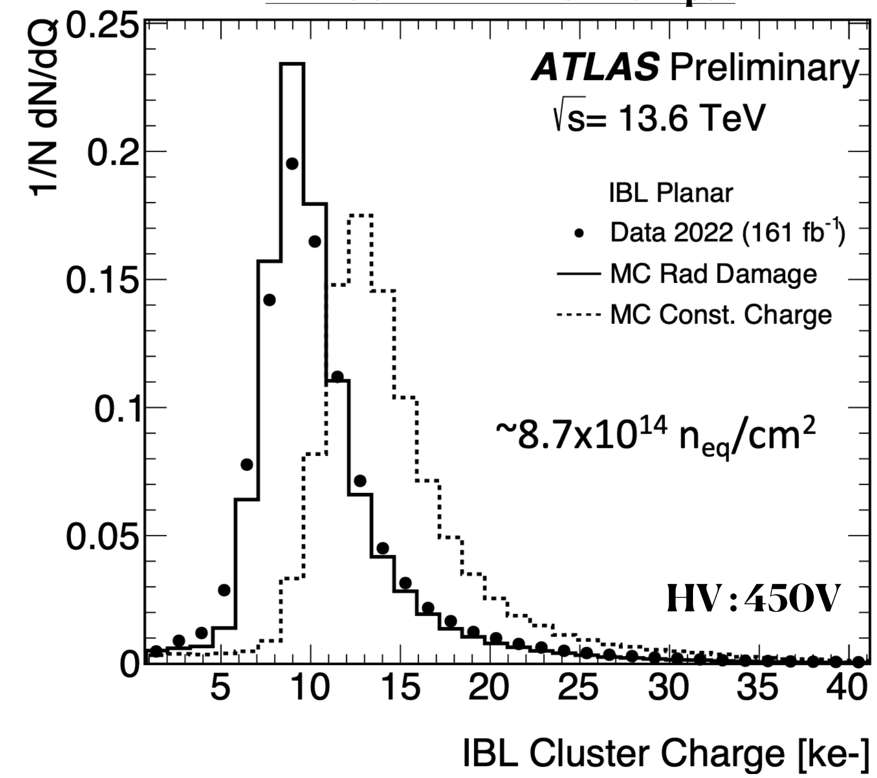
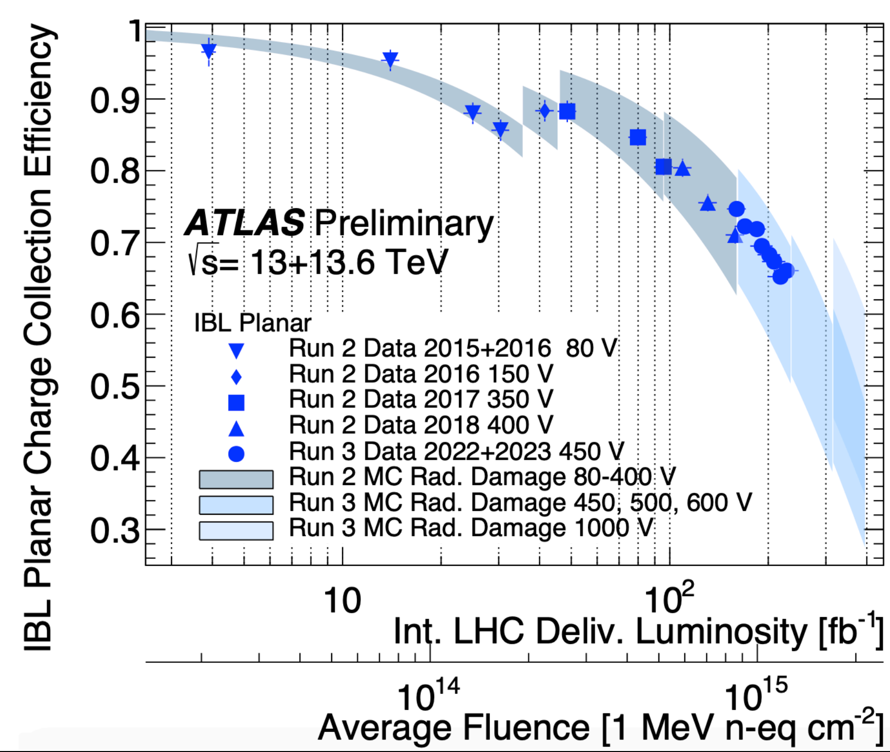


Most Probable Values match at 1 % level!

ATL-COM-INDET-2023-008.pdf

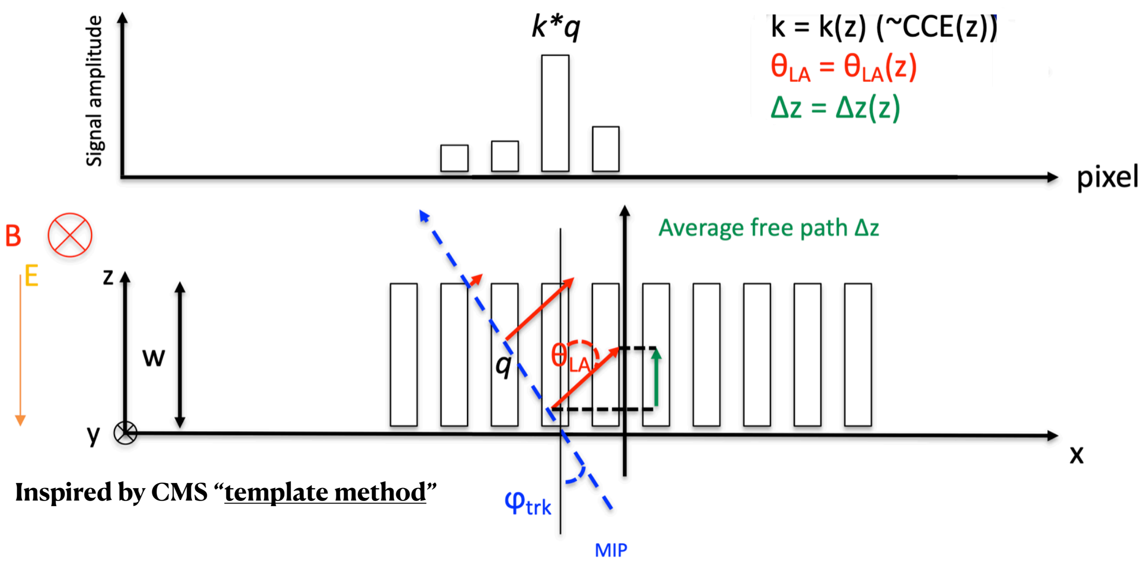


Excellent agreement over almost two order of magnitudes of fluence!

Radiation damage modelling : ATLAS approach

HL-LHC strategy

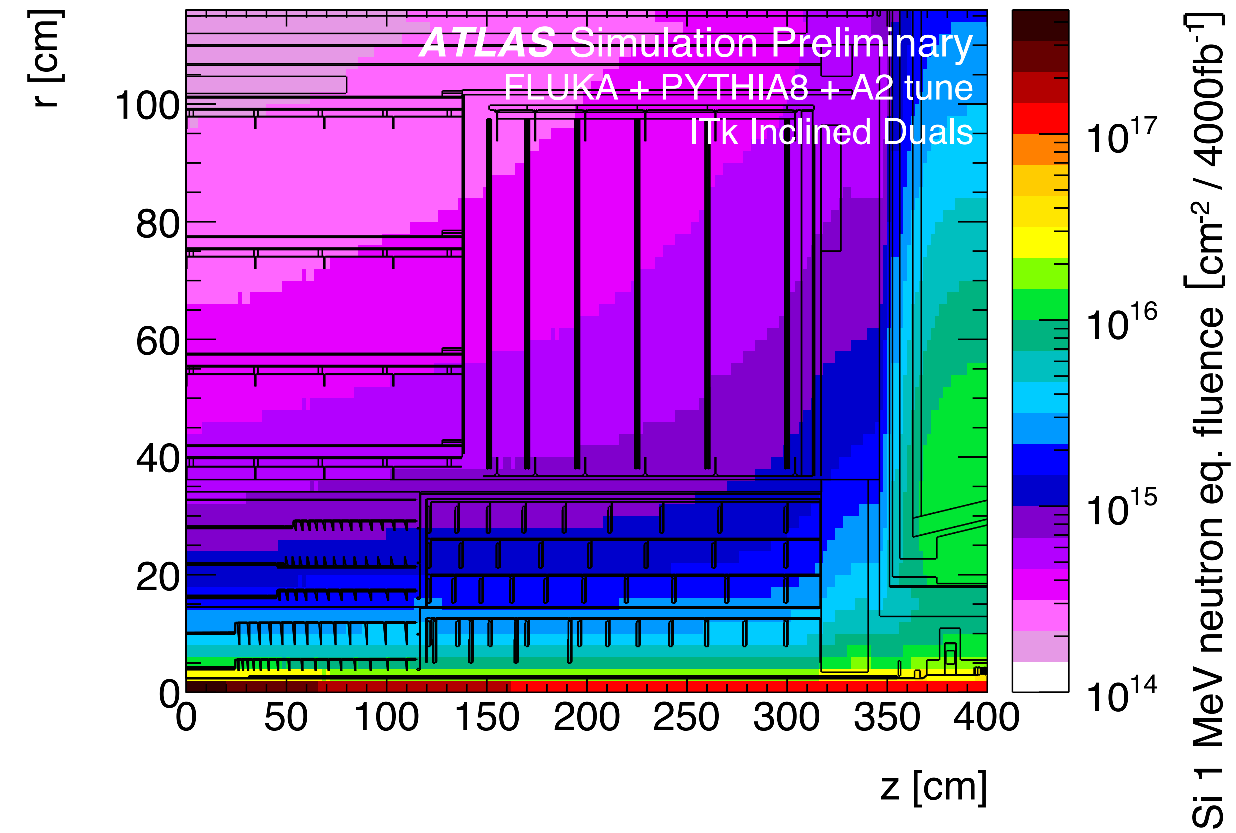
- HL-LHC : ATLAS/CMS pixel detectors exposed to unprecedented levels of radiation damage
- Expected increase of particles density and rates in HL-LHC -> need for a faster algorithm
  - ✦ New strategy is planed : charge reweighing from look-up tables (**LUTs**)



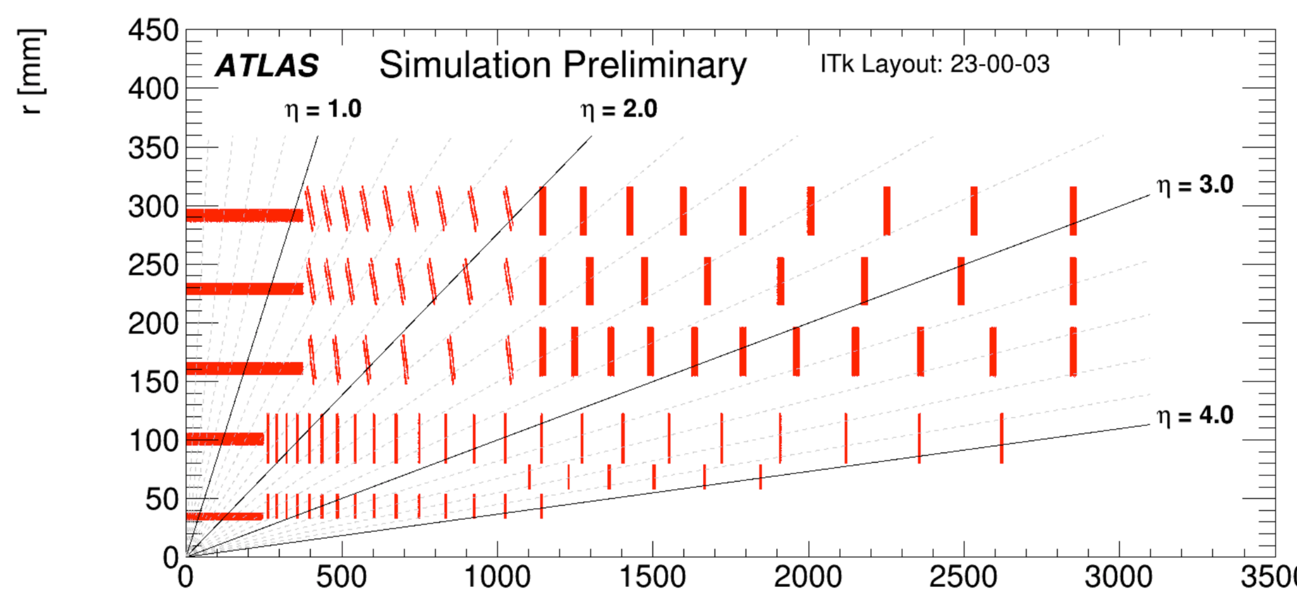
Inspired by CMS "template method"

- 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)

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



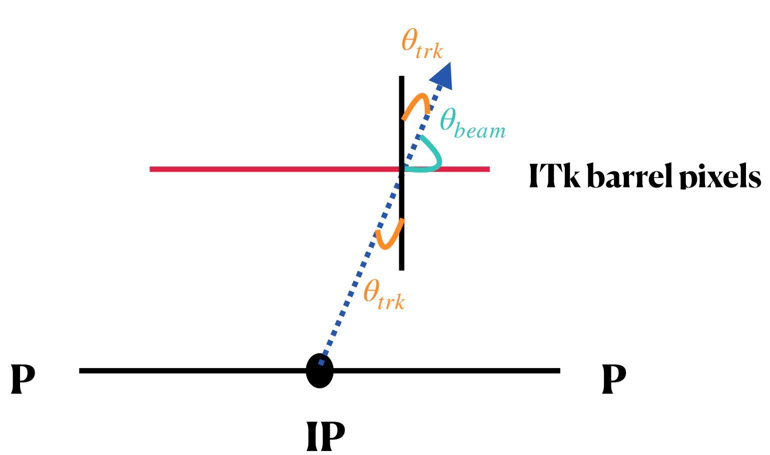
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2021-024/fig_01b.png

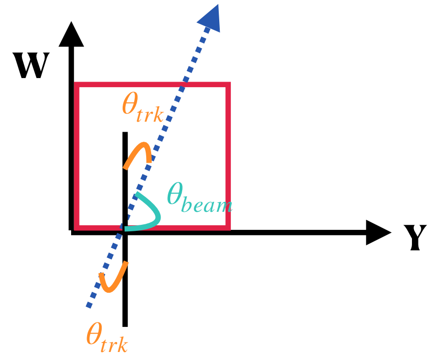


Realistic simulation studies of ITk barrel pixels

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



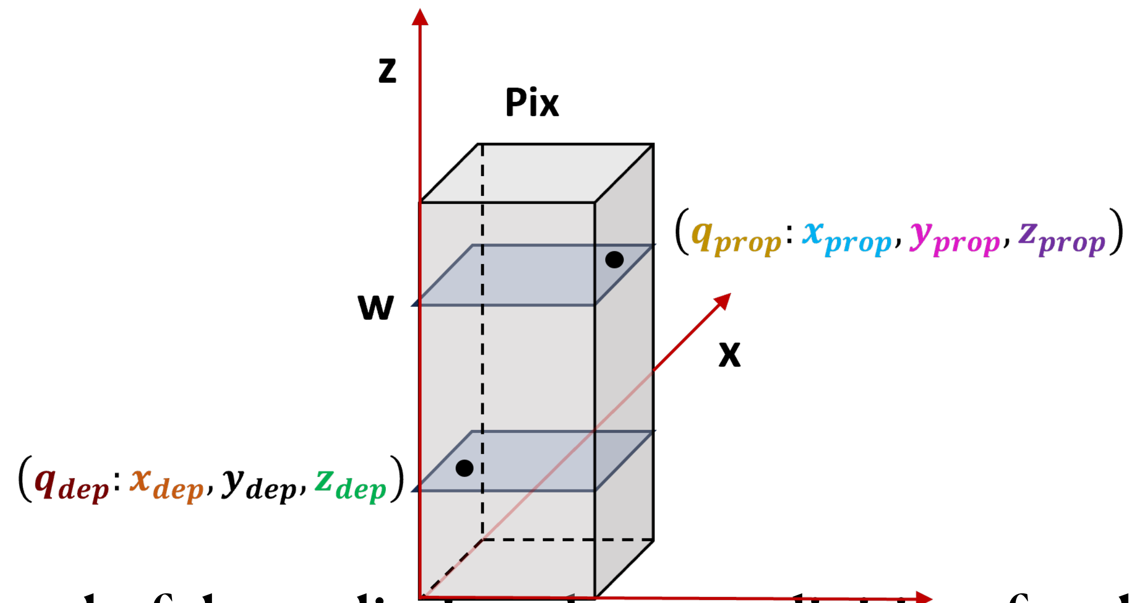


- Comparison of Allpix-Squared full simulation (FS) with LUTPropagator based simulations (LUT)
  - LUTPropagator module : Scale the charges using **CCE** LUT , propagate the carriers using **tan(LA)** and **ΔZ** LUTs
- Comparison variables : propagated X position, cluster size x, cluster size y, cluster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

ITk Pixel Radiation Damage Digitiser Speed Test

First tests in Athena

- 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

ITk Pixel Radiation Damage Digitiser Speed Test

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

- 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 :)