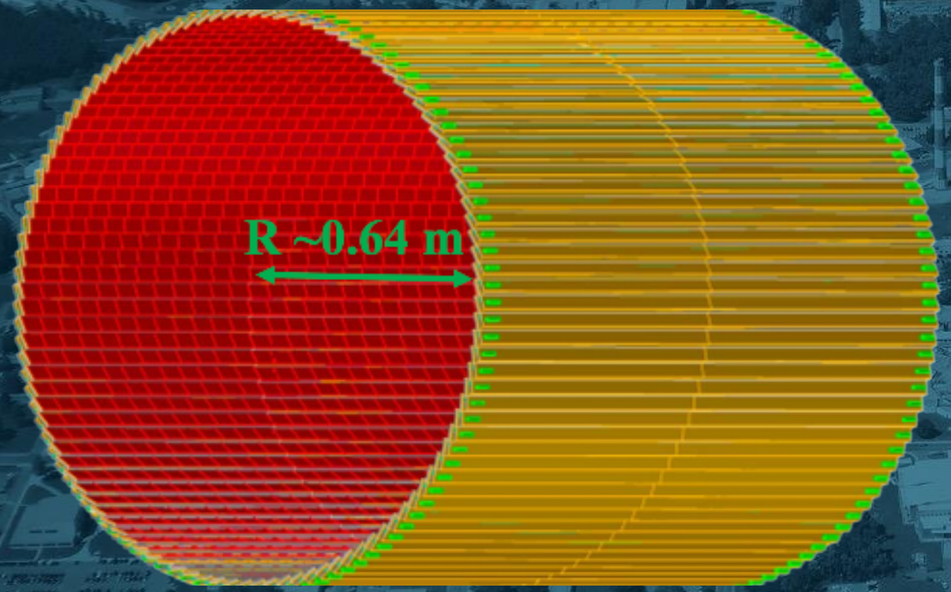
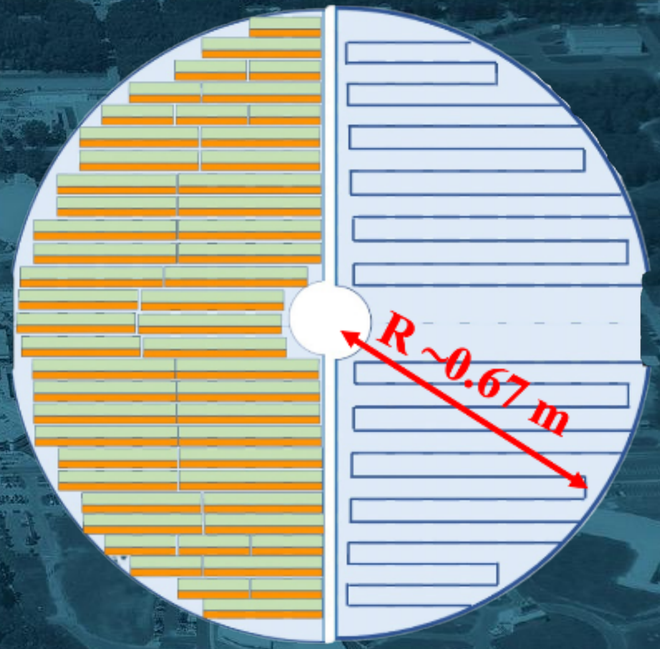
ToF Digitization in ePIC simulation





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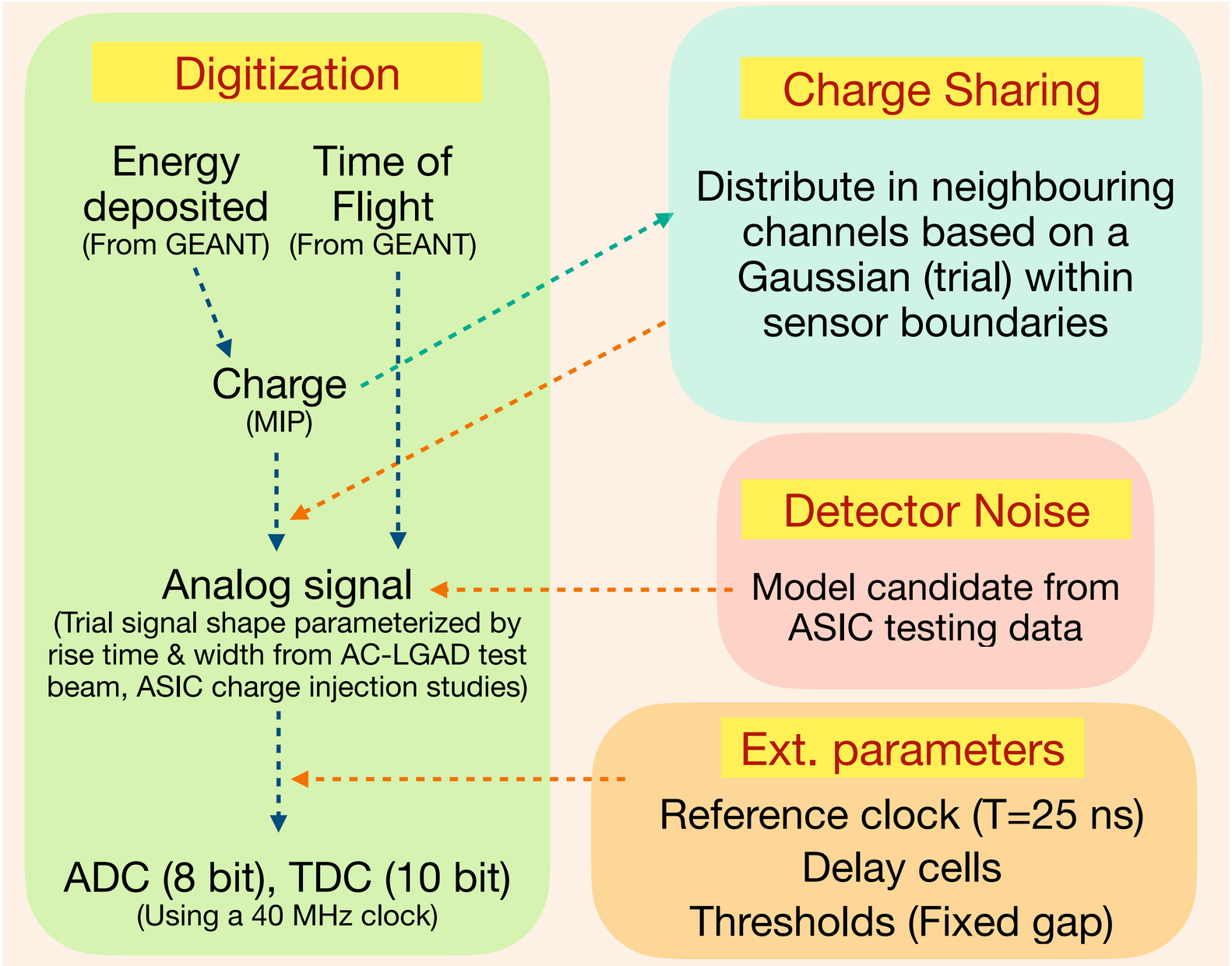
7th November 2023

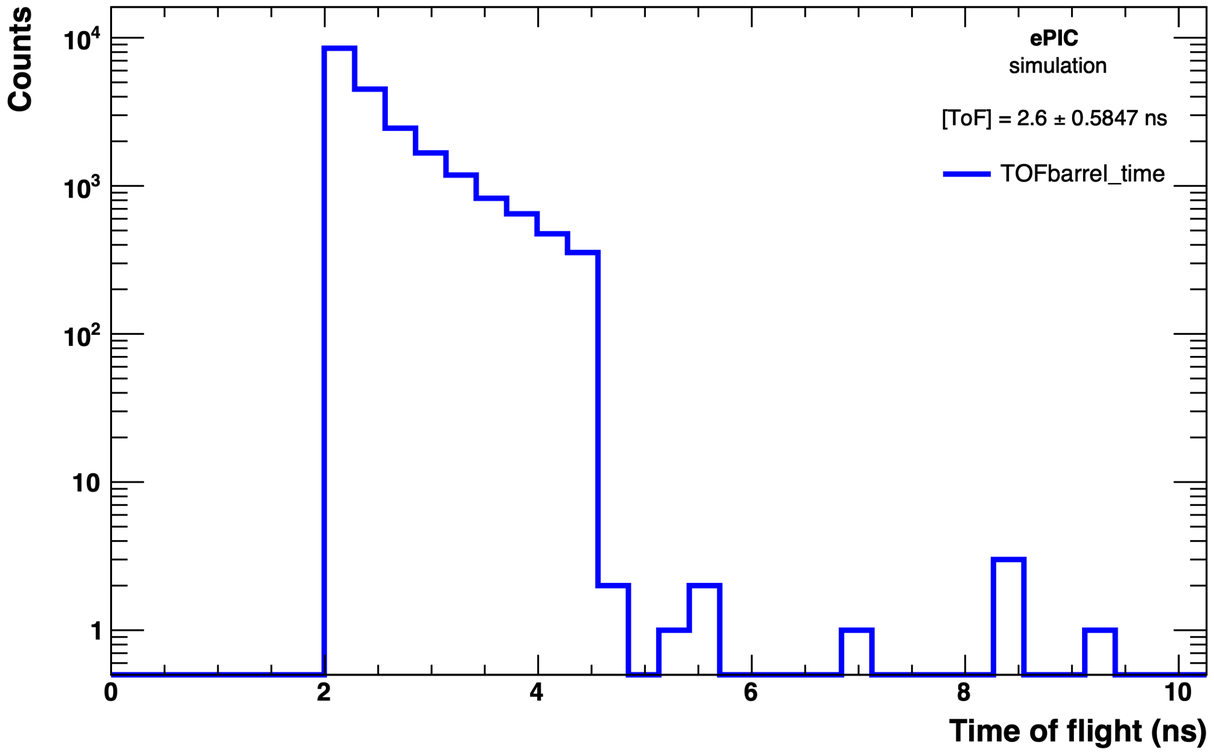
Objectives

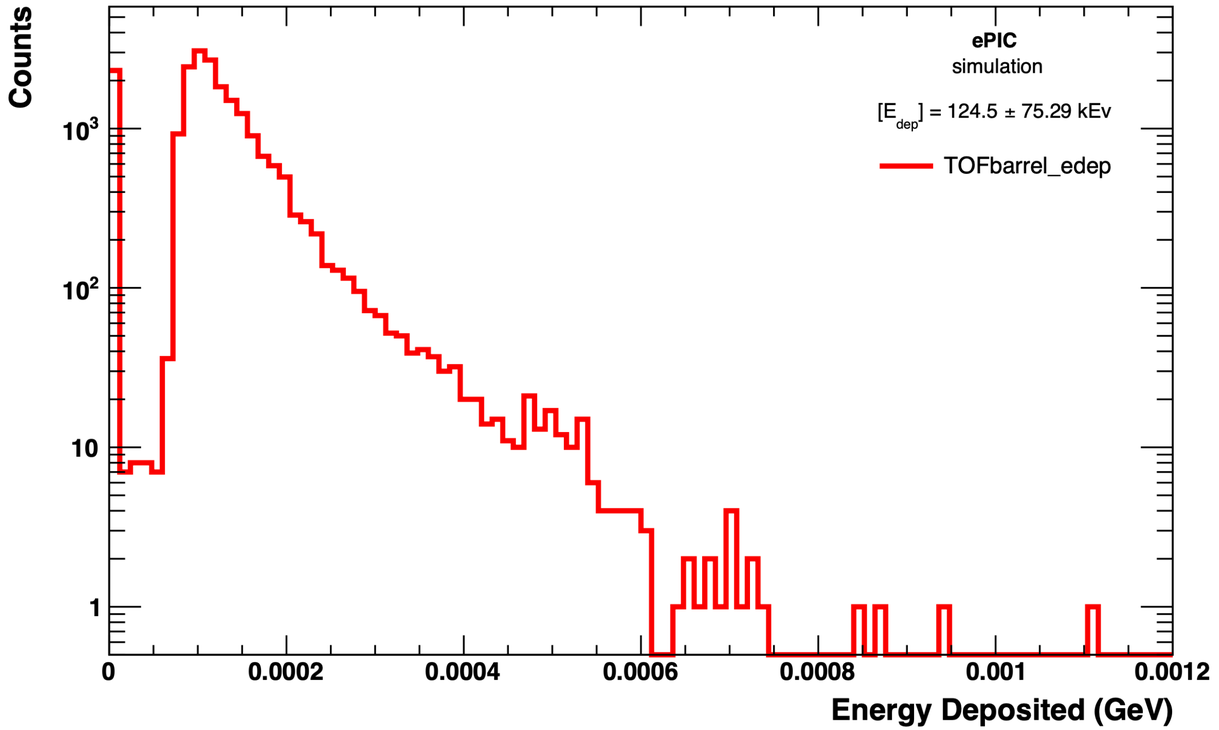

Digitization
Energy deposited
(From GEANT)
Time of Flight
(From GEANT)
Charge
(MIP)
Analog signal
(Trial signal shape parameterized by rise time & width from AC-LGAD test beam, ASIC charge injection studies)
ADC (8 bit), TDC (10 bit)
(Using a 40 MHz clock)
Charge Sharing
Distribute in neighbouring channels based on a Gaussian (trial) within sensor boundaries
Detector Noise
Model candidate from ASIC testing data
Ext. parameters
Reference clock (T=25 ns)
Delay cells
Thresholds (Fixed gap)

Digitization: Energy Deposition & Time of Flight

GEANT run specifications:

- Single particle generation (μ-) using npsim in DD4HEP
- # Events = 250k
- 0 GeV ≤ Particle Gun Momentum ≤ 30 GeV
- 0° ≤ Particle Gun Azimuthal Angle ≤ 180°





- Every sample of energy deposited is converted to charge for digitization.
- Corresponding time sample (Time of Flight) is used as input for TDC calculation.

Digitization: Analog Signal, Voltage Threshold & ADC

- Energy deposited (**E_{dep}** from GEANT) is multiplied **MIP charge per unit energy** (~19/0.0001 fC/GeV) to give the **area** of the analog signal, which equals the total input charge.
- The **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

Should be set at the mean of noise

V_{th_1}: 0

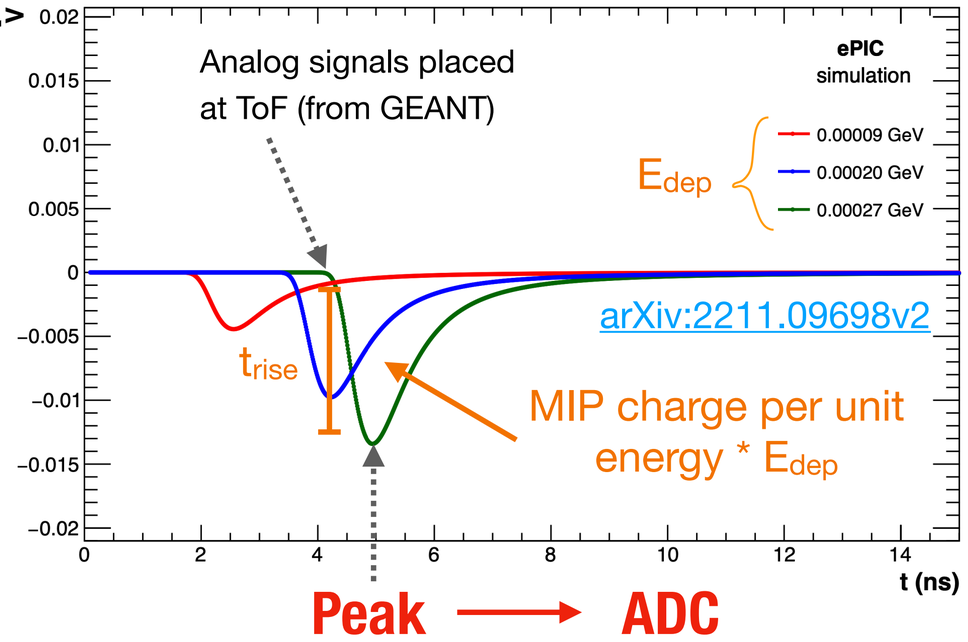
$V_{th\text{-}2}$: 0.005 ← $V_{th\_max}/10$

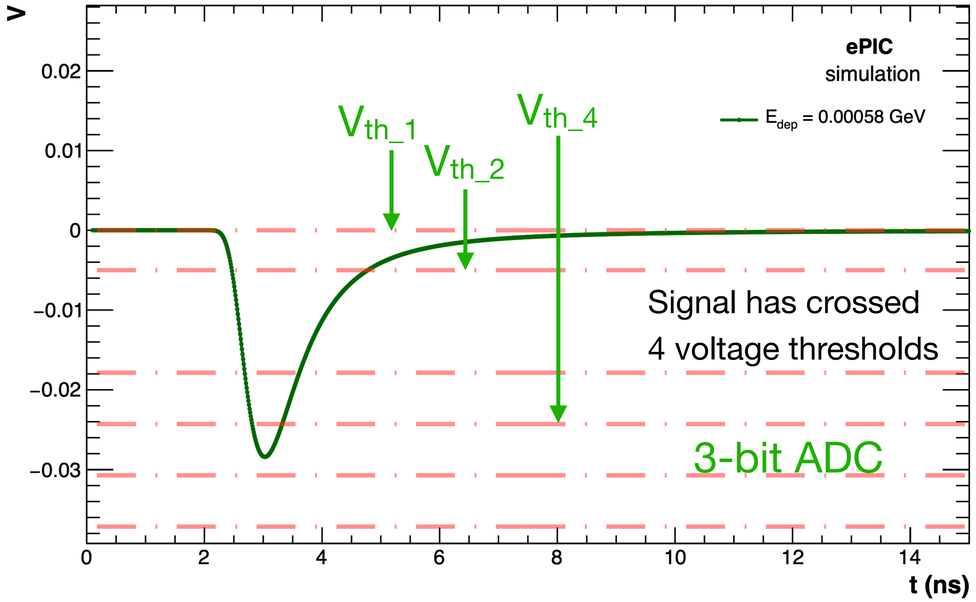
V_{th_n}: V_{th_2} + (n-1)*(V_{th_max}-V_{th_2})/(2^8-1)

$3 \le n \le 256$

n_{max} (for 8-bit ADC)

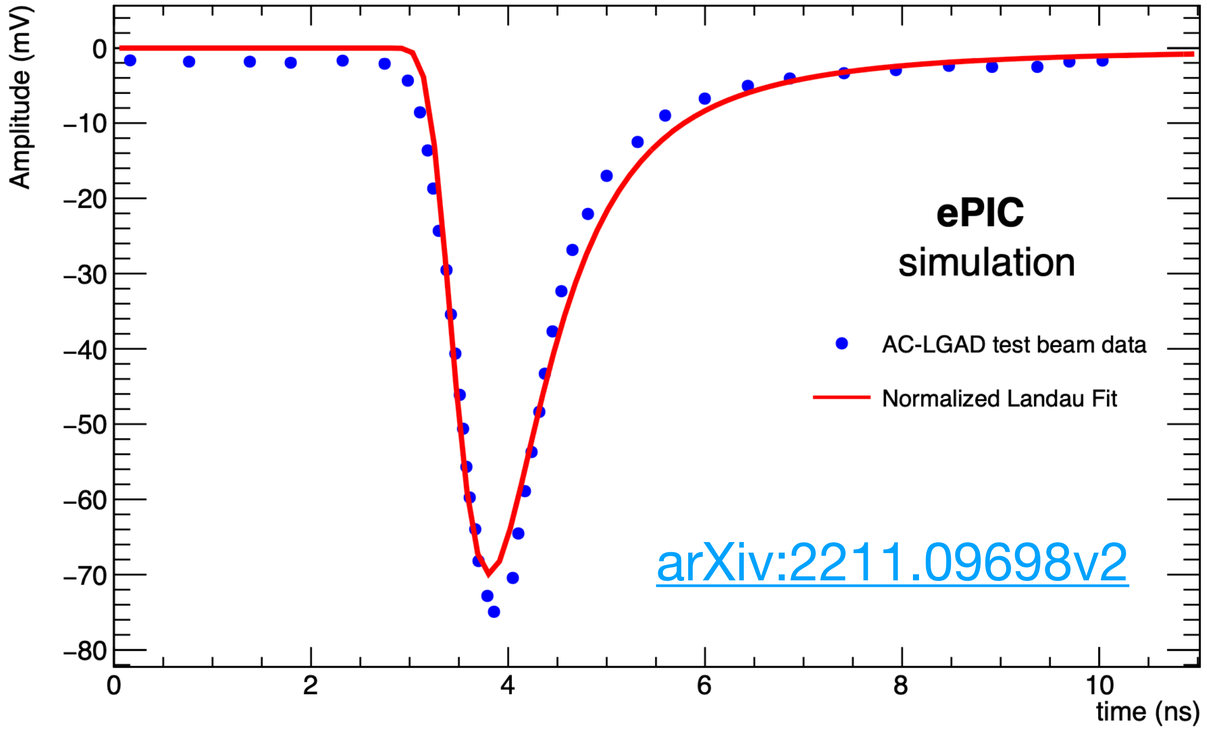
- The number of voltage thresholds crossed by the analog signal ($1 \le n \le 256$) is converted to a 8-bit ADC code.
- Will be updated according to latest EICROC results.

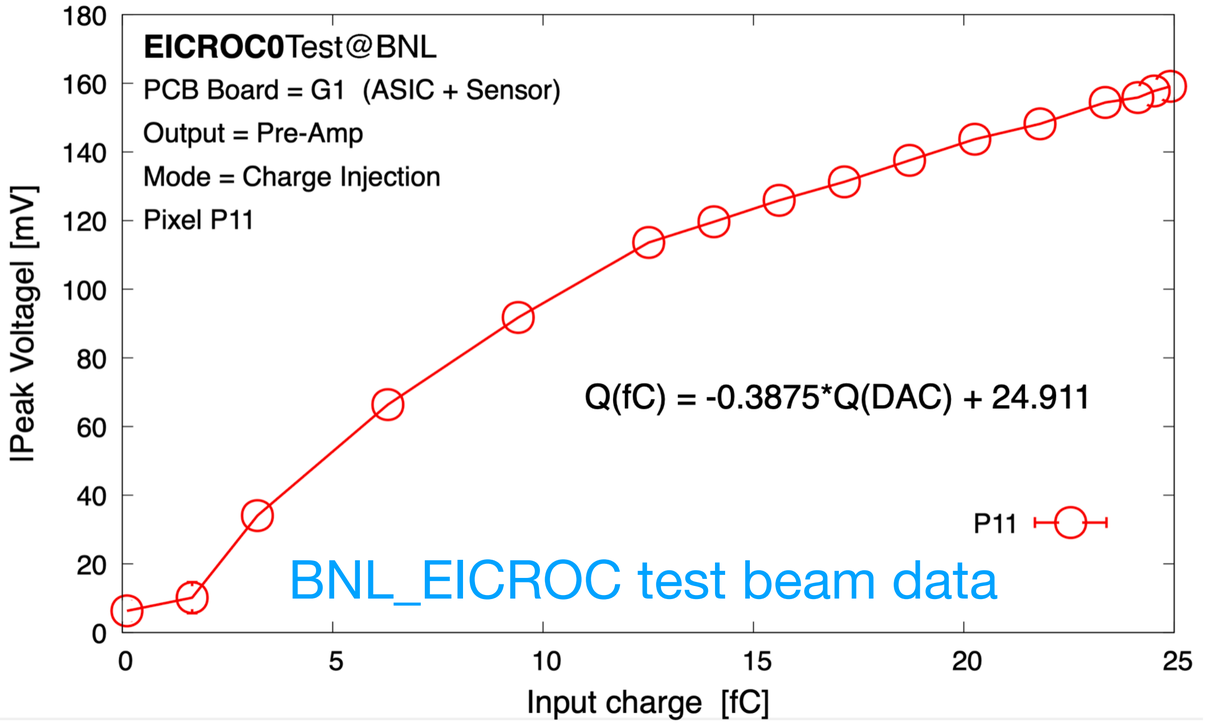




Data-driven Simulation

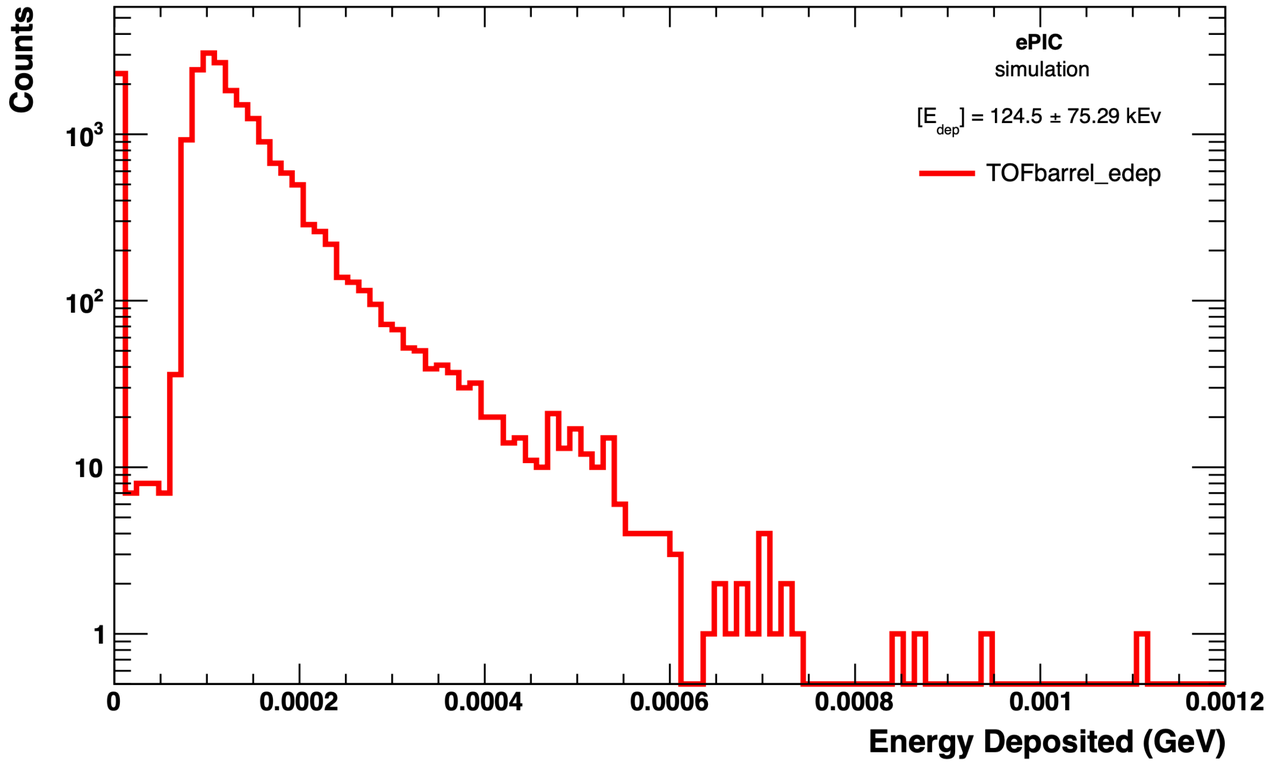
Parameterization of the Analog Signal shape using a Landau distribution.

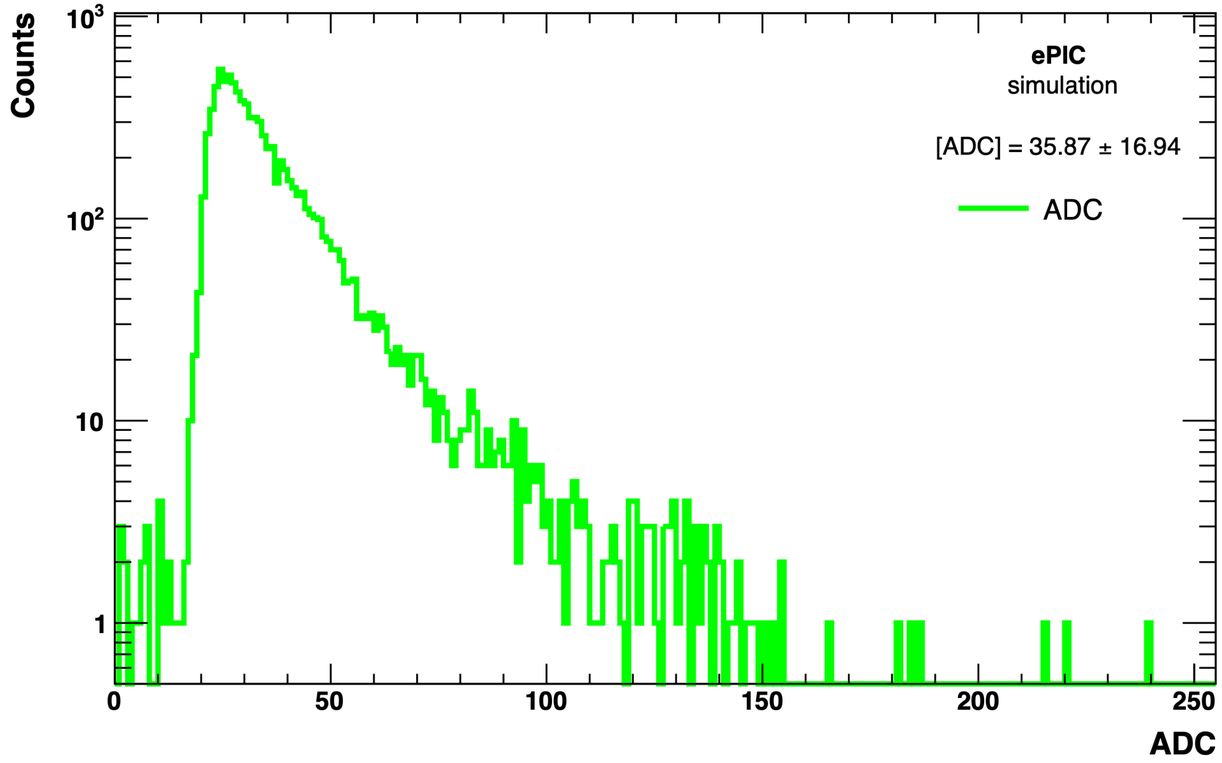




Relation between input charge and maximum voltage.

Digitization: Energy Deposition & ADC





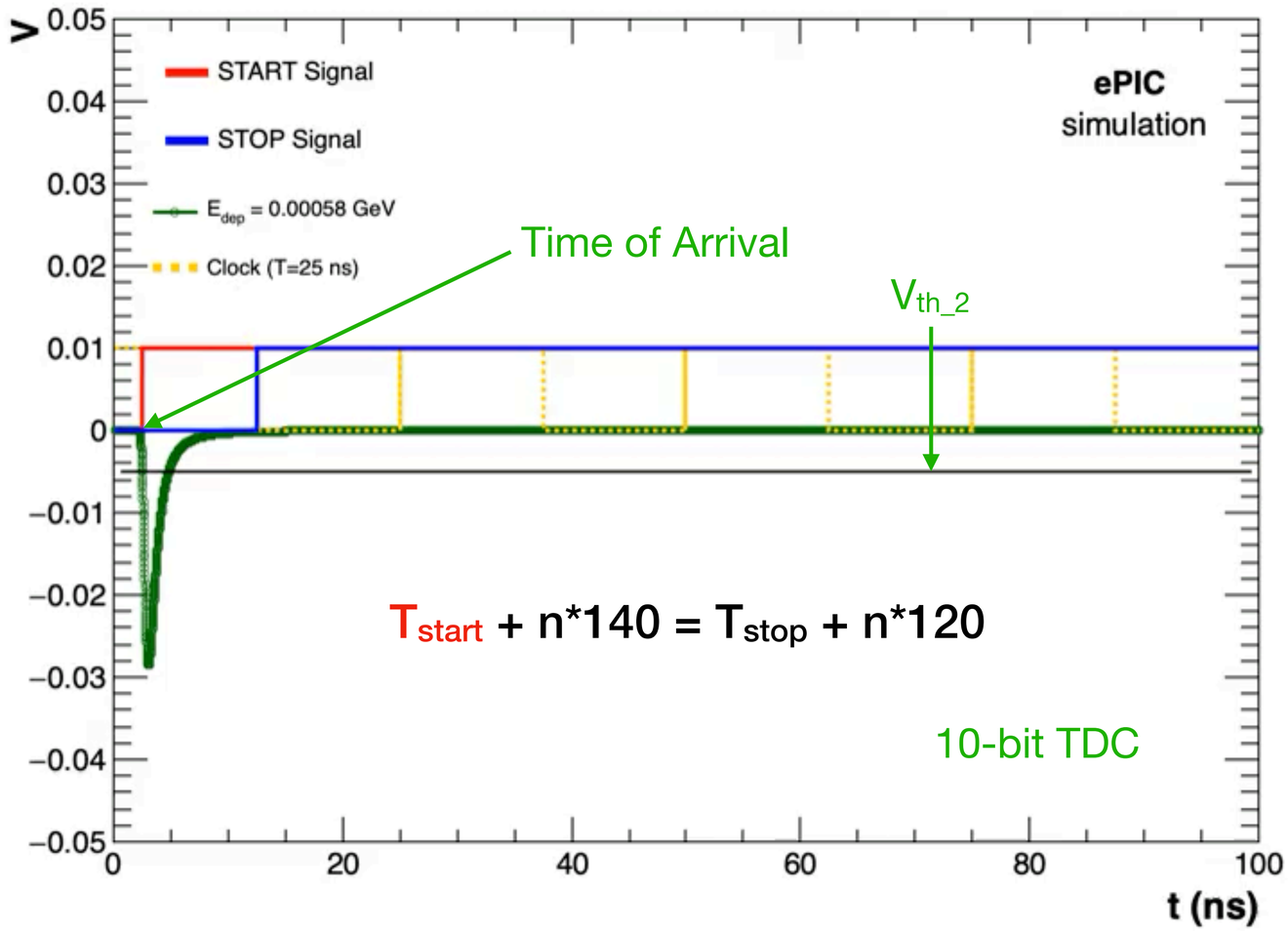
Energy Deposited → Charge → V_{max} of Signal → ADC

Digitization: Analog Signal & TDC

- Almost all hits occur in the 1st half-cycle 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 flips from the 1st to the 2nd half-cycle, 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**).

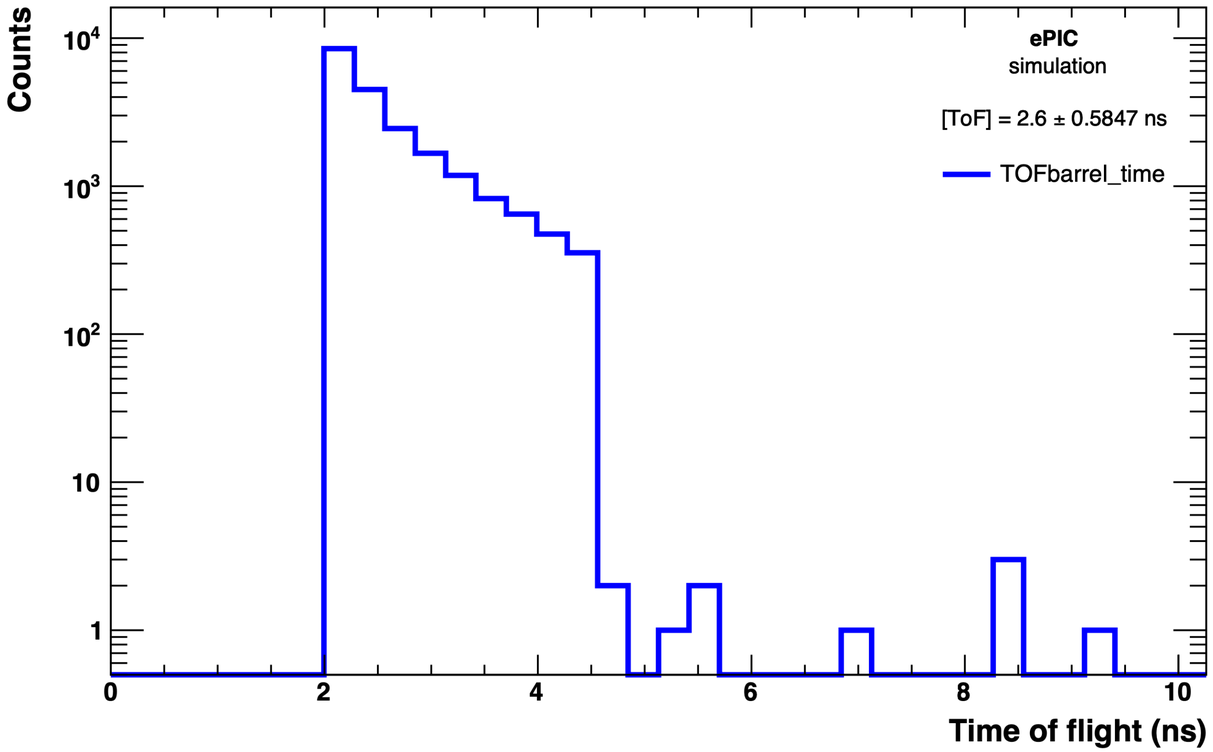
Quantization time of ePIC ToF detector

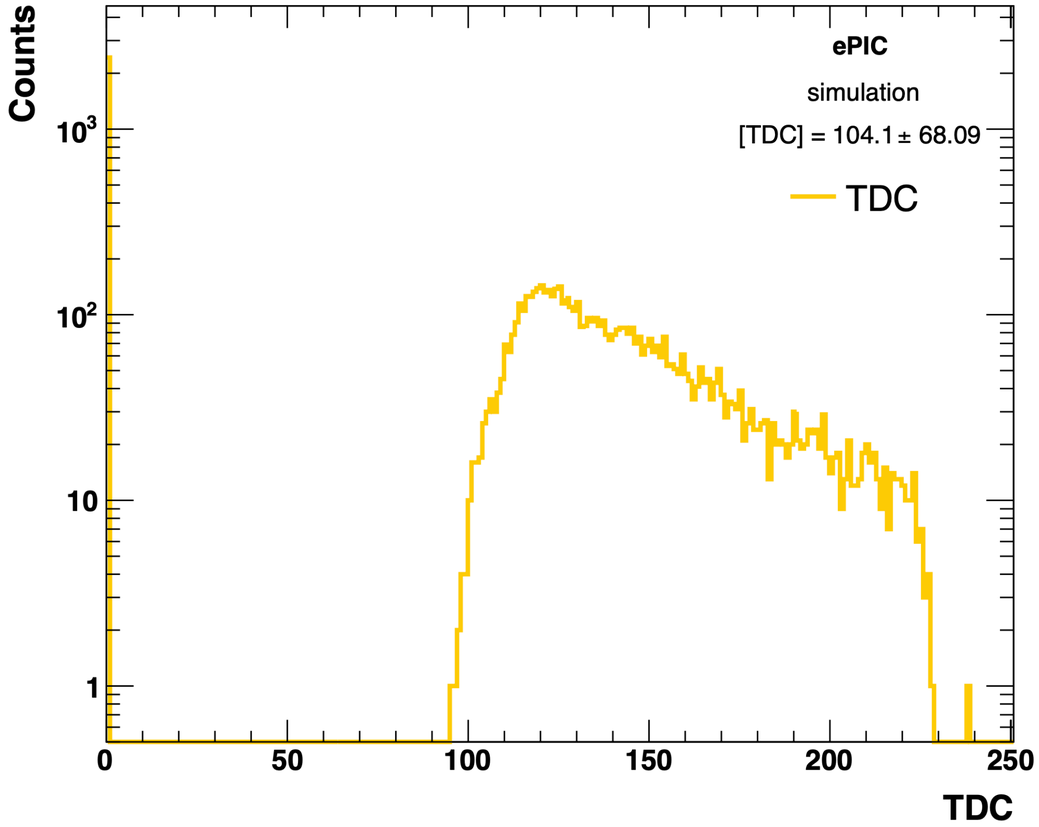
Time of Arrival → TDC



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

Digitization: Time of Flight & TDC

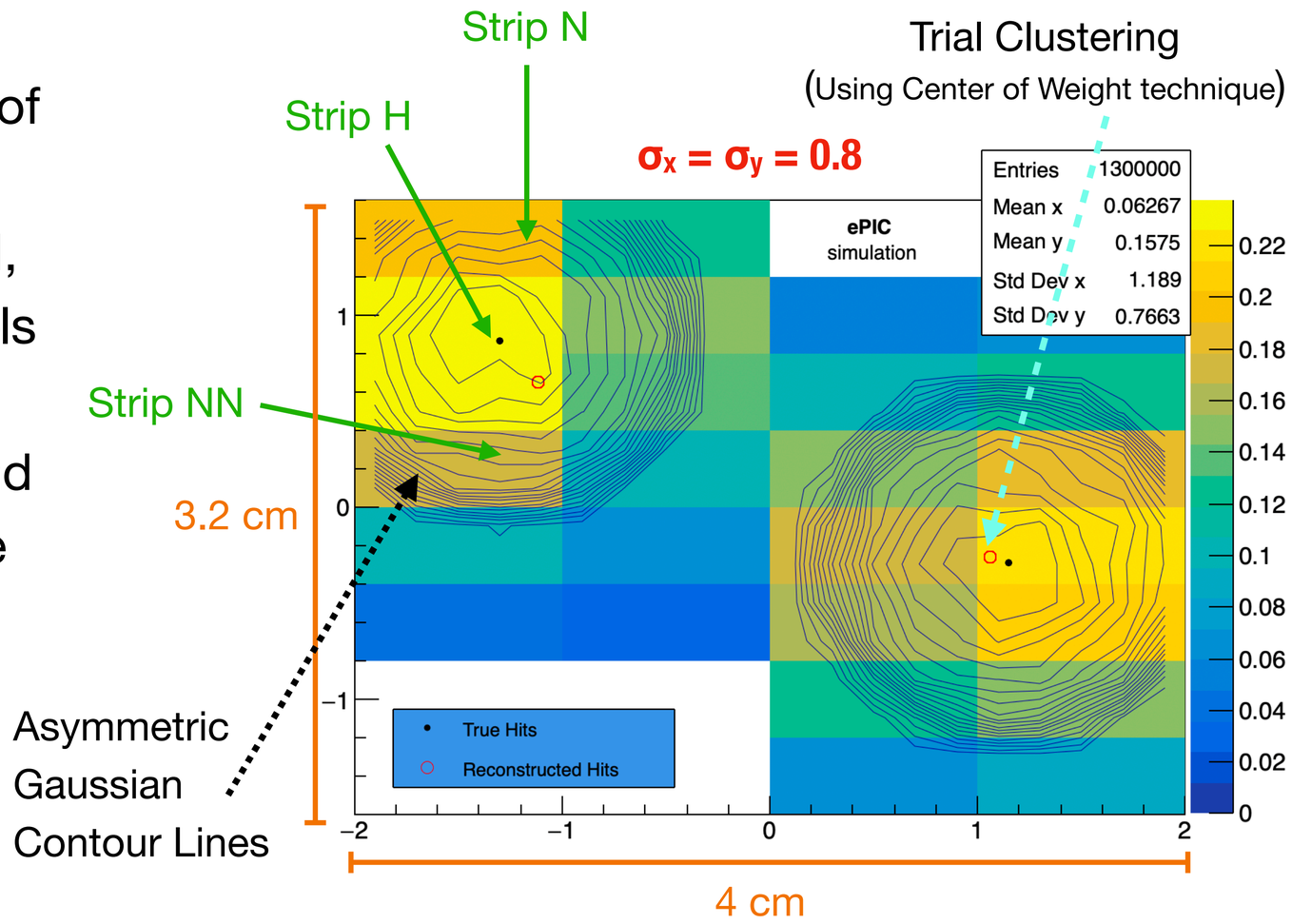




Time of Flight ⊕ Rise Time ⟶ Time of Arrival ⟶ TDC

Charge Sharing

- A hit in Strip H has a Gaussian-like distribution of charge vs distance.
- Strip H induces charge to the centers of Strip N, NN, NNN, … (depending on the number of pixels in the sensor) in a Gaussian manner.
- 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) and optimized.
- The maximum distance to which Pixel H can induce charge can also be limited.



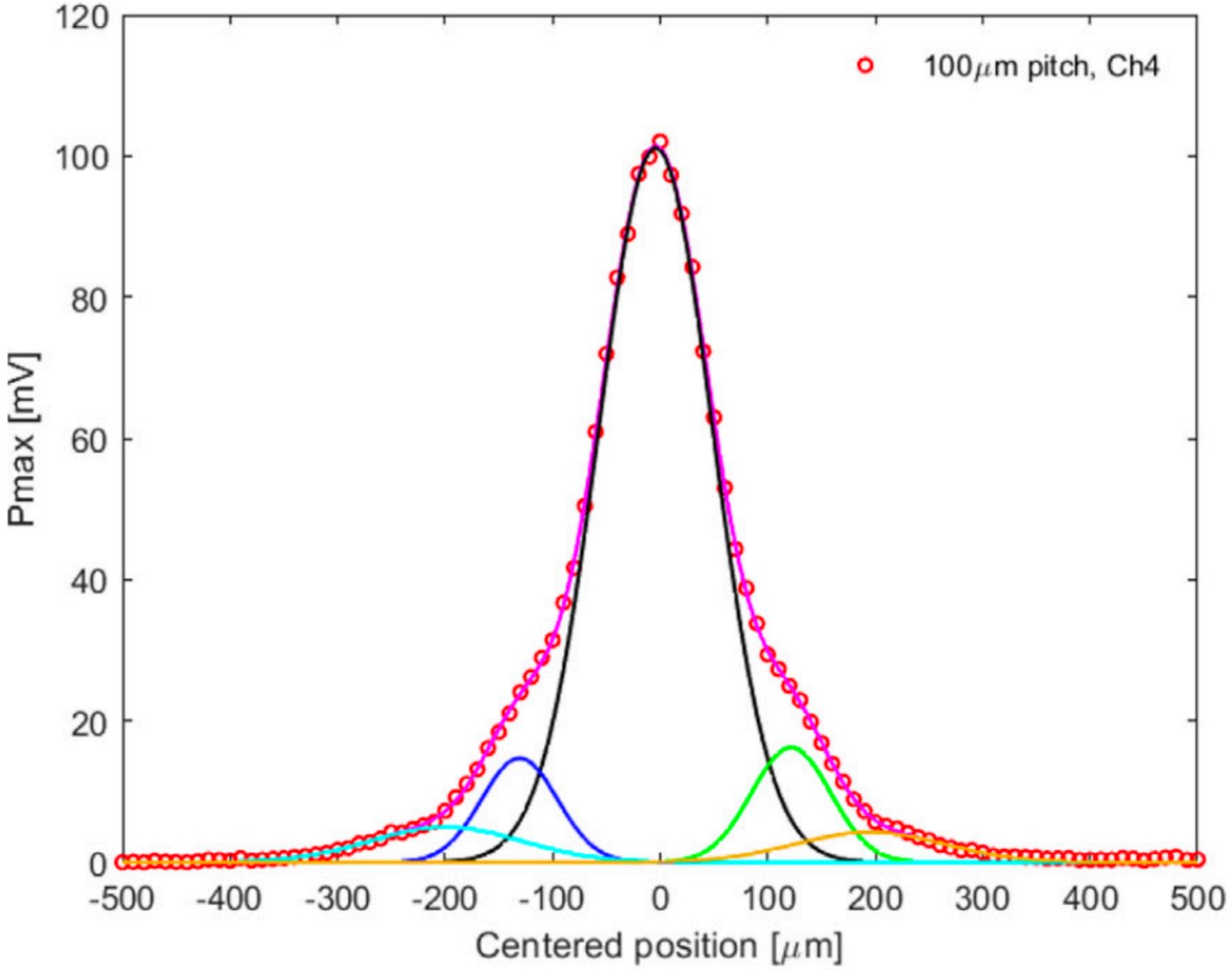
Each AC-LGAD strip sensor has 8X4 = 32 channels

- A hit in a pixel sensor also has a Gaussian-like distribution of charge vs distance, but is symmetric in X and Y, for the same standard deviation in X and Y.

Barrel ToF	→	Strip Sensor
Endcap ToF	→	Pixel Sensor

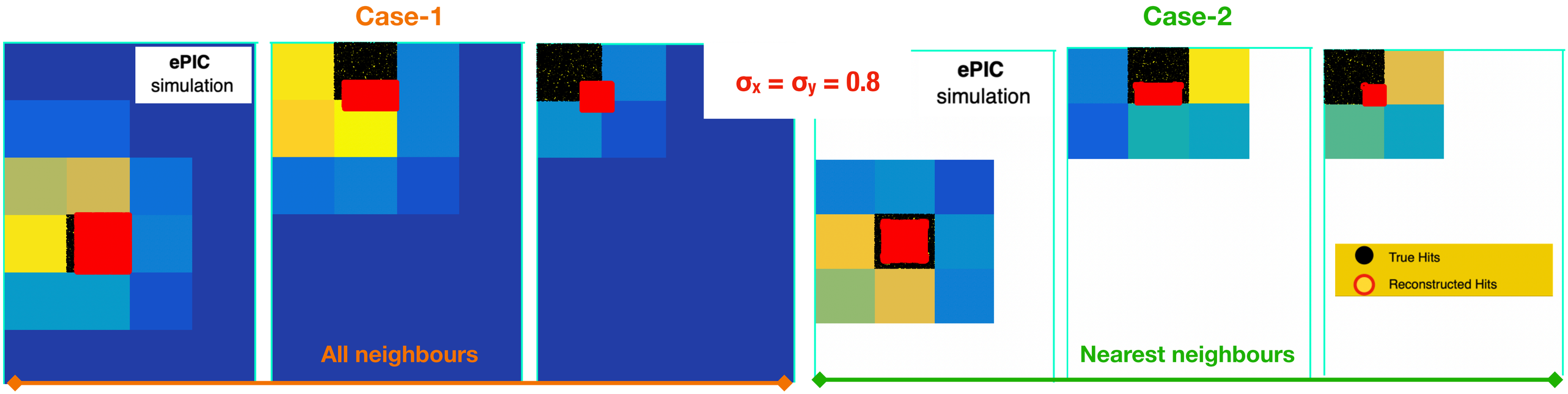
Data-driven Simulation

https://doi.org/10.1016/j.nima.2022.167541



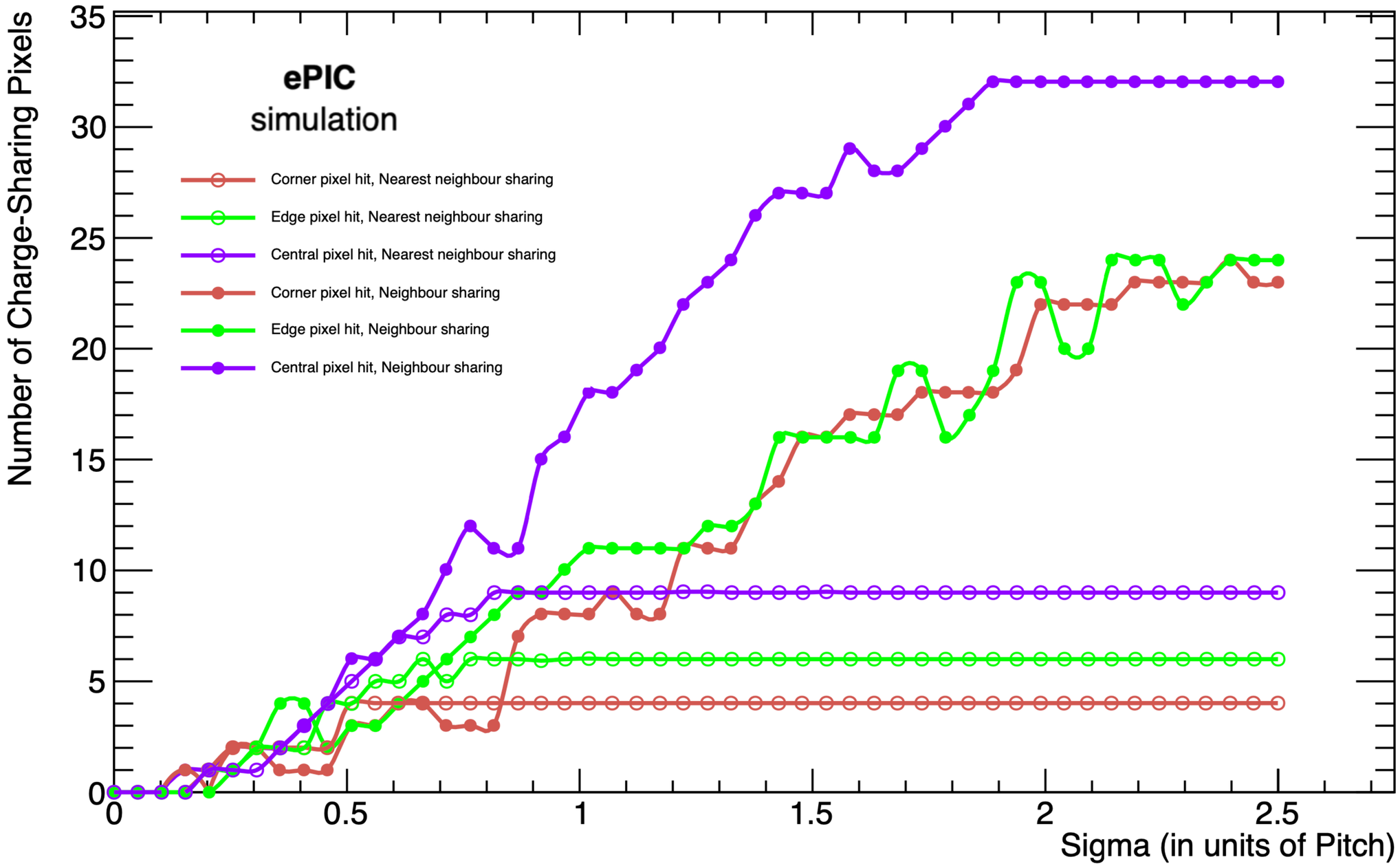
Gaussian profile of charge sharing for AC-LGAD test beam measurements with laser.

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.

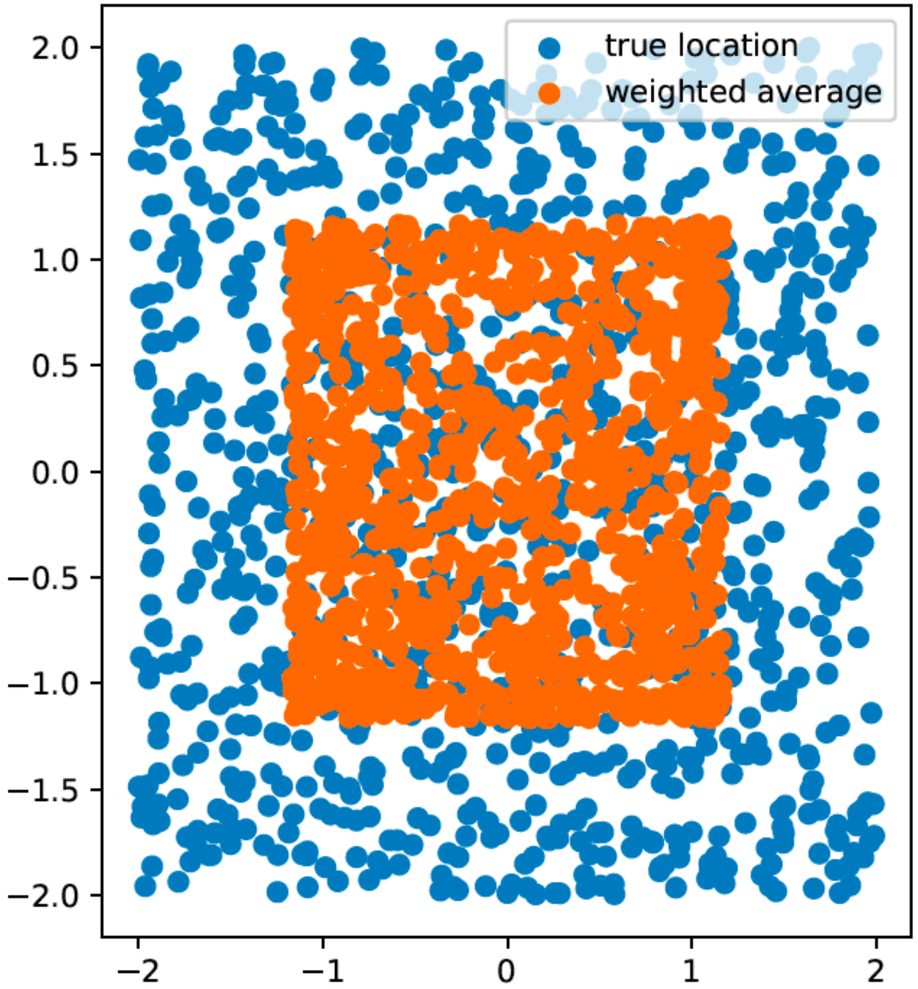
Charge Sharing: Geometric effects contd.



Charge Sharing: Reconstruction Technique Comparison

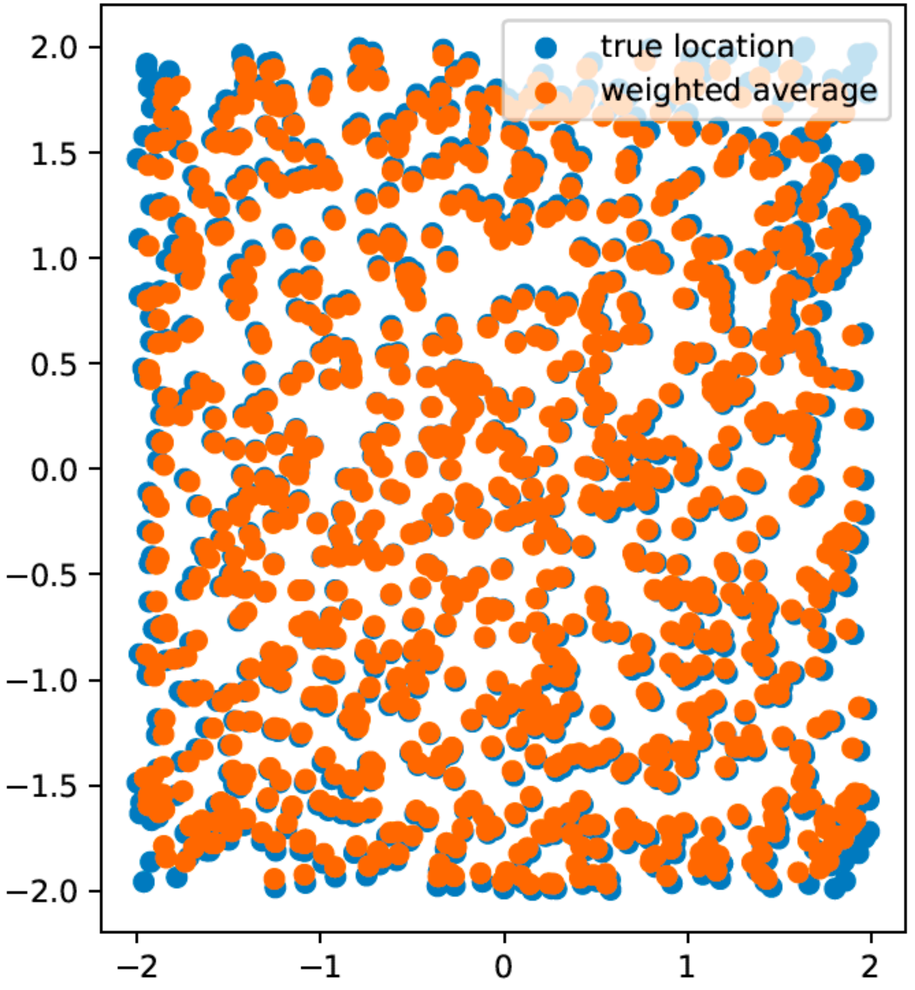
Courtesy of *Tommy Tsang*

Center of Weight technique



Reconstruction accuracy remains constant with σ.

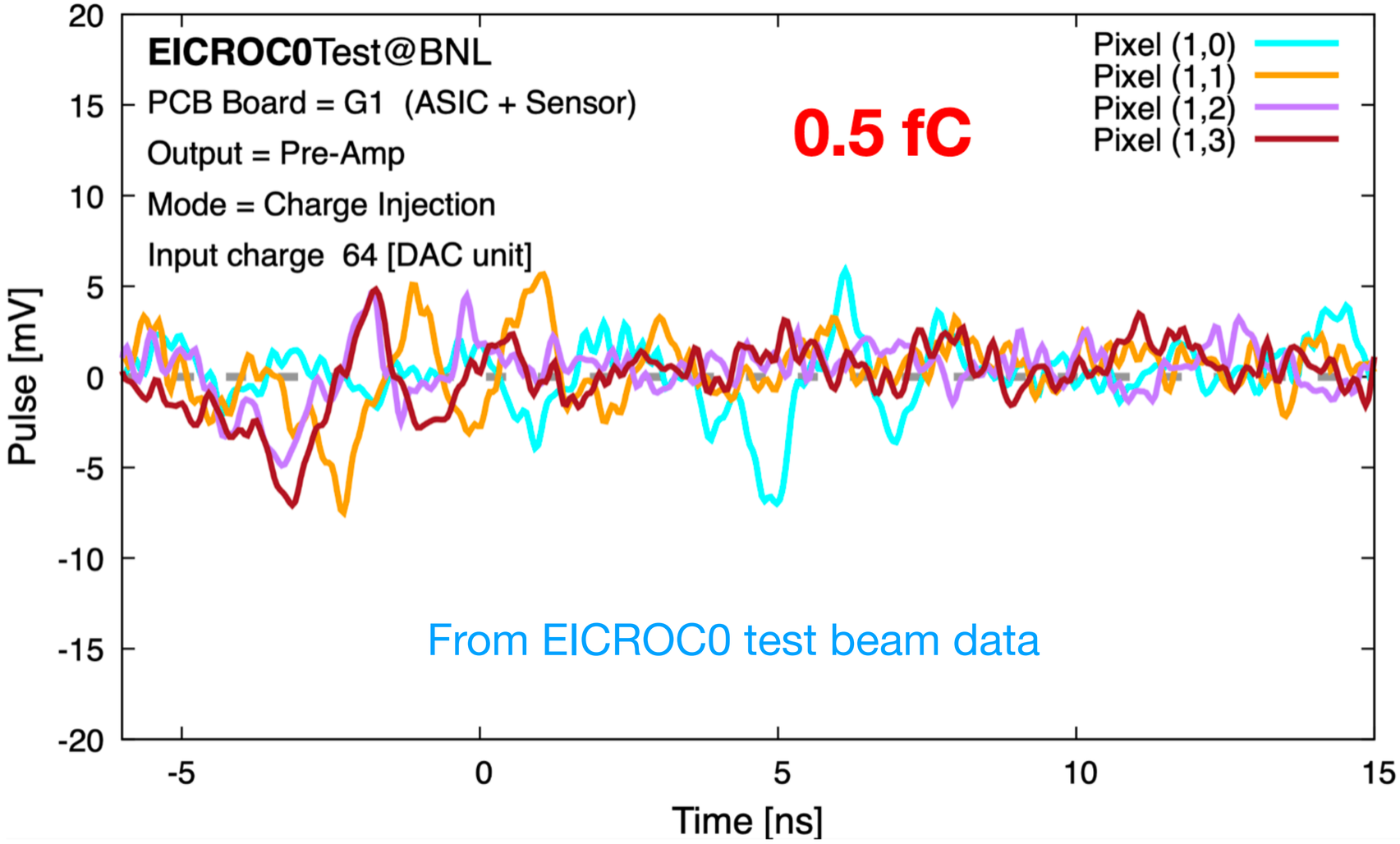
AI/ML reconstruction technique



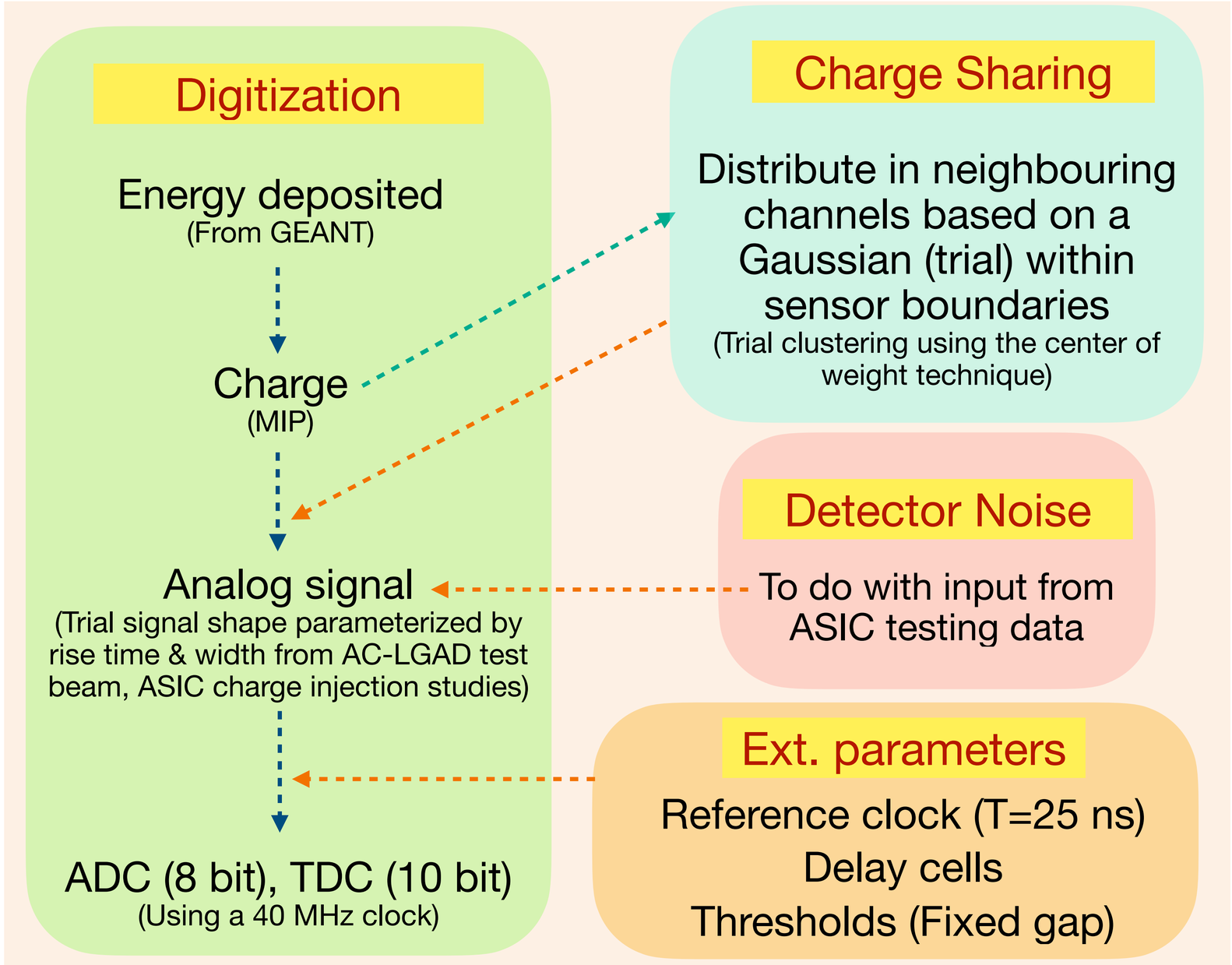
Reconstruction accuracy worsens with increasing σ.

Noise

- EICROC0 test beam data for lowest charge injected into an ASIC is a candidate to model noise.
- Separation of signals and noise by in-time and out-of-time will be achieved for a more precise reconstruction.



Summary & Future Work

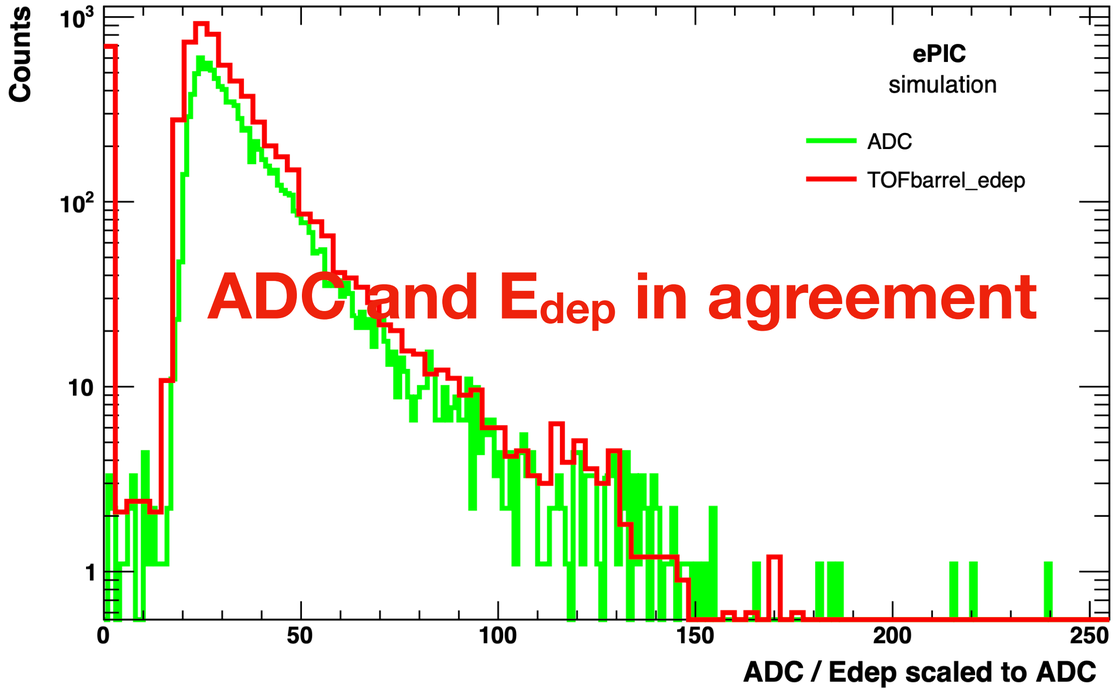


Future Plan:

1. Delay correction.
2. Spatial resolution studies (Comparison of standard deviation of X_{true}-X_{reco} and X_{true}-X_{digi} with $\sigma_{th}/\sqrt{12}$).
3. Effect of different charges on charge-sharing.
4. Incorporating realistic noise.
5. Implementation of local work on digitization in ePIC simulation framework.

THANK YOU

BACKUP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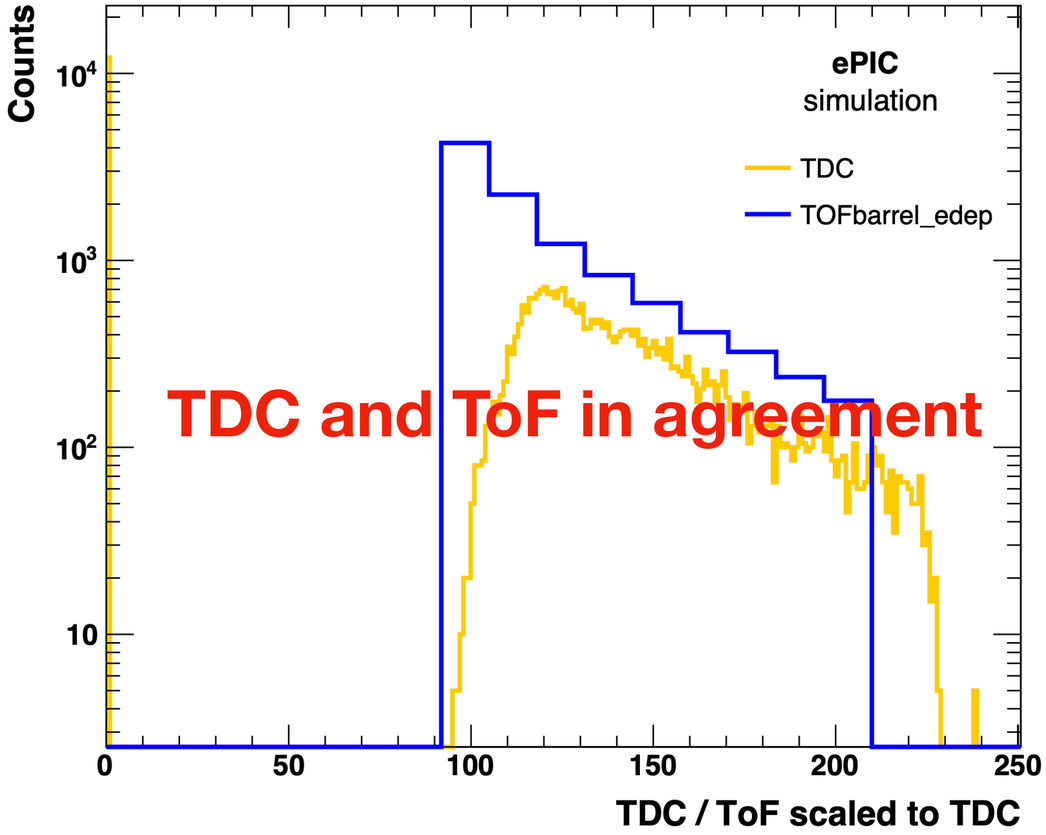
10^3
10^2
10
1
0
50
100
150
200
250
ADC / Edep scaled to ADC
ePIC
simulation
ADC
TOFbarrel_edep
ADC and E_{dep} in agreement


Counts
10^4
10^3
10^2
10
0
50
100
150
200
250
TDC / ToF scaled to TDC
ePIC
simulation
TDC
TOFbarrel_edep
TDC and ToF in agreement