Digitization in ePIC: Lessons from AC-LGAD subsystems

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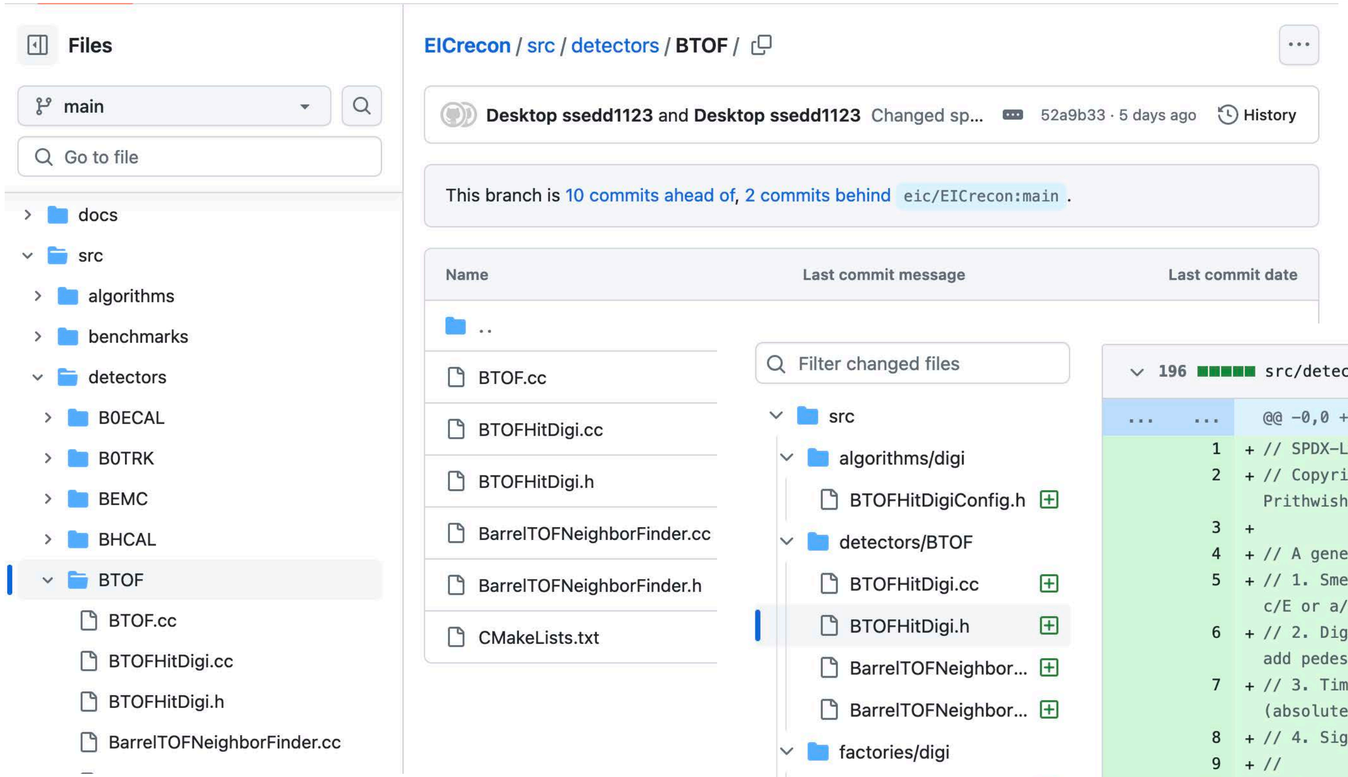
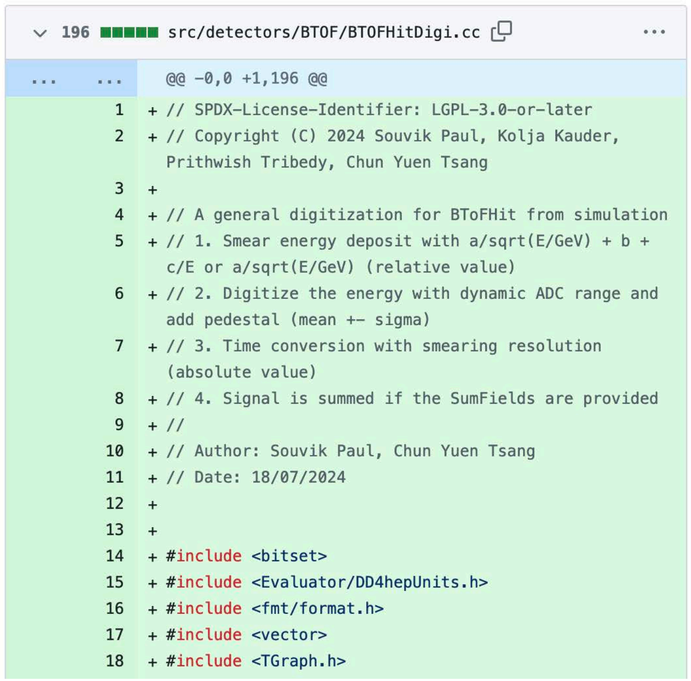
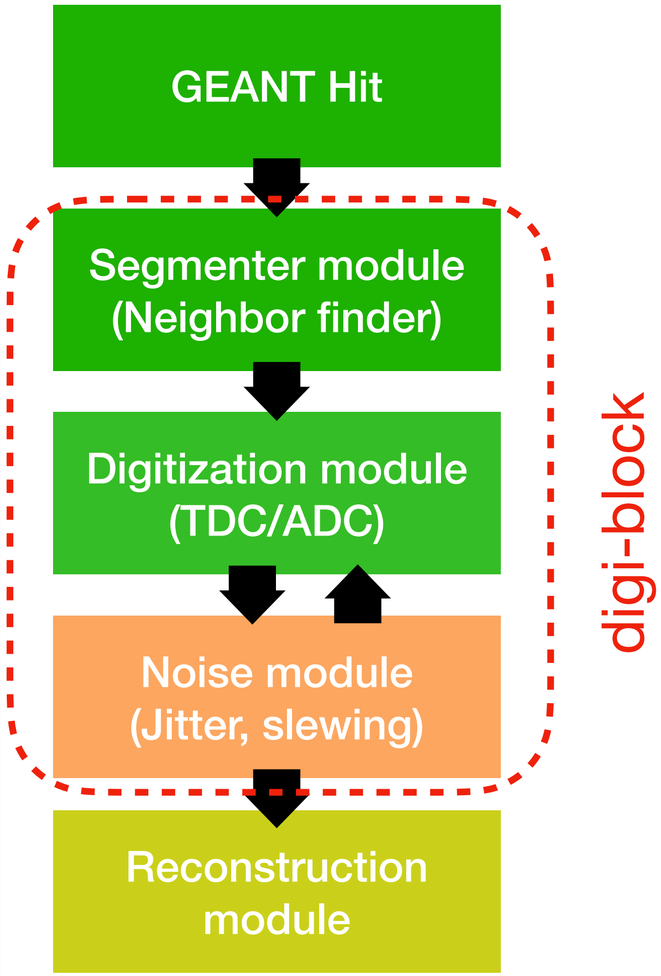
Join EICUG & ePIC collaboration meeting, Lehigh University, Jul 22–27, 2024

Quick summary of the current status





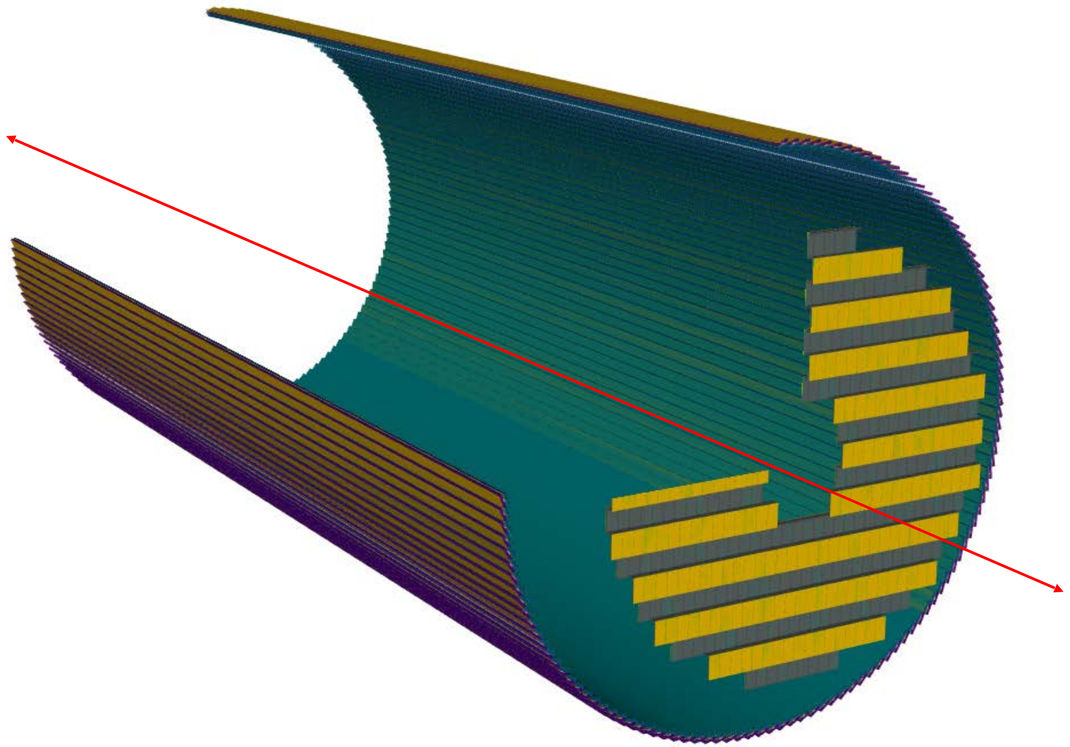


Recently we finished first implementation of the digitization model for AC-LGAD-based BTOF — work on other subsystems, FTOF and B0, is ongoing.

Overview

The digitization model for AC-LGAD system has step:

- Conversion of GEANT deposited energy into ADC/TDC
- Implementation of a charge-sharing
- Incorporating noise due to full readout chain

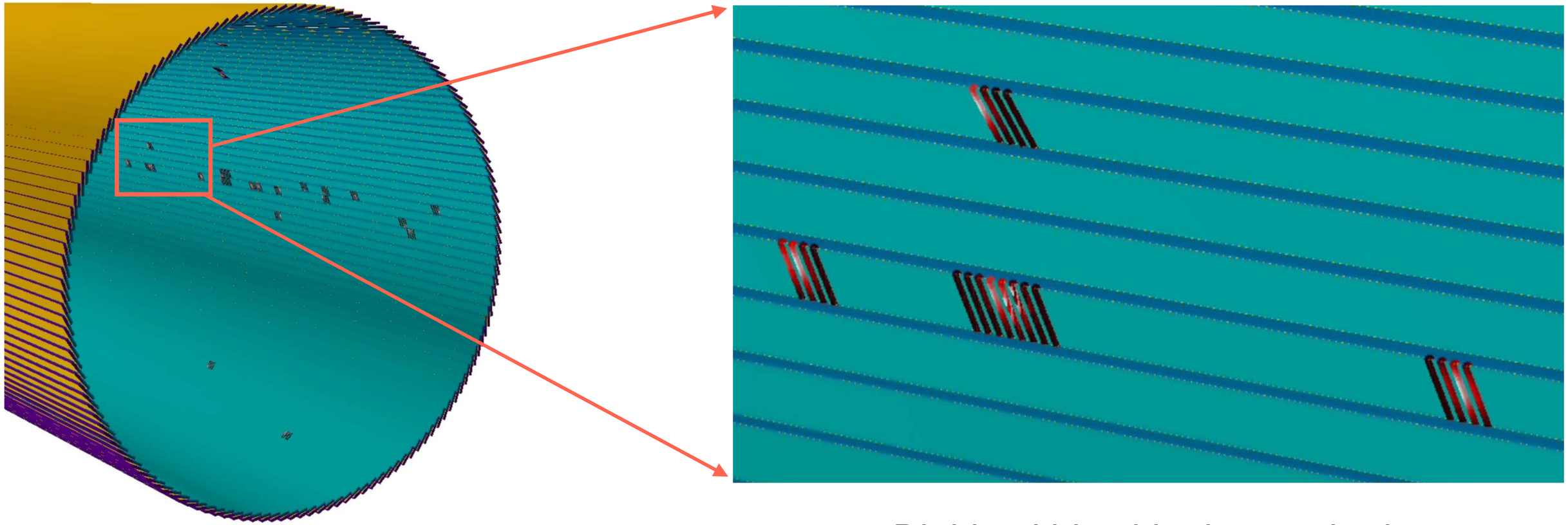


In EICrecon has two modules:

1) Segmentation/neighbor finder,
2) Digitization/noise

Using BTOF as the reference example for digitization of AC-LGAD systems

Task at hand



GEANT hit

```
TOFBarrelRecHit.cellID = 18425070710973014364
TOFBarrelRecHit.position.x = 636.281799
TOFBarrelRecHit.position.y = 32.092369
TOFBarrelRecHit.position.z = 1077.500000
TOFBarrelRecHit.time = 4.227000
TOFBarrelRecHit.edep = 0.000184
```

Digitized hit with charge sharing

```
TOFBarrelADCTDC.cellID = 18425352185949725020,
18425070710973014364, 18424789235996303708,
18424507761019593052, 18424507782494429532...

TOFBarrelADCTDC.charge = 359, 785, 359, 34, 34 ...
TOFBarrelADCTDC.timeStamp = 197, 194, 197, 215, 215 ...
```

First challenge: Deciphering the cell ID

Cell ID helps to go to local co-ordinates & group cells together for signal sharing

1. Convert the ID to the 64-bit binary ID

$1842338138437162223 6_{(10)}$

Cell ID for a strip in Barrel ToF

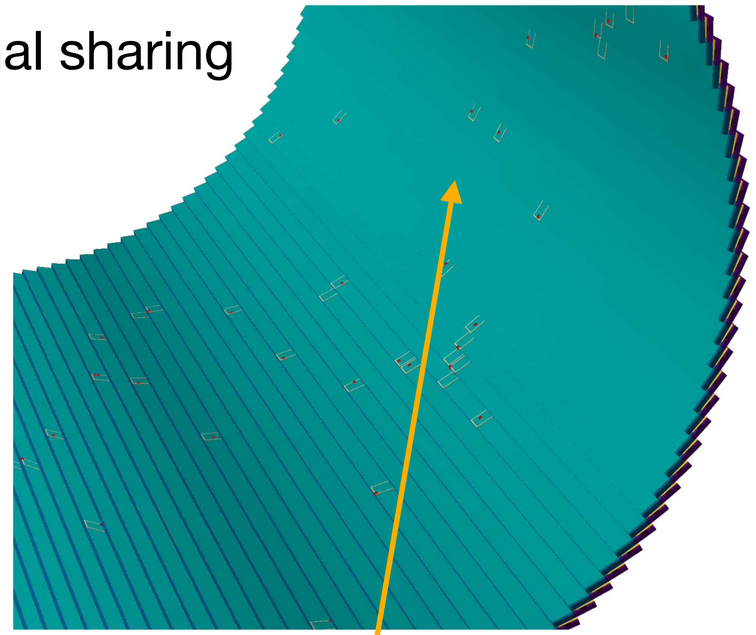
$111111111010110011111111110000100000000100000011110100010101110 0_{(2)}$

2. Split the binary ID based on the identifier in the xml code. For Barrel ToF, the identifier is:

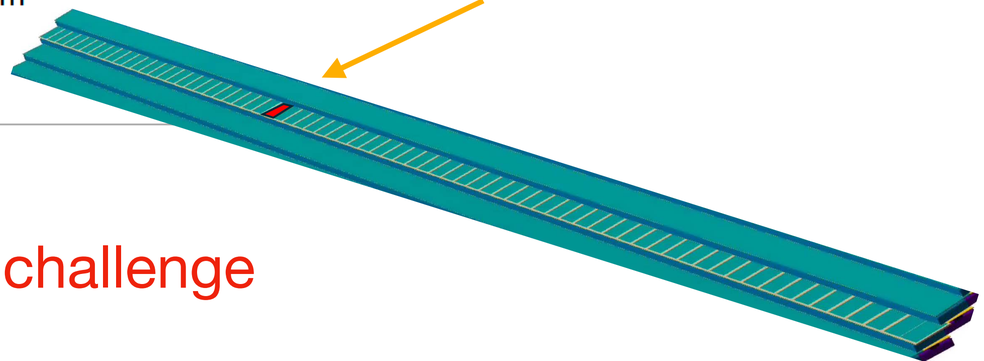
<id>system:8,layer:4,module:12,sensor:2,x:32:-16,y:-16</id>

111111 11101011001111111111000010000000 01 000000111101 0001 01011100

y | x | Sensor | Module | Layer | System



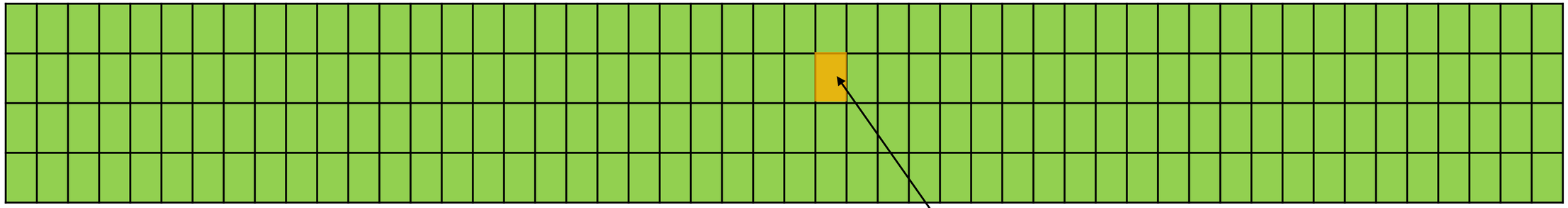
Each GEANT hit deposits energy in a BToF cell at a particular time (TOF)



Deciphering the cell-id is the first step & was our major challenge

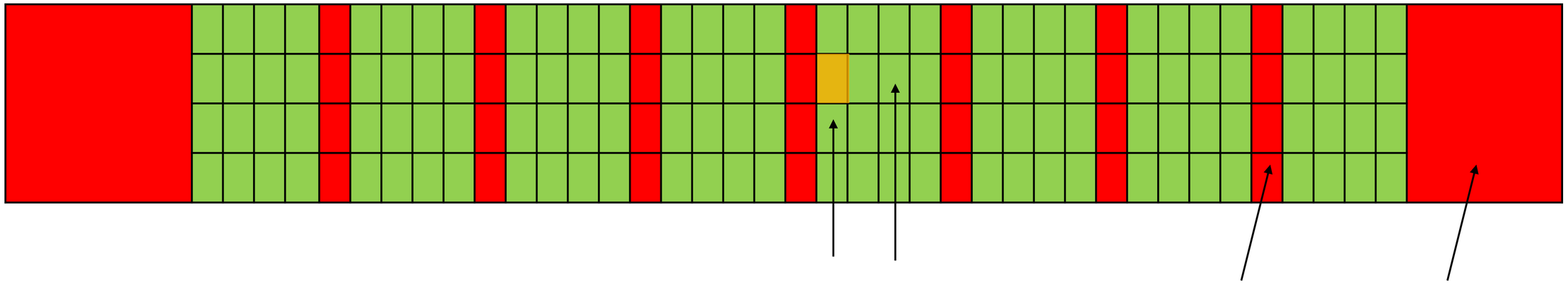
Put cell in local co-ordinate, find edges & neighbors

Current EICrecon simulation: Pixels (cells) are populated in a regular grid from left edge to the right edge.



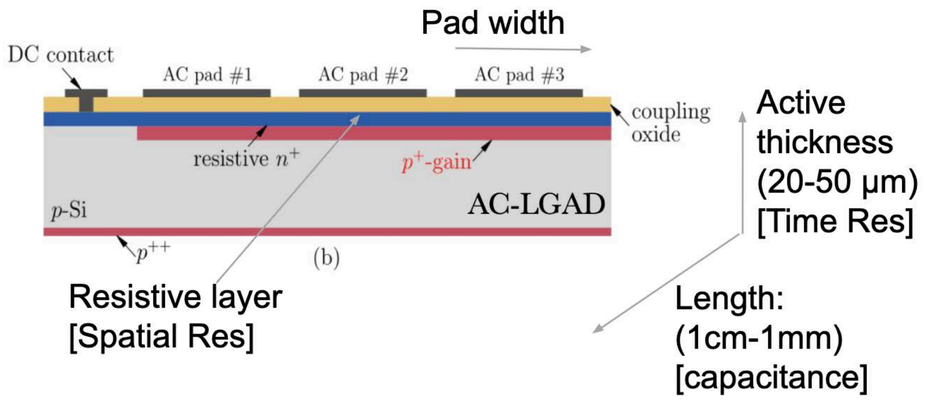
Reality:

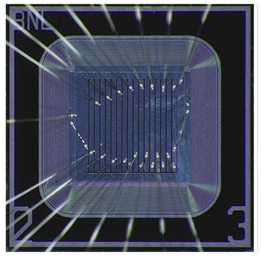
- Dead space in the left and right edges.
- Dead space between every nth cell.

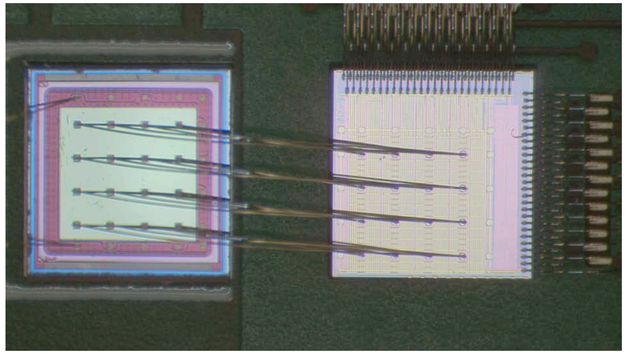


Finding the boundaries are next steps

Input from sensor+asic+RDO

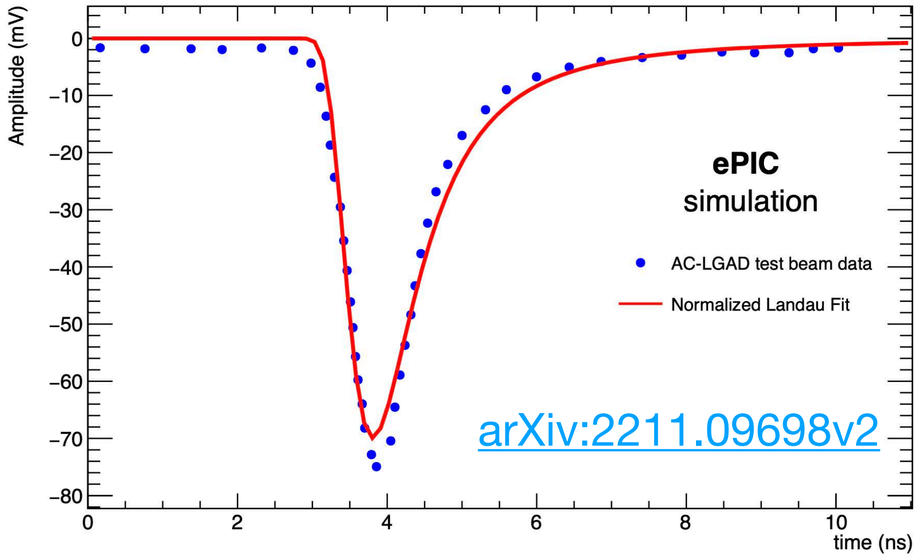


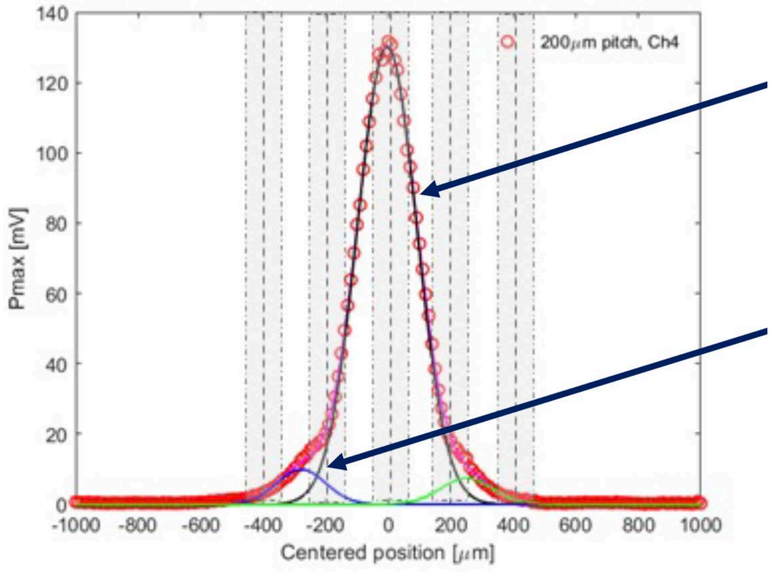


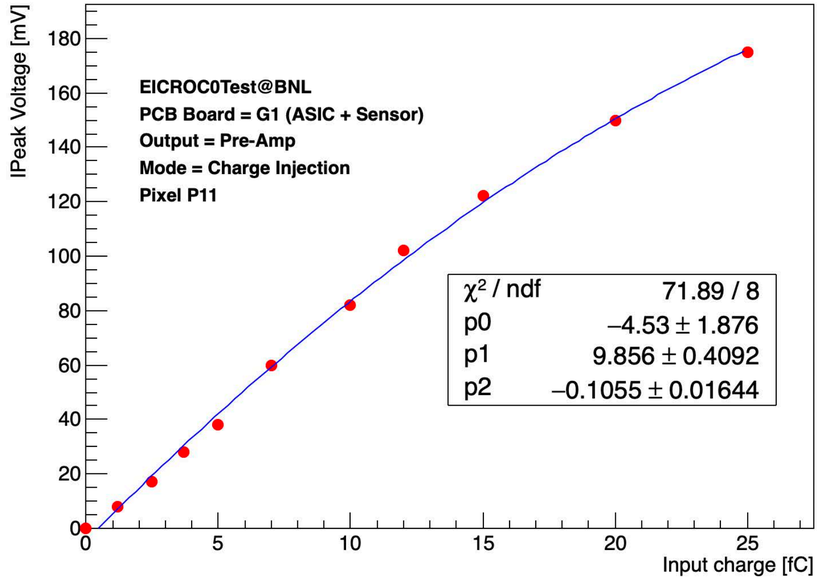


AC-LGAD

EICROC0





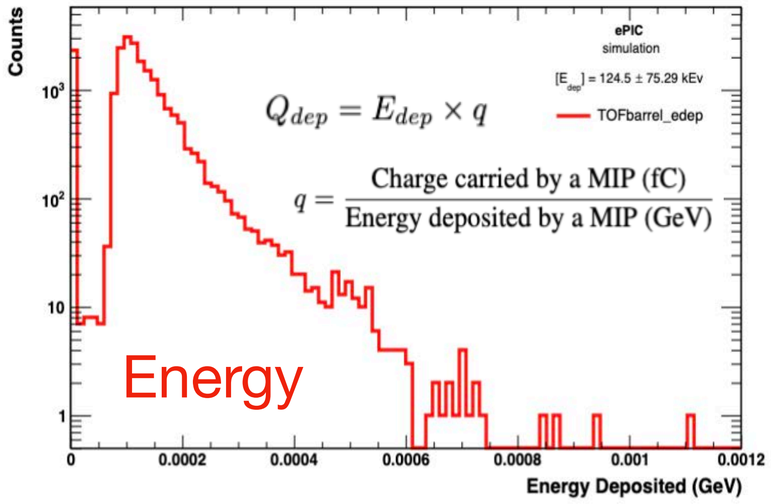


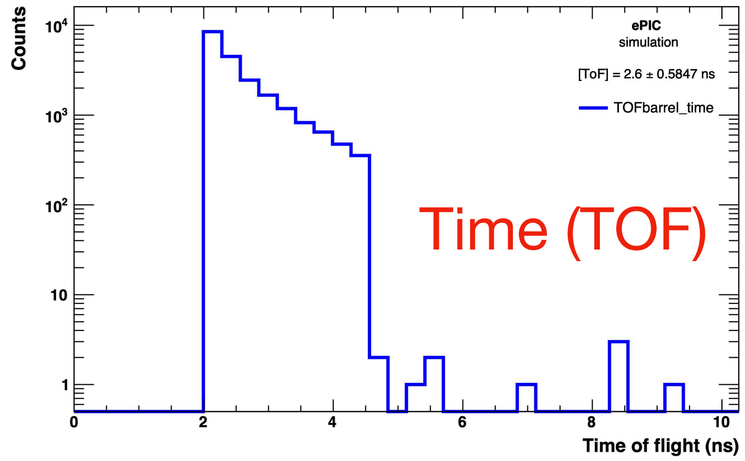
Input from hardware on signal shape, charge spread, pre-Amp output

Energy & time to Peak (ADC) & TOA (TDC)

Event Generation & Transport:

- 250k μ– particles
- 0 GeV ≤ p ≤ 30 GeV
- $0^o \leq \Theta \leq 180^o$



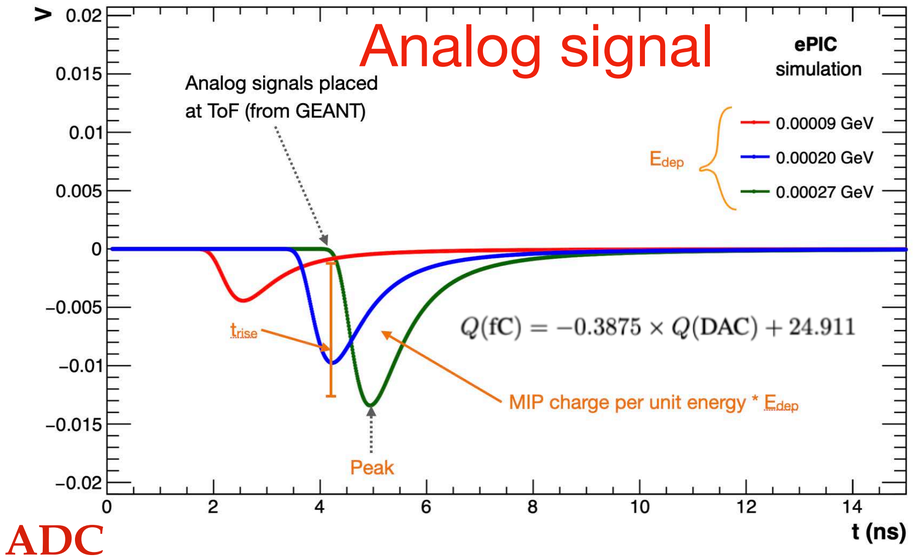


GEANT input:

- Q_{dep}: Area under analog signal
- Analog signals placed at ToF

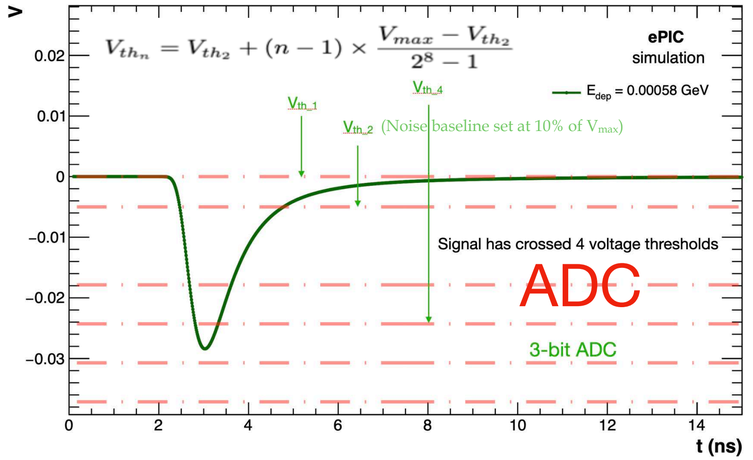
Data-driven input:

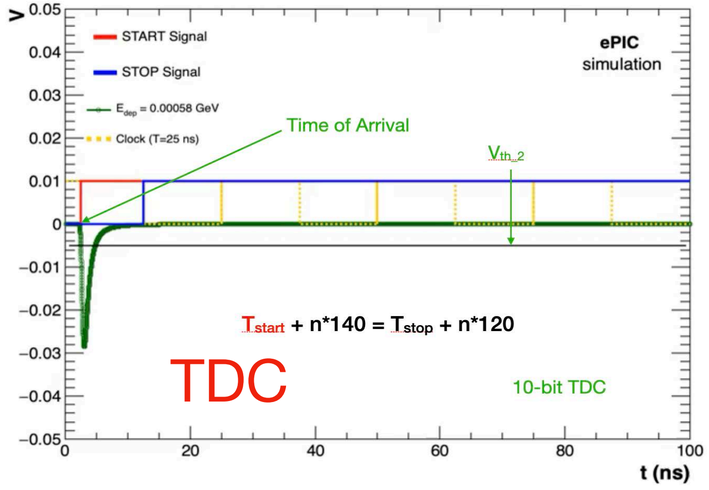
- Analog signal parameterized by Landau distribution
- Risetime ~ 450 ps
- Shape width ~294 ps.



Voltage thresholds ⟶ **8-bit ADC**

CLK + START/STOP ⟶ **10-bit TDC**

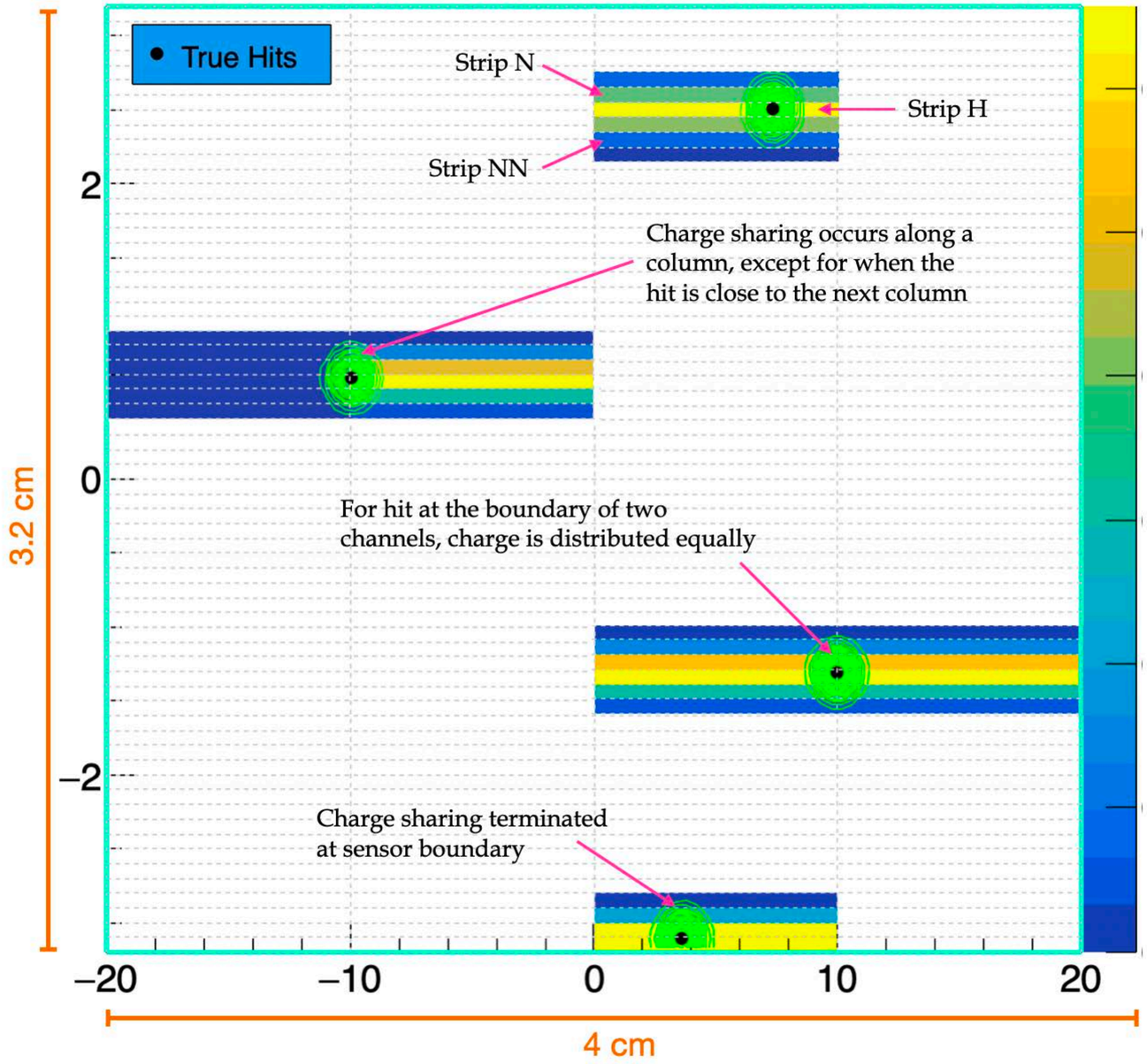




Energy Deposited ⟶ Charge ⟶ Peak of Signal ⟶ ADC

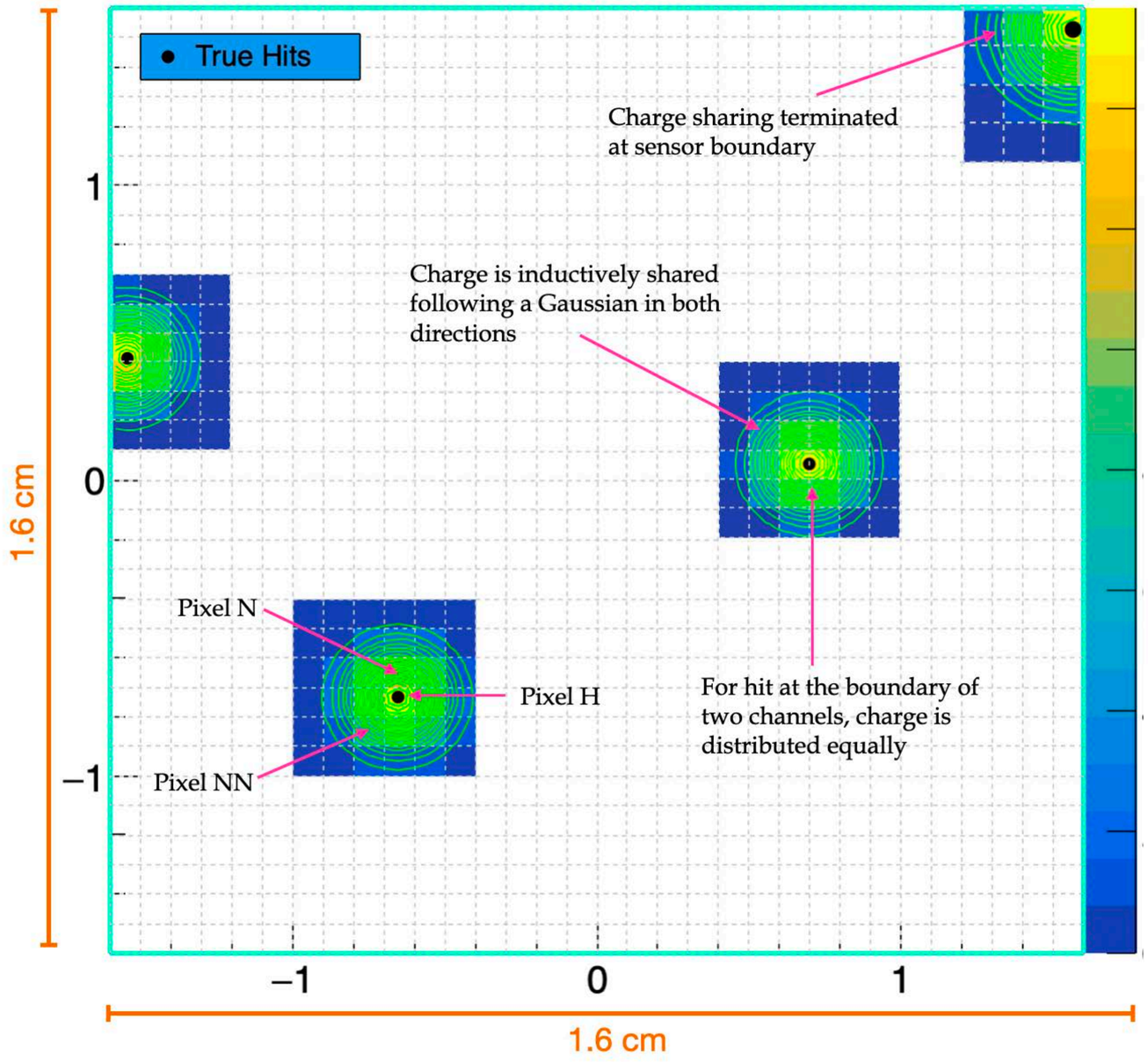
Time of Flight ⊕ Rise Time ⟶ Time of Arrival ⟶ TDC

Charge sharing: Strip geometry



- A hit in Strip H has a Gaussian-like distribution of charge vs distance (Charge shared inductively in sensor).
- The Gaussian peaks at the center of Strip H, and has a standard deviation in X and Y, that can be tuned (Property of AC-LGAD).
- The maximum distance to which Pixel H can induce charge can also be optimized.

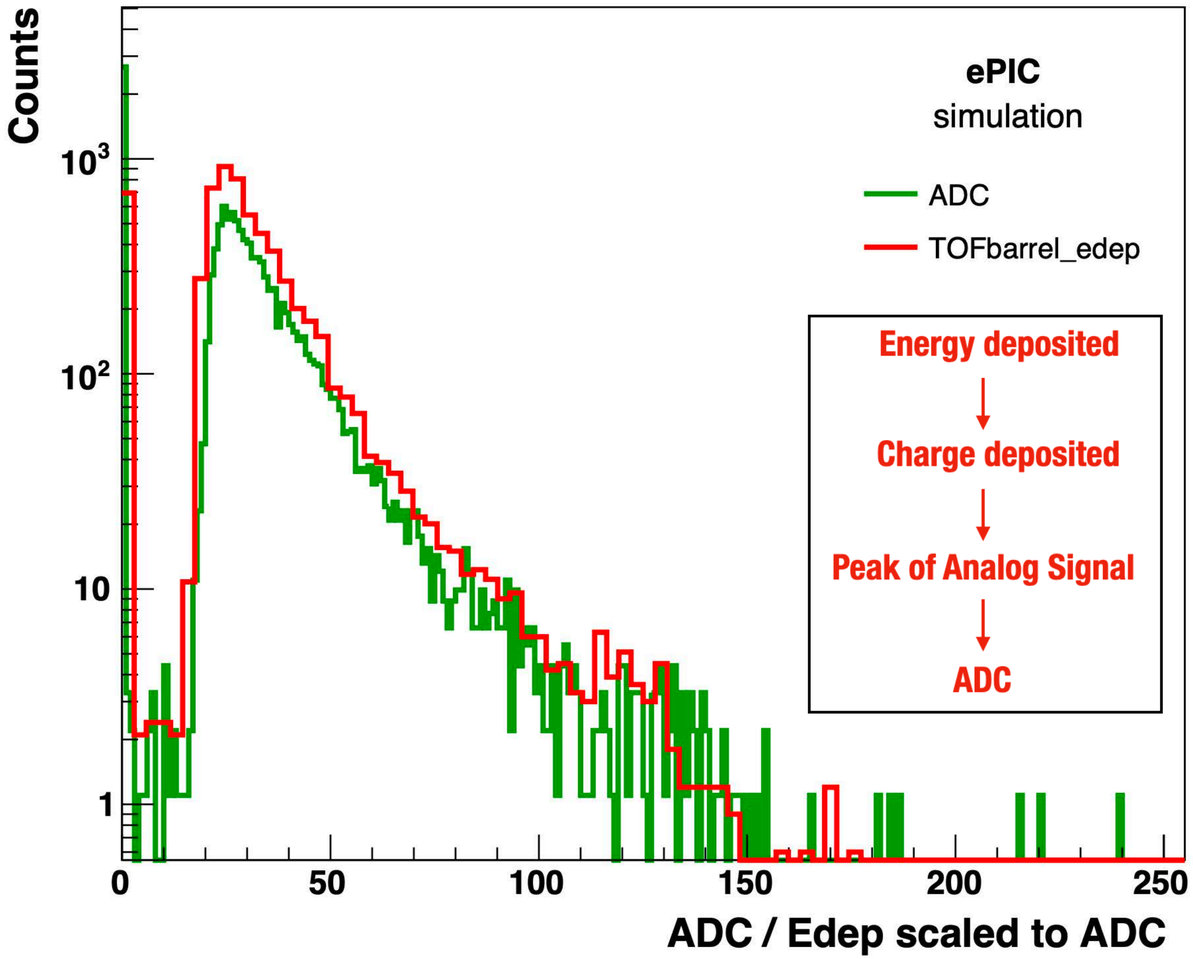
Charge sharing: Pixel geometry



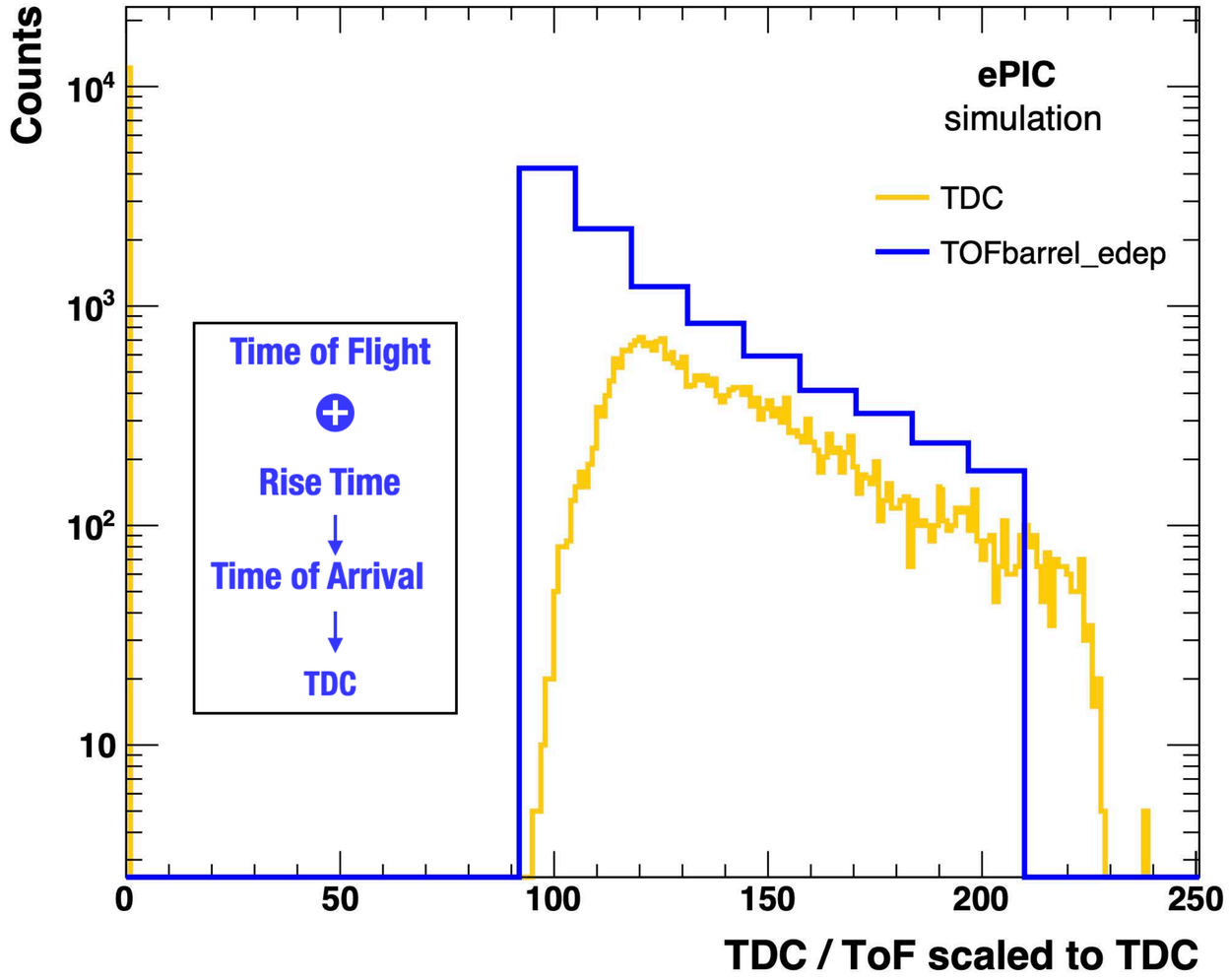
- A hit in Pixel H has a Gaussian-like distribution of charge vs distance (Charge shared inductively in sensor).
- The Gaussian peaks at the center of Pixel H, and has a standard deviation in X and Y, that can be tuned (Property of AC-LGAD).
- The maximum distance to which Pixel H can induce charge can also be optimized.

Energy/ADC & time/TDC comparison

ADC and E_{dep} comparion

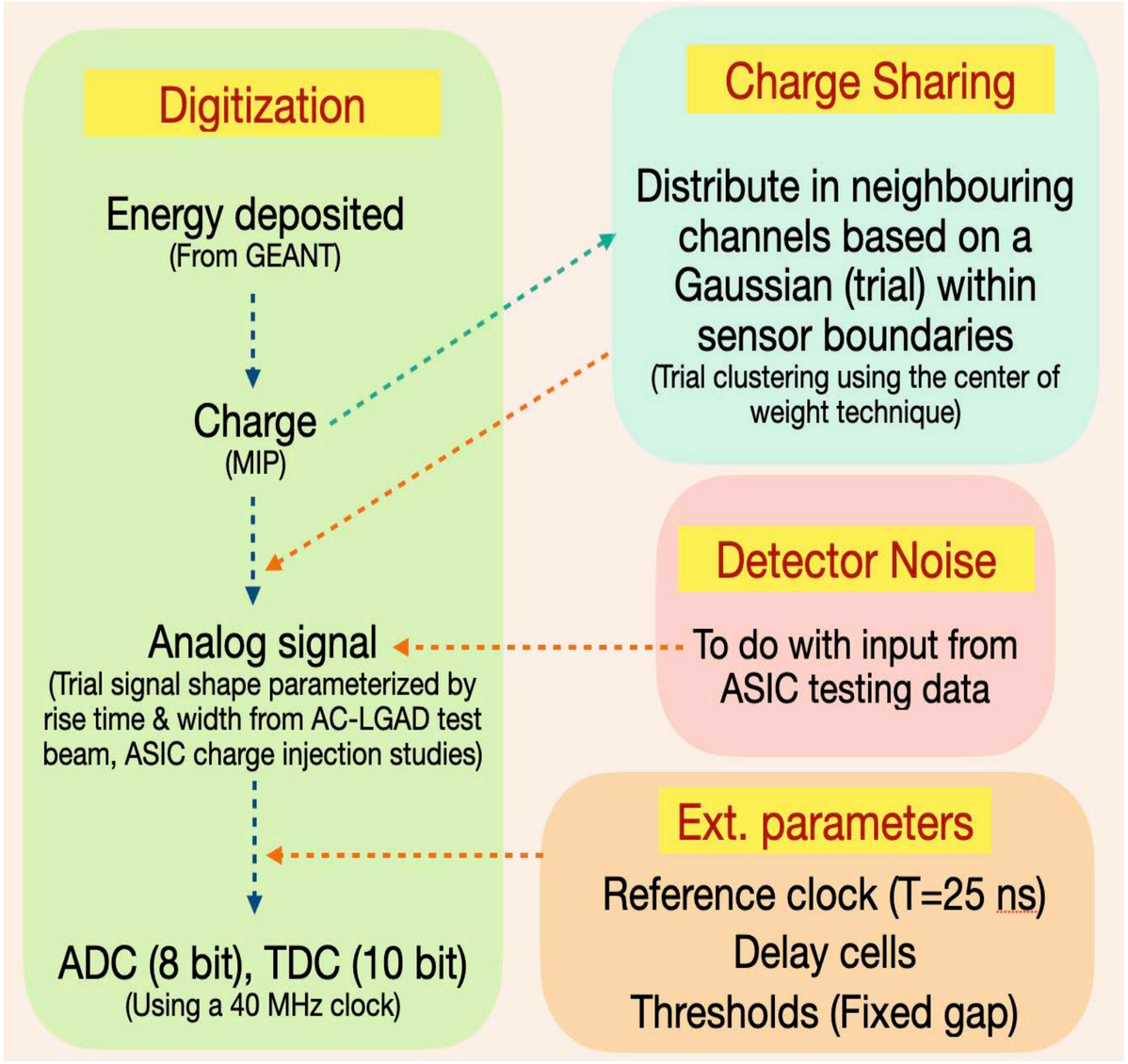


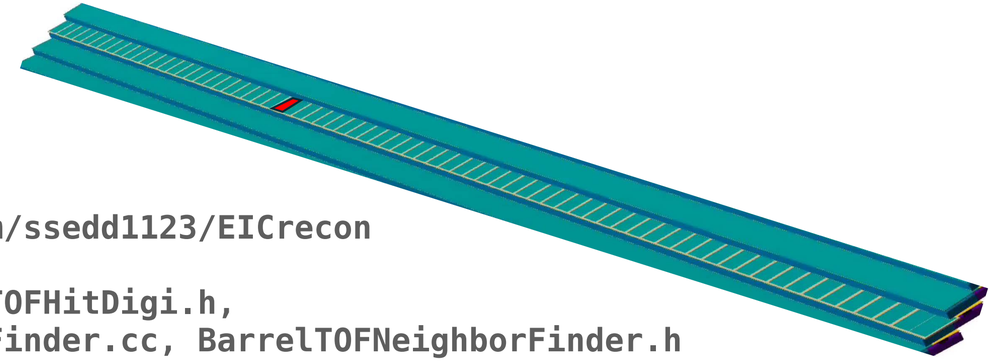
TDC and ToF



ADC and TDC distribution are final output consistent with GEANT input

Summary





`https://github.com/ssedd1123/EICrecon`

`BTOFHitDigi.cc, BTOFHitDigi.h, BarrelTOFNeighborFinder.cc, BarrelTOFNeighborFinder.h in EICRecon/src/detectors/BTOF`

`BTOFHitDigi_factory.h in EICrecon/src/factories/digi`

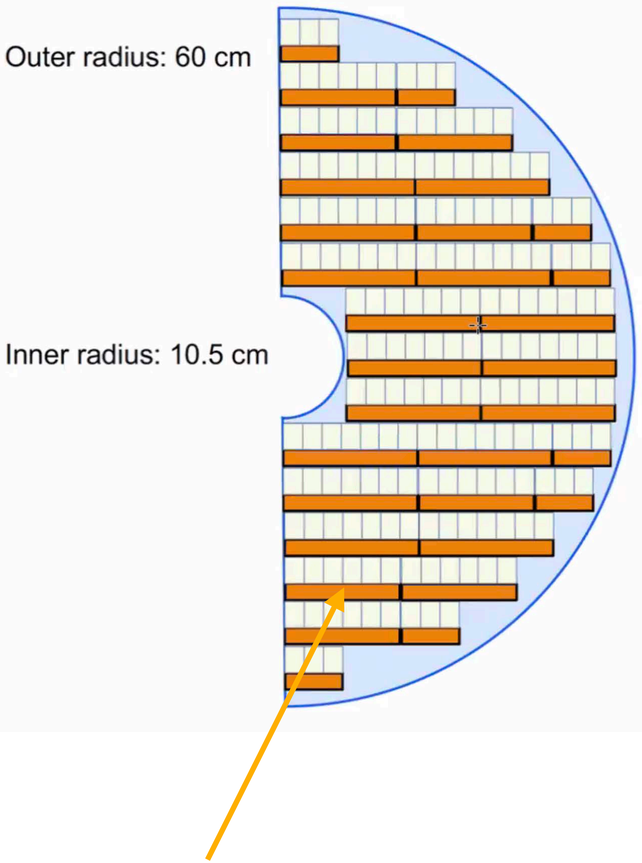
`BTOFHitDigiConfig.h in EICrecon/src/algorithms/digi`

Parameter	Value
Rise time (Landau MPV)	0.45 ns
Shape Width (Landau) = FWHM/2	0.293951 ns
Amplitude (Landau)	-113.766 V
MIP charge/energy	190000 $fC.GeV^{-1}$
Time period (Reference clock)	25 ns
Std. Dev. in X, Y (Gaussian for charge sharing)	0.5 mm, 0.5 mm
ToF Quantization time	0.02 ns

https://github.com/ssedd1123/EICrecon/tree/main/src/detectors/BTOF

Other AC-LGAD systems

FTOF Layout (x-y view): Scenario 2

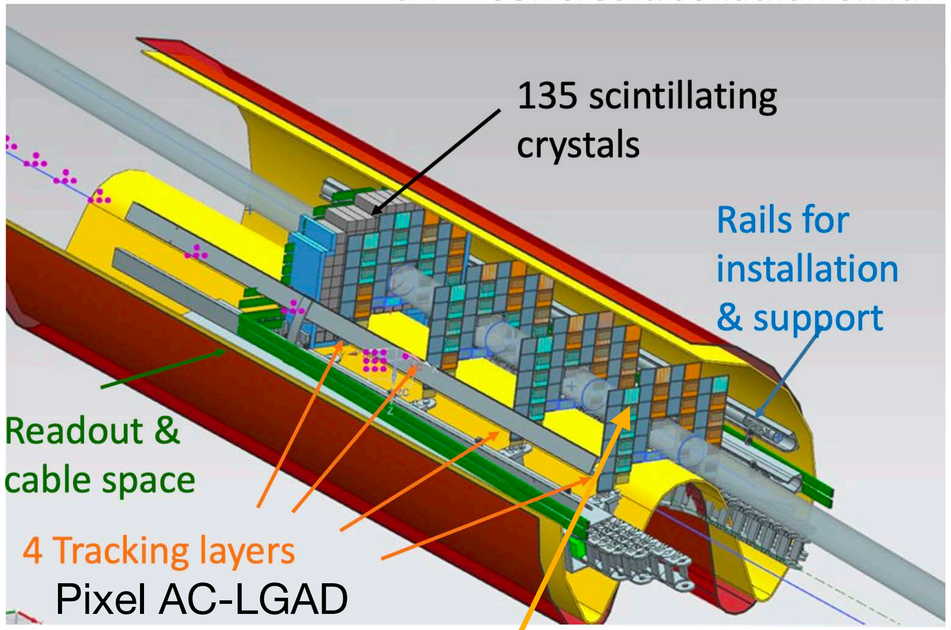


Row	modules	RB3	RB6	RB7	All RBs
1	3	1	0	0	1
2	9	1	1	0	2
3	12	0	2	0	2
4	14	0	0	2	2
5	16	1	1	1	3
6	17	1	0	2	3
7	14	0	0	2	2
8	14	0	0	2	2
9	14	0	0	2	2
10	17	1	0	2	3
11	16	1	1	1	3
12	14	0	0	2	2
13	12	0	2	0	2
14	9	1	1	0	2
15	3	1	0	0	1
Sum	**184**	8	8	16	**32**

Total number of modules: 184*4 = **736**
Total number of service hybrids: 32*4 = **128**

One square is four sensors

Pixel AC-LGAD

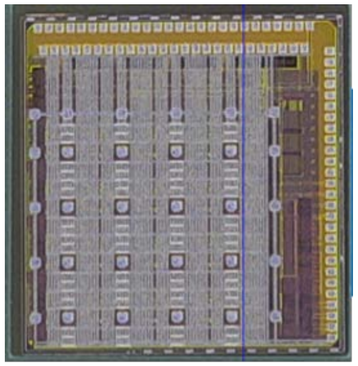


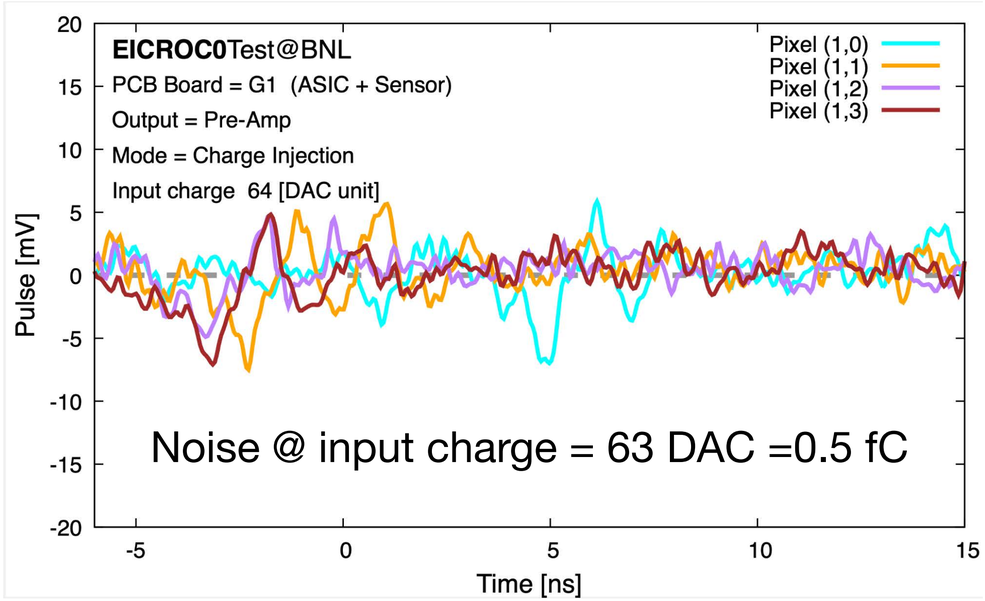
One square is one sensors

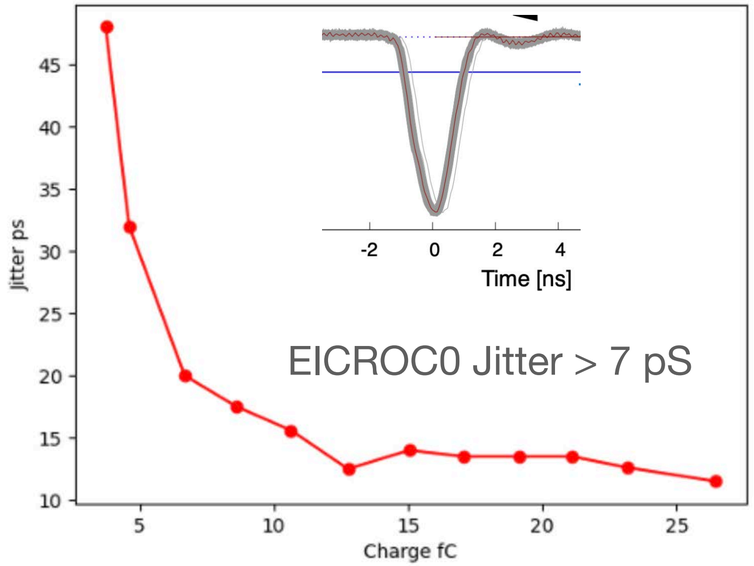
FTOF and B0 digitization in progress ….

Noise implementation

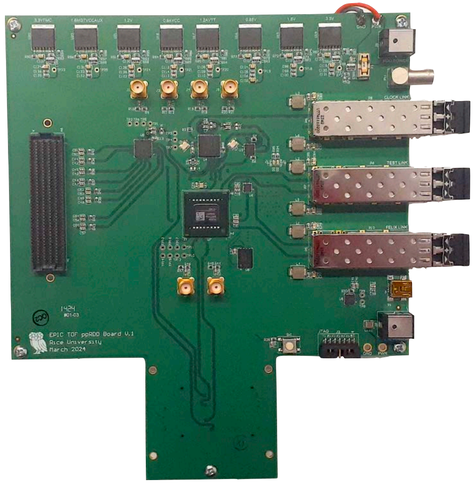
EICROC0 ASIC





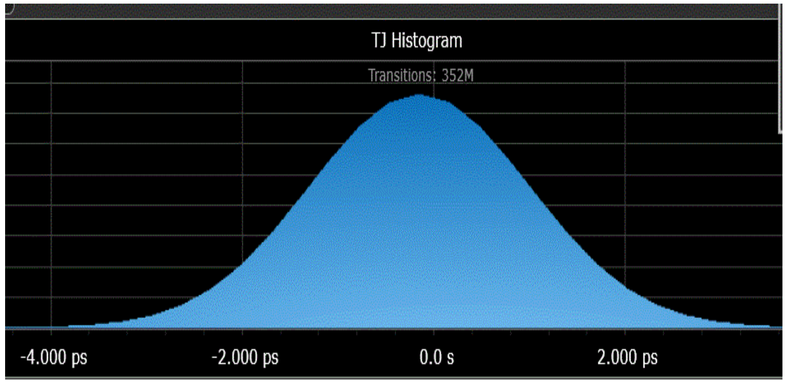


AC-LGAD ppRDO



PLL output 98.5 MHz clock distribution

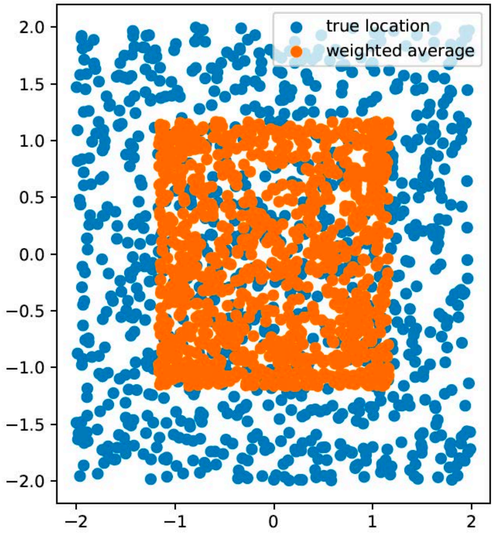
Clock jitter ~1.12 pS



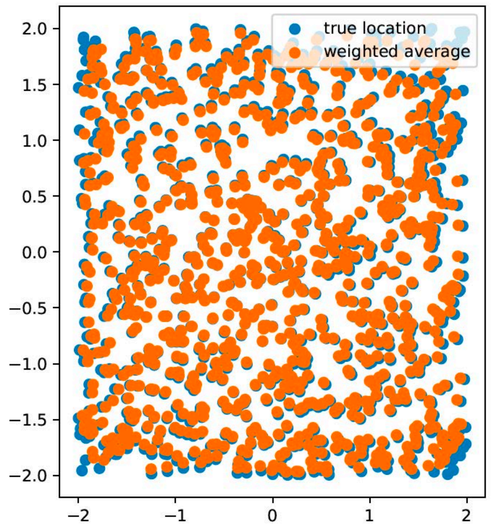
Noise implementation in progress…

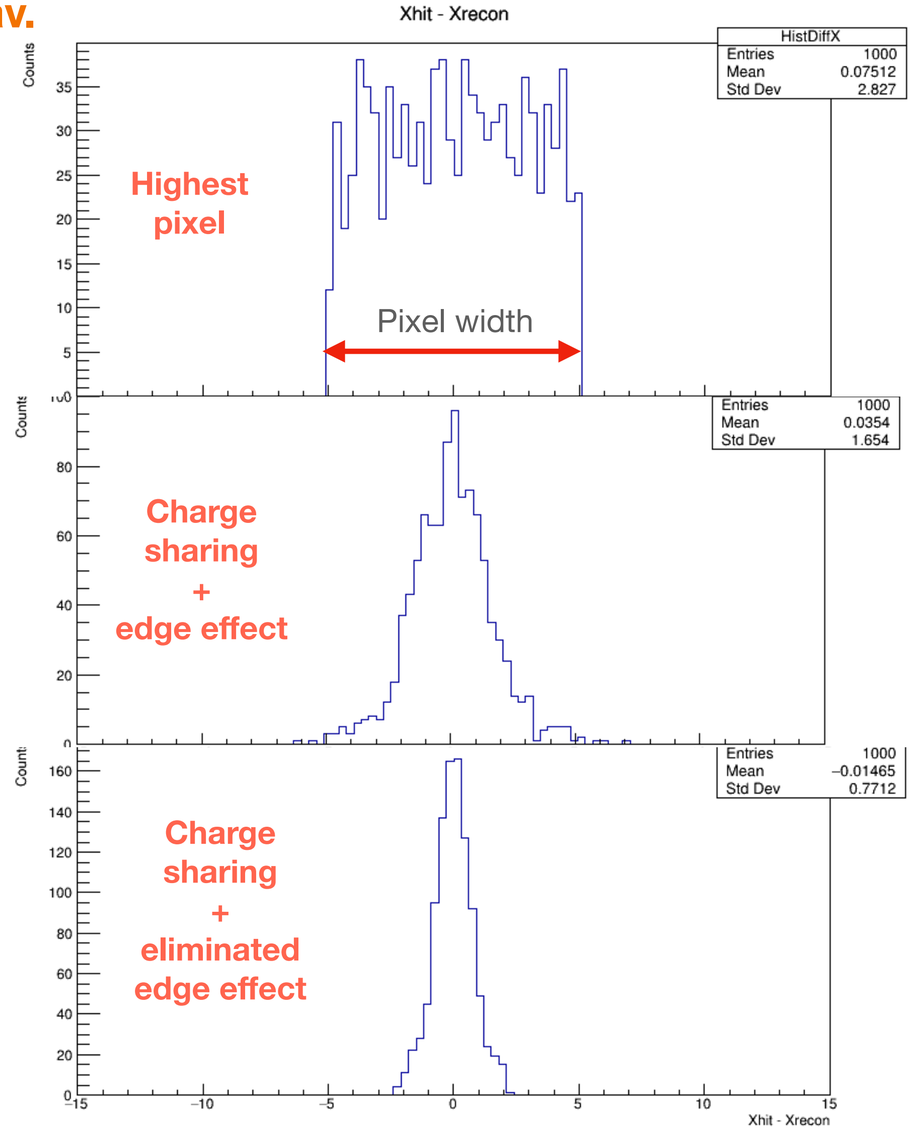
What's after digitization: reconstruction

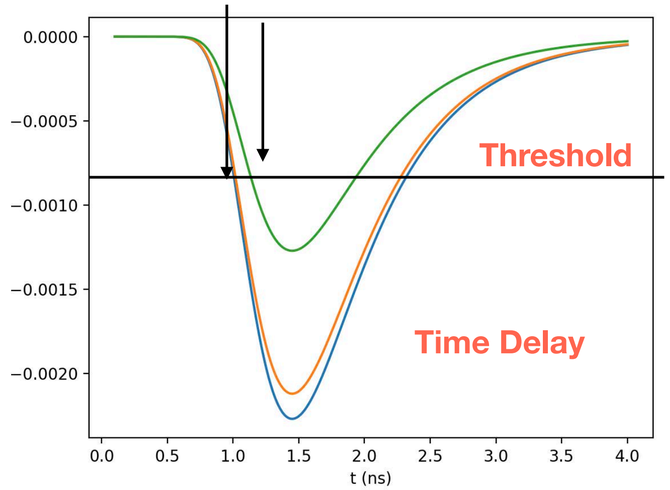
Charge sharing + center of grav.

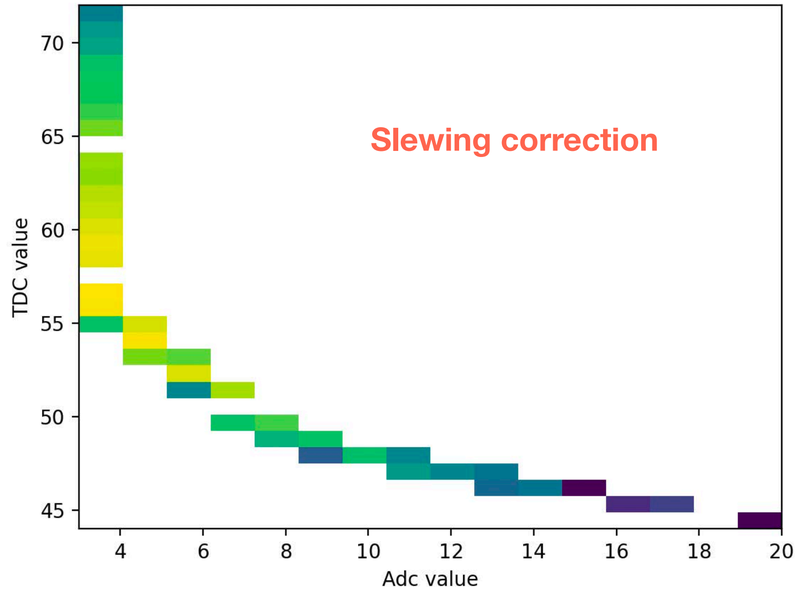


Charge sharing + AI/ML





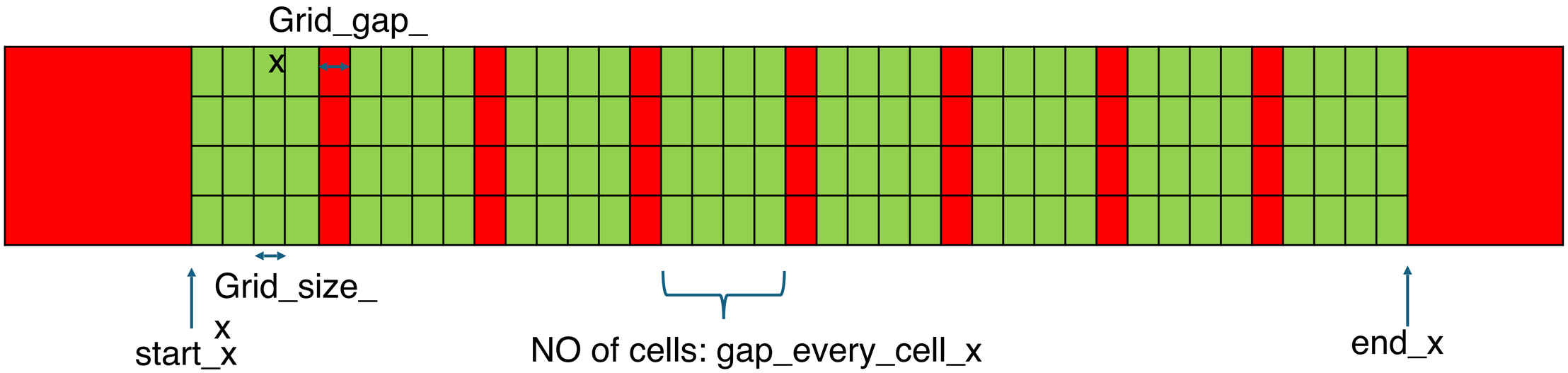




Reconstruction with digitization in progress…

Thank you

Put pixels in the right place:



Work done: Wrote an “UnevenCartesianGridXY” class to put dead space and pixels in the right place.

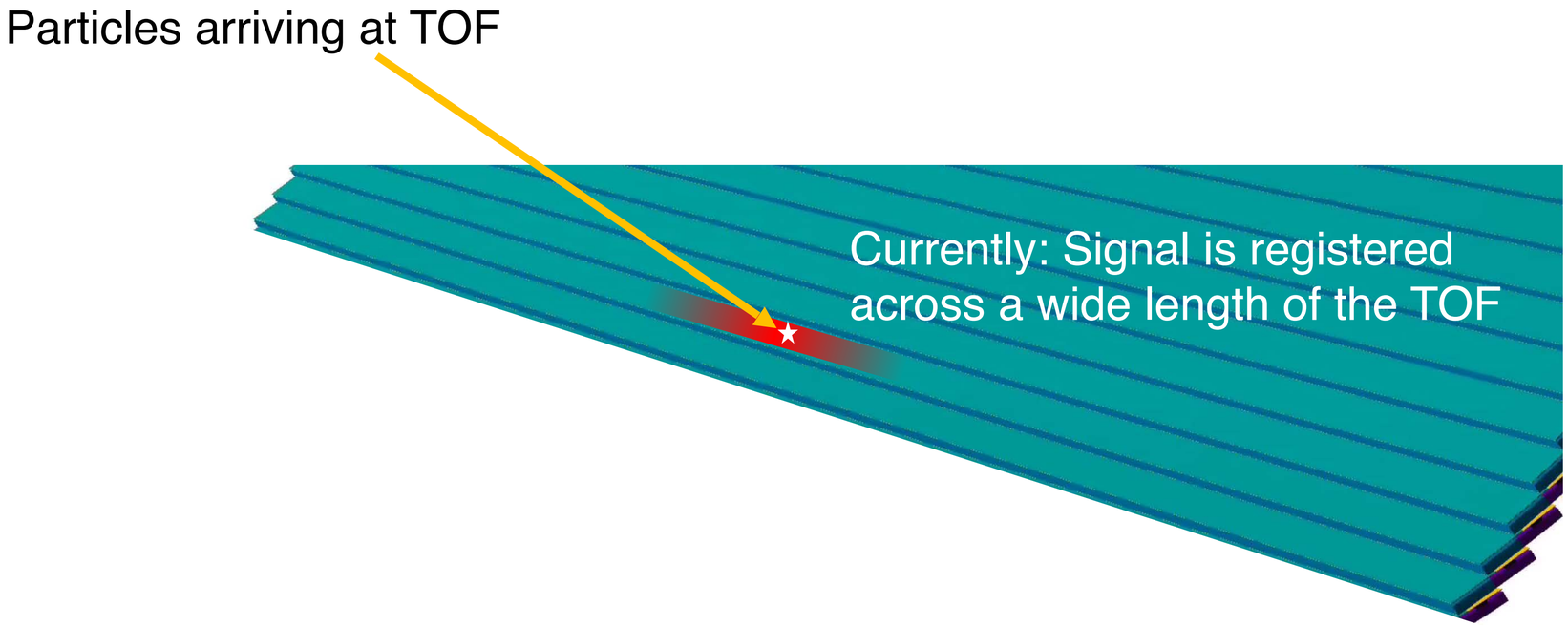
New “tof_barrel.xml”:

```
<readouts>
  <readout name="TOFBarrelHits">
    <segmentation type="UnevenCartesianGridXY" grid_size_x="0.1*mm" grid_size_y="1*cm" grid_gap_x="0.01*mm" grid_gap_y="0.5*cm" start_x="-1.8*cm" start_y="-128*cm" end_x="1.8*cm" end_y="128*cm" gap_every_cell_x="64" gap_every_cell_y="4"/>
    <id>system:8,layer:4,module:12,sensor:2,x:32:8,y:40:12,sx:52:2,sy:54:10</id>
  </readout>
</readouts>
```

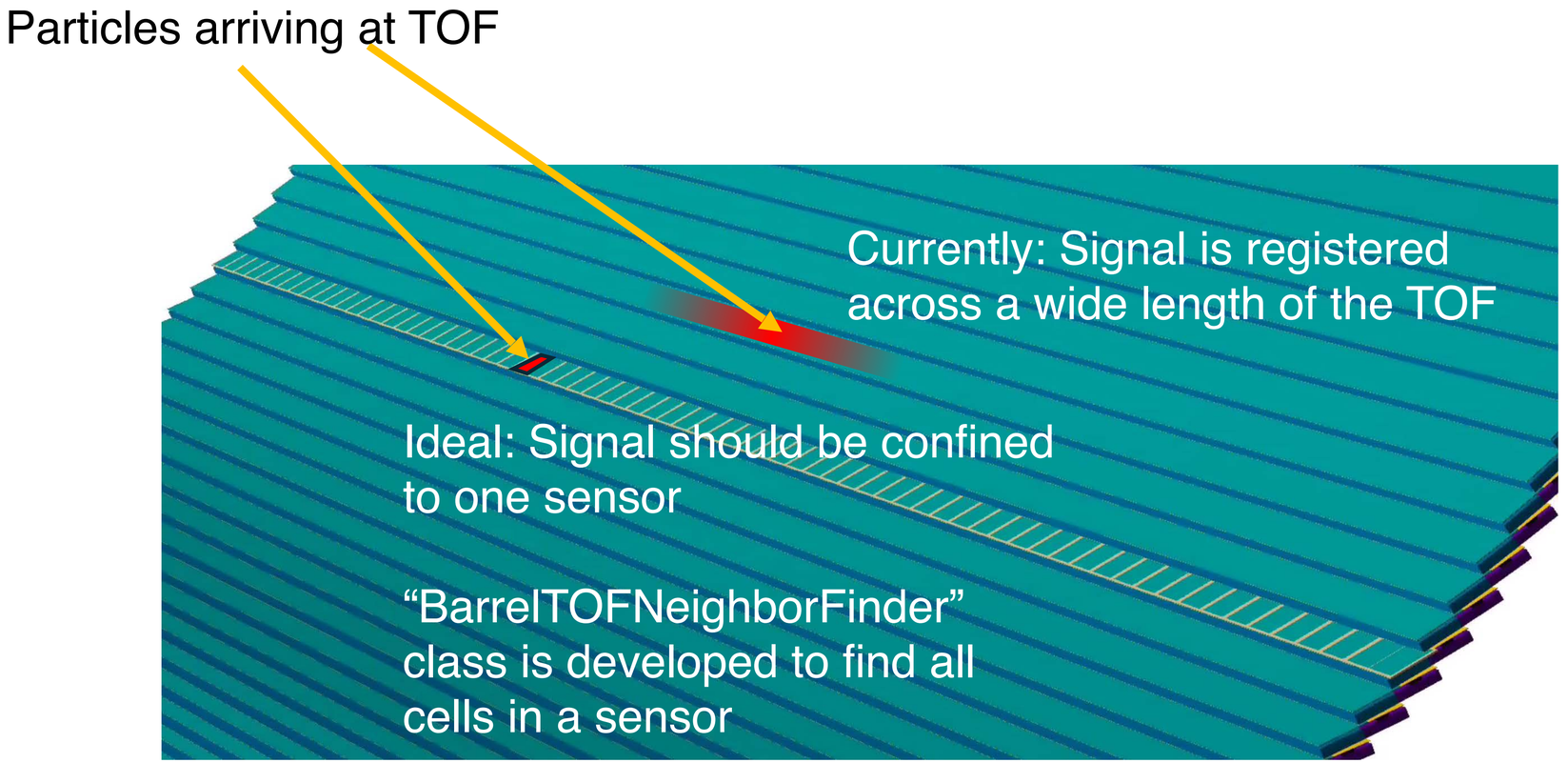
Don’t have the accurate numbers, but they are free parameters. Can be adjusted easily.

Calculate energy for each pixel.

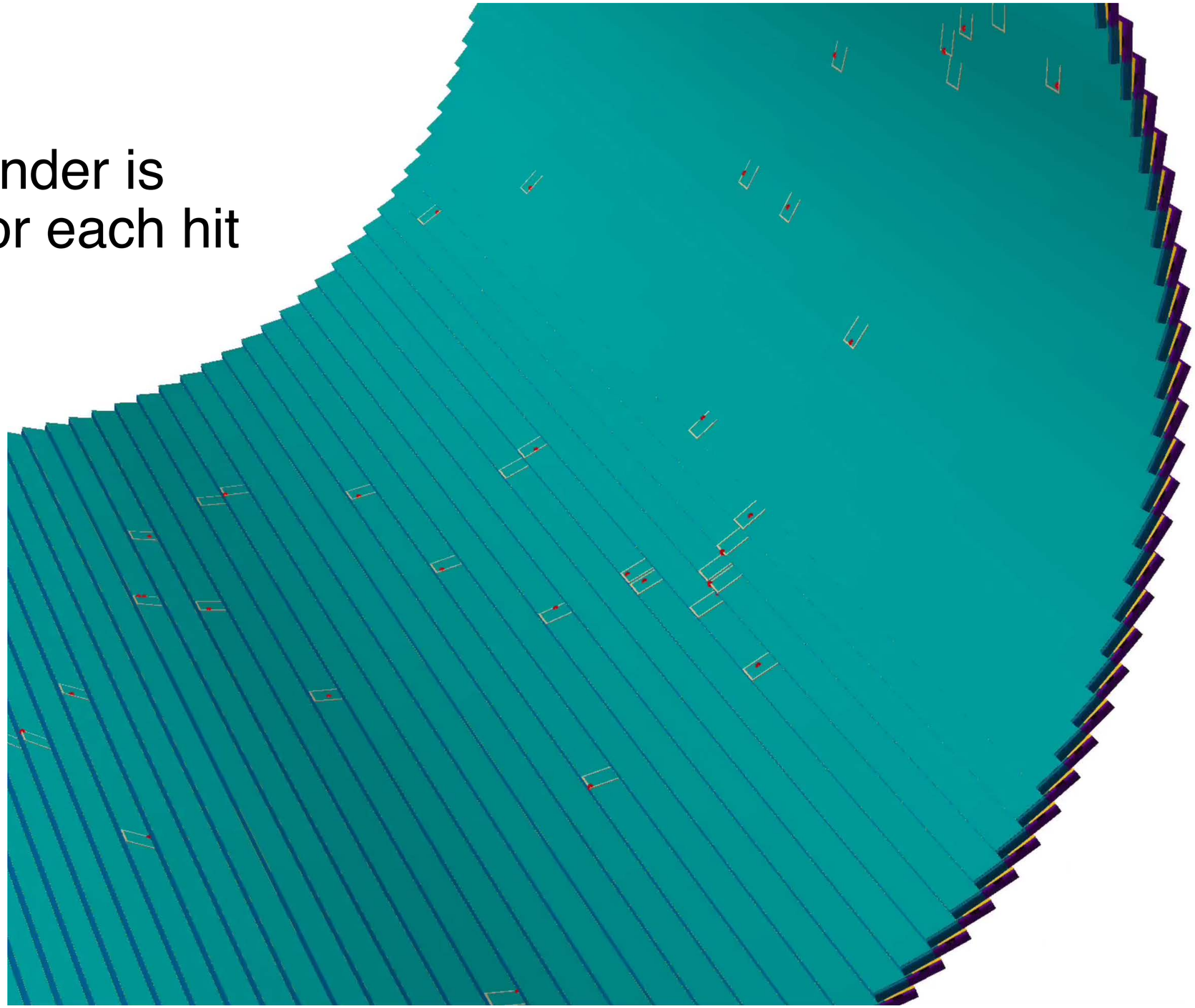
- Currently in GEANT, each stave of TOF is one entire unit.



Solution: Write a class that interface with UnevenCartesianGridXY to get cell boundaries



Simulation results:
BarrelTOFNeighborFinder is able to find sensors for each hit



Analog Signal, Voltage Threshold & ADC

- Energy deposited (**Edep** from GEANT) is multiplied by the realistic AC-LGAD **gain** (~80) to give the **area** of the analog signal.
- The $\mathbf{t_{rise}}$(~450 ps) and the **standard deviation**(~294 ps) of a real AC-LGAD signal (obtained from ASIC charge injection studies), and the **area** (calculated from E_{dep}) are used to parameterize a **Landau**-like analog signal.

Voltage Thresholds

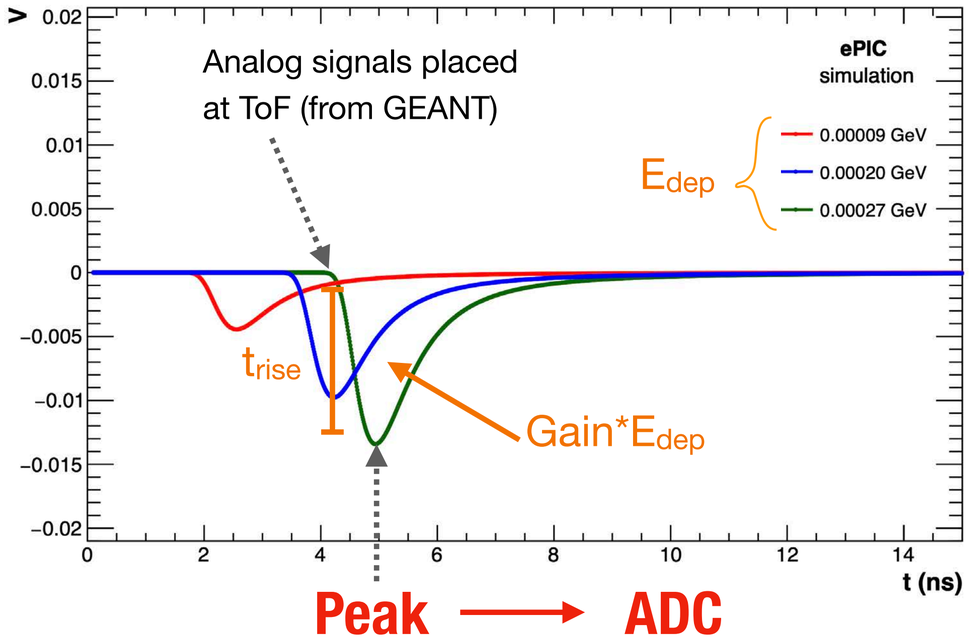
V_{th_1}: 0 — Should be set at the mean of noise

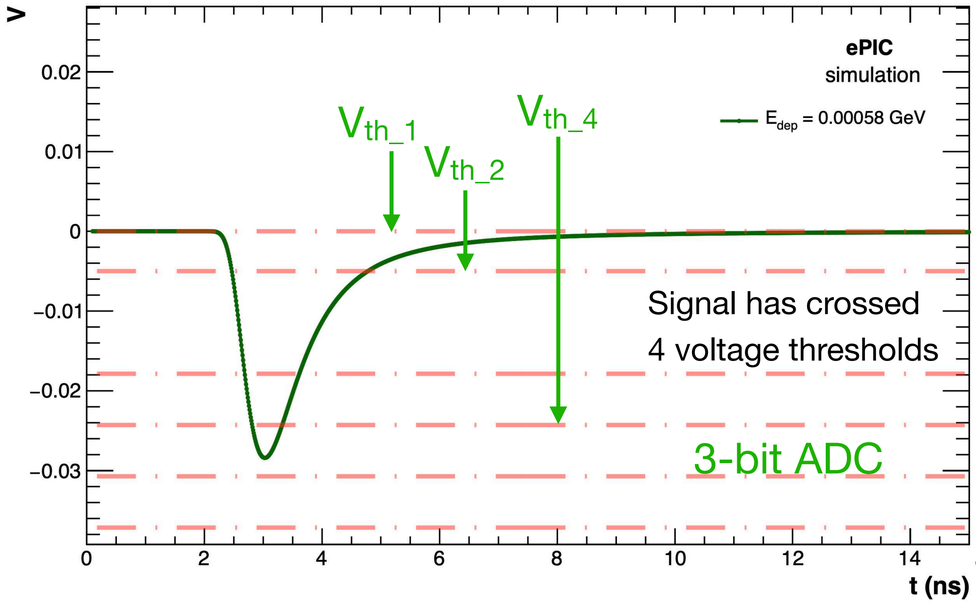
$V_{th\text{-}2}$: 0.005 — $Th_{max}/10$

V_{th_n}: $Th_2 + (n-1)*(Th_{max}-Th_2)/(2^8-1)$

$3 \le n \le 256$

n_{max} (for 8-bit ADC)





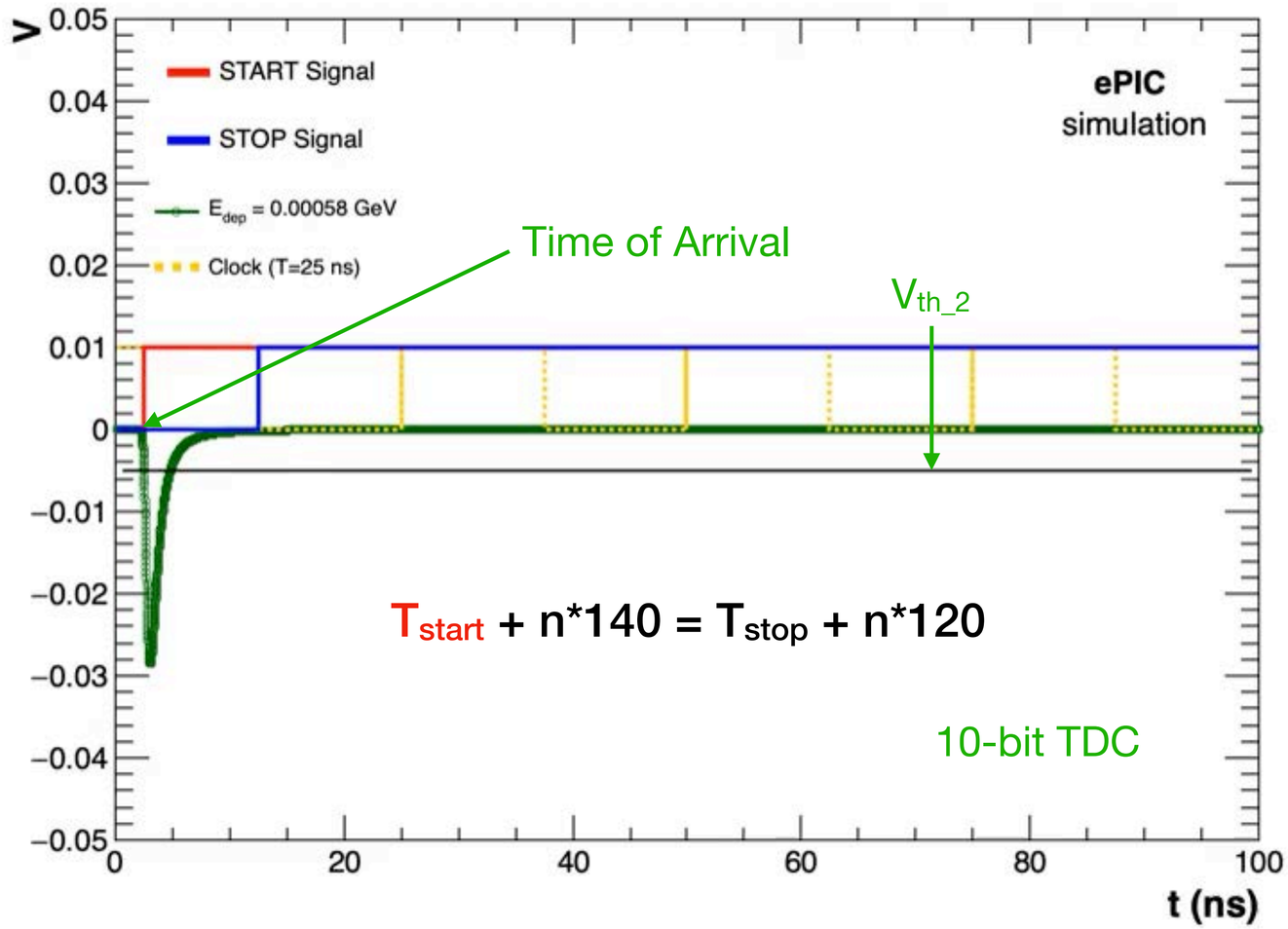
- The number of voltage thresholds crossed by the analog signal ($1 \le n \le 256$) is converted to a 8-bit ADC code.
- Will be updated according to latest EICROC results.

Analog Signal & TDC

- Almost all hits occur in the 1st half-period of the clock(f = 40MHz). When the analog signal crosses V_{th_2} (Time of Arrival), the **START** signal flips from 0 to 1. When the clock cycle flips from the 1st to the 2nd half-period, the **STOP** signal flips from 0 to 1.
- Consecutive delay cells propagate the START signal (140 ps delay) and the STOP signal (120 ps delay) in parallel until the START signal crosses the STOP signal (Mathematically, **|START-STOP| < 20 ps**).

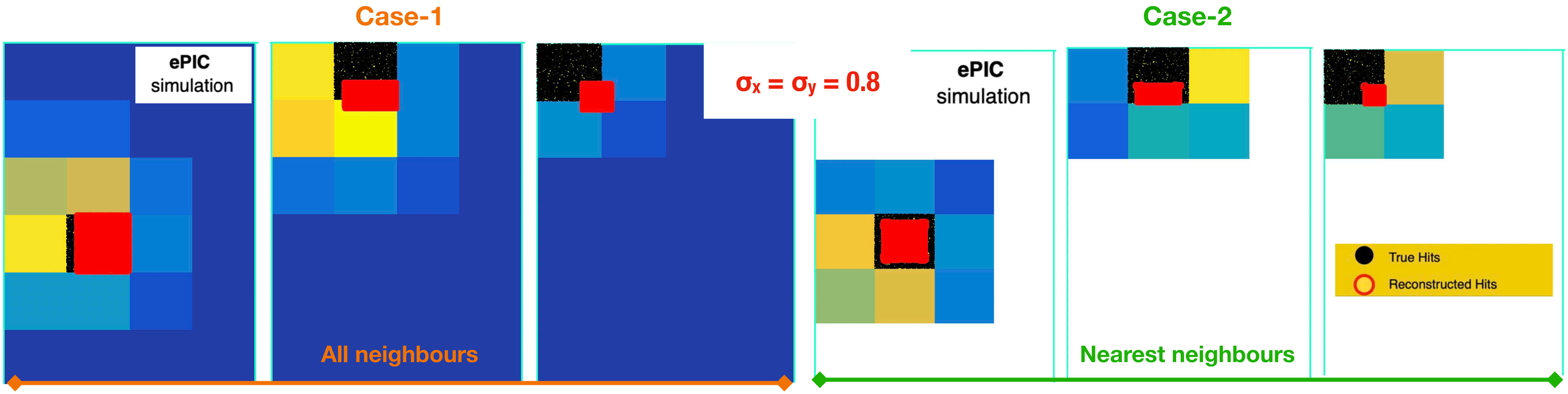
Quantization time of ePIC ToF detector

Time of Arrival → TDC



- The number of times the signals move ($1 \le n \le 1024$) is converted to a 10-bit TDC code.

Charge Sharing (Geometric effects)



- The position of the hit pixel and the number of charge-sharing neighbours has an effect on the reconstruction accuracy of the hits.
- Reconstruction accuracy decreases as the pixel hit position changes from central to corner.
- Central pixel has 8 nearest neighbours, edge pixel has 5 nearest neighbours and corner pixel has 3 nearest neighbours.
- Reconstruction accuracy for Case-2 is **greater** than that for Case-1.

Charge Sharing (More geometric effects)