AC-LGAD readout chain & digitization

Project Goal: Completing the readout chain for an AC-LGAD based ePIC systems, implement digitization in EICRecon

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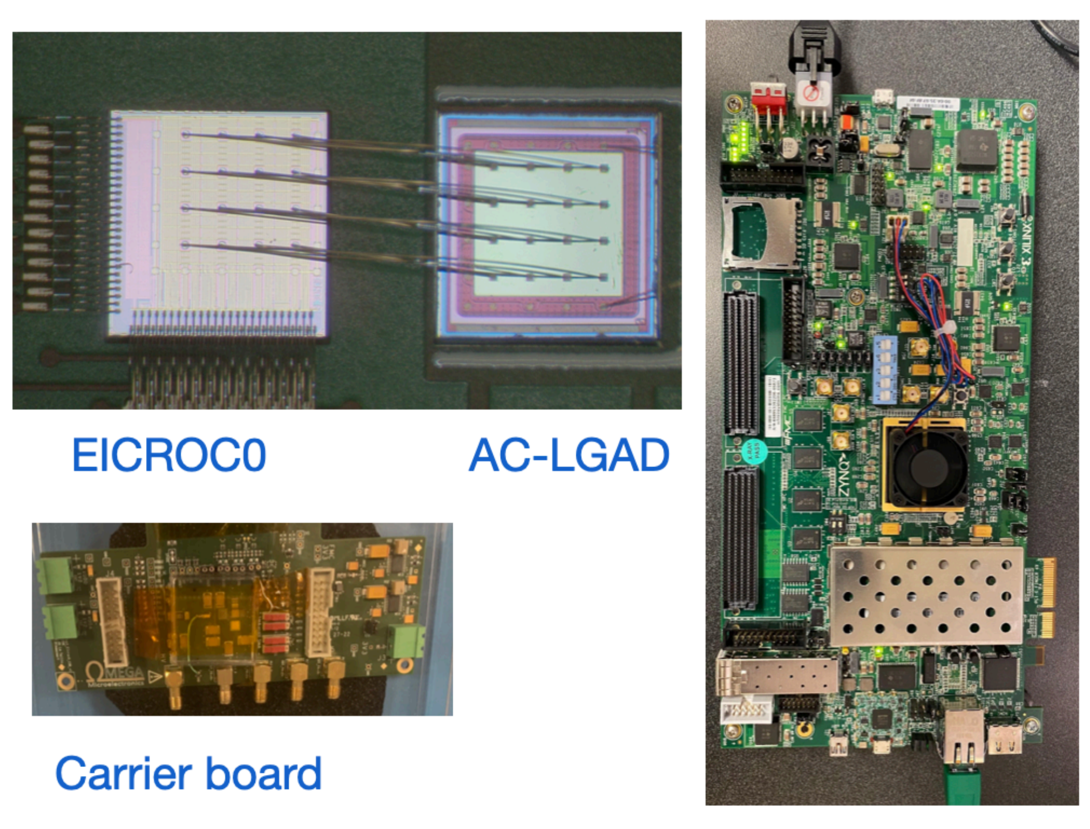

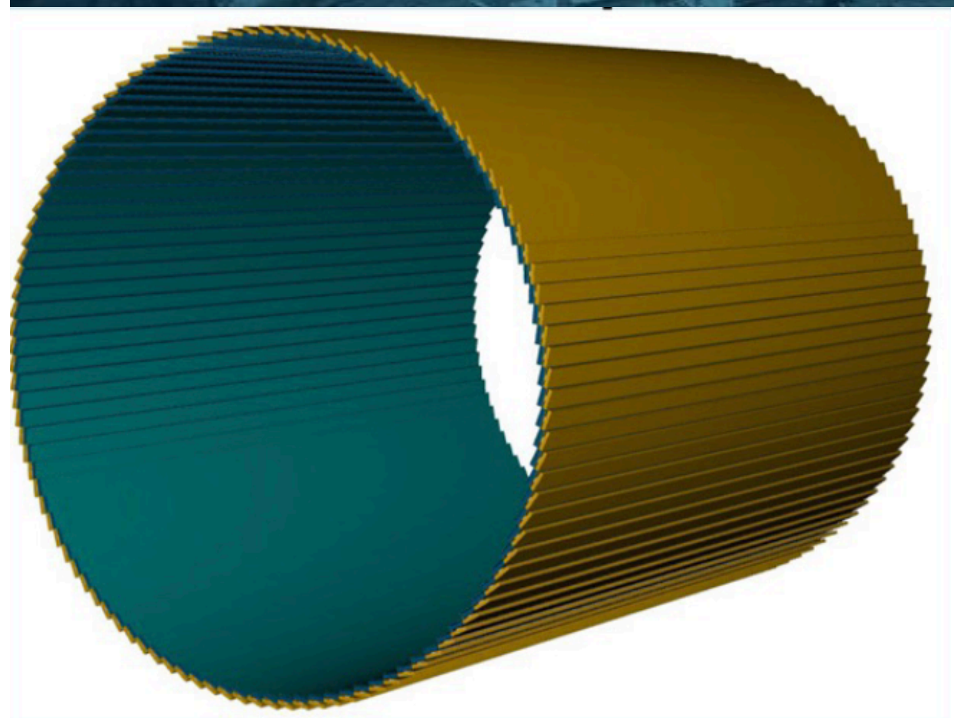

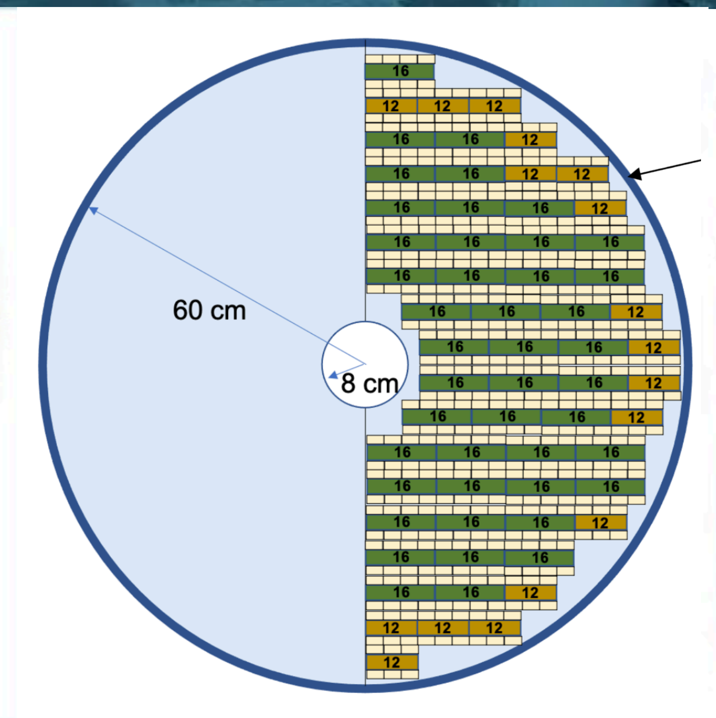

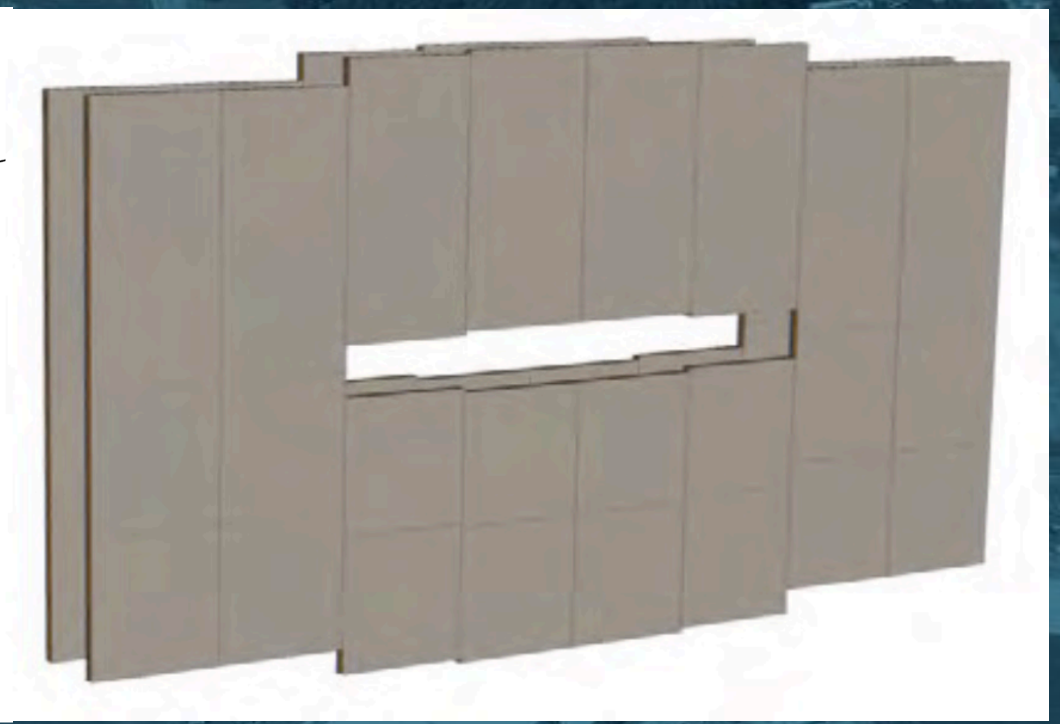

Other BNL collaborators:
Giacomini Gabriele (I/O),
External Collaborators:
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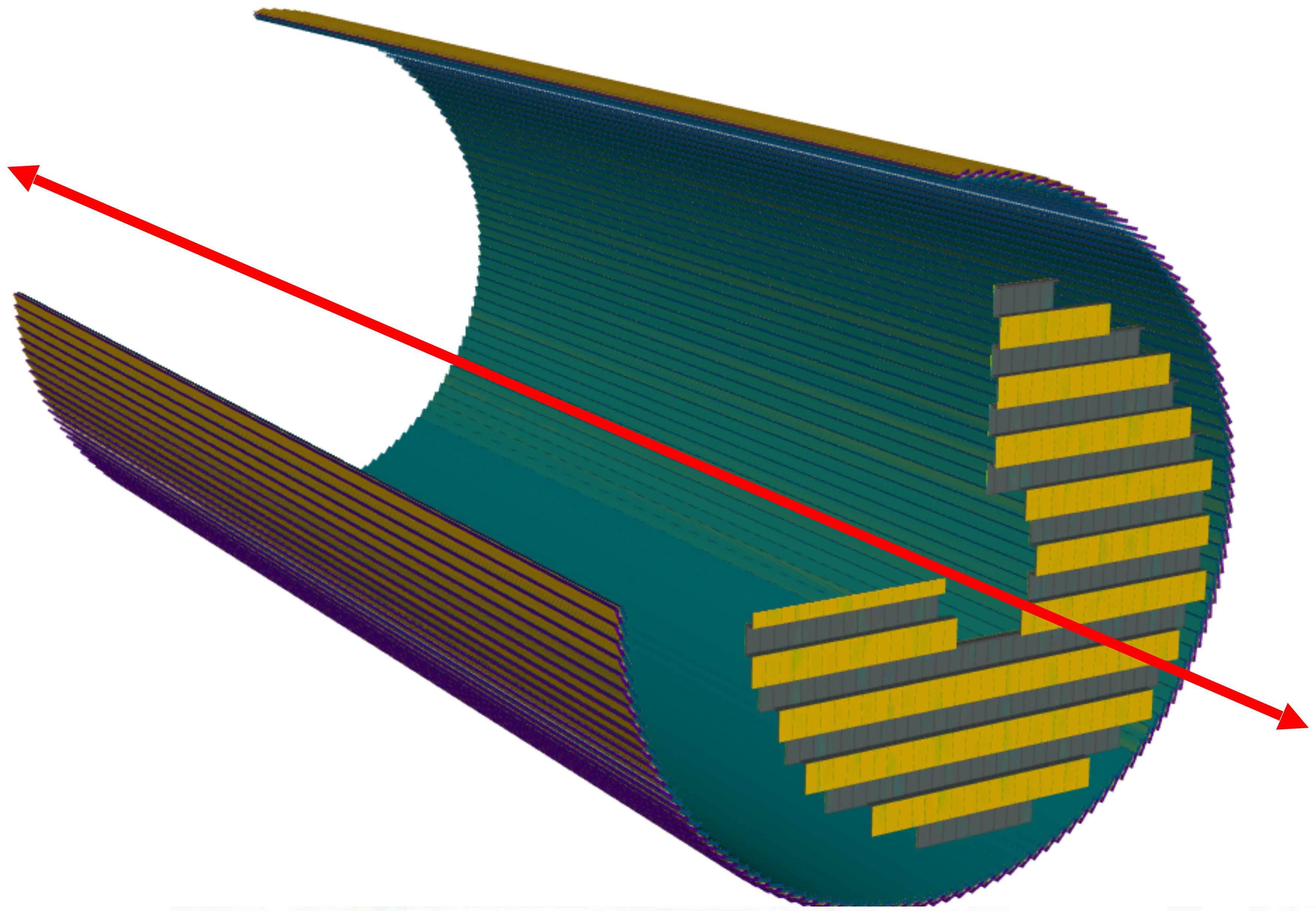
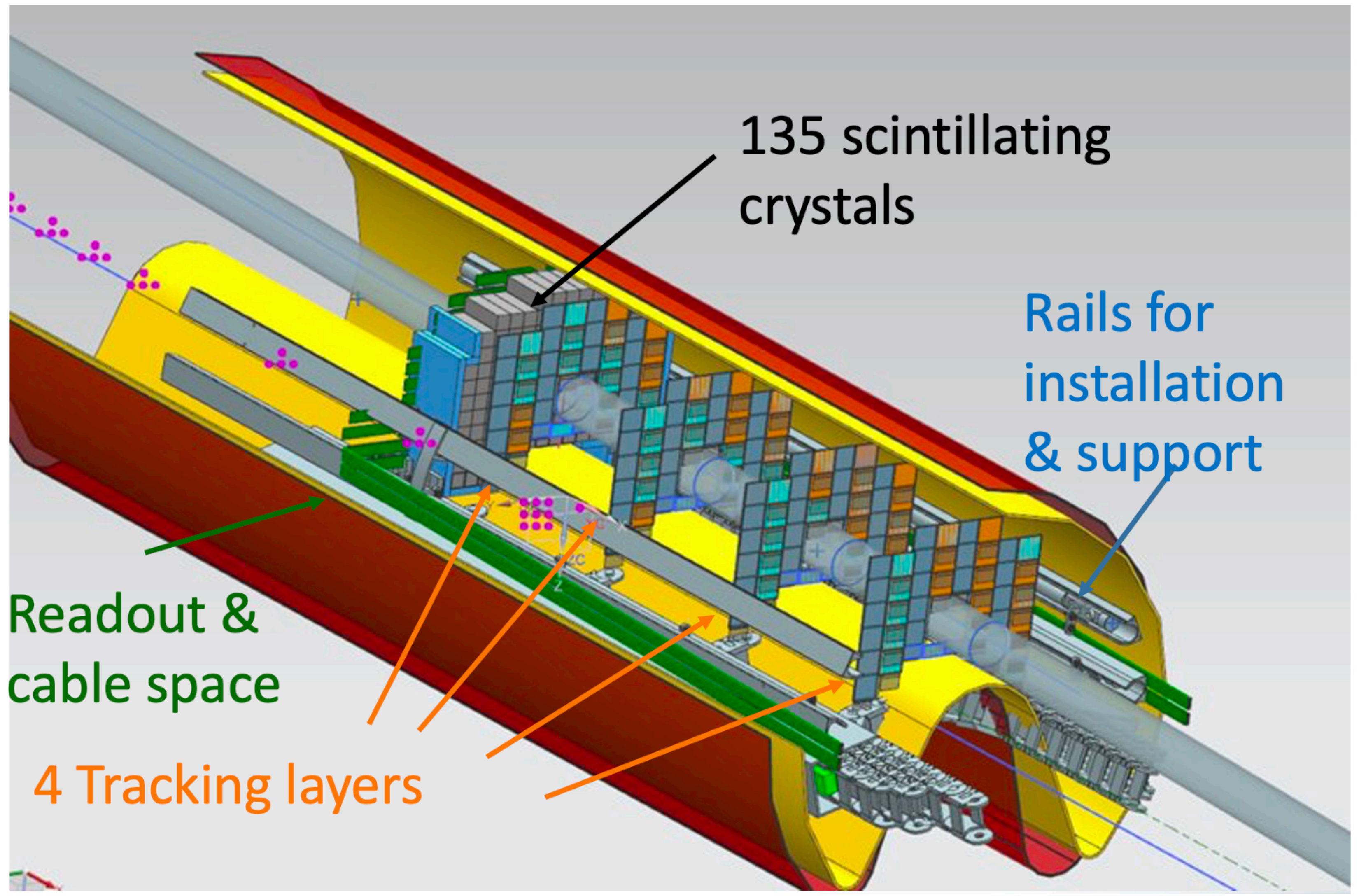
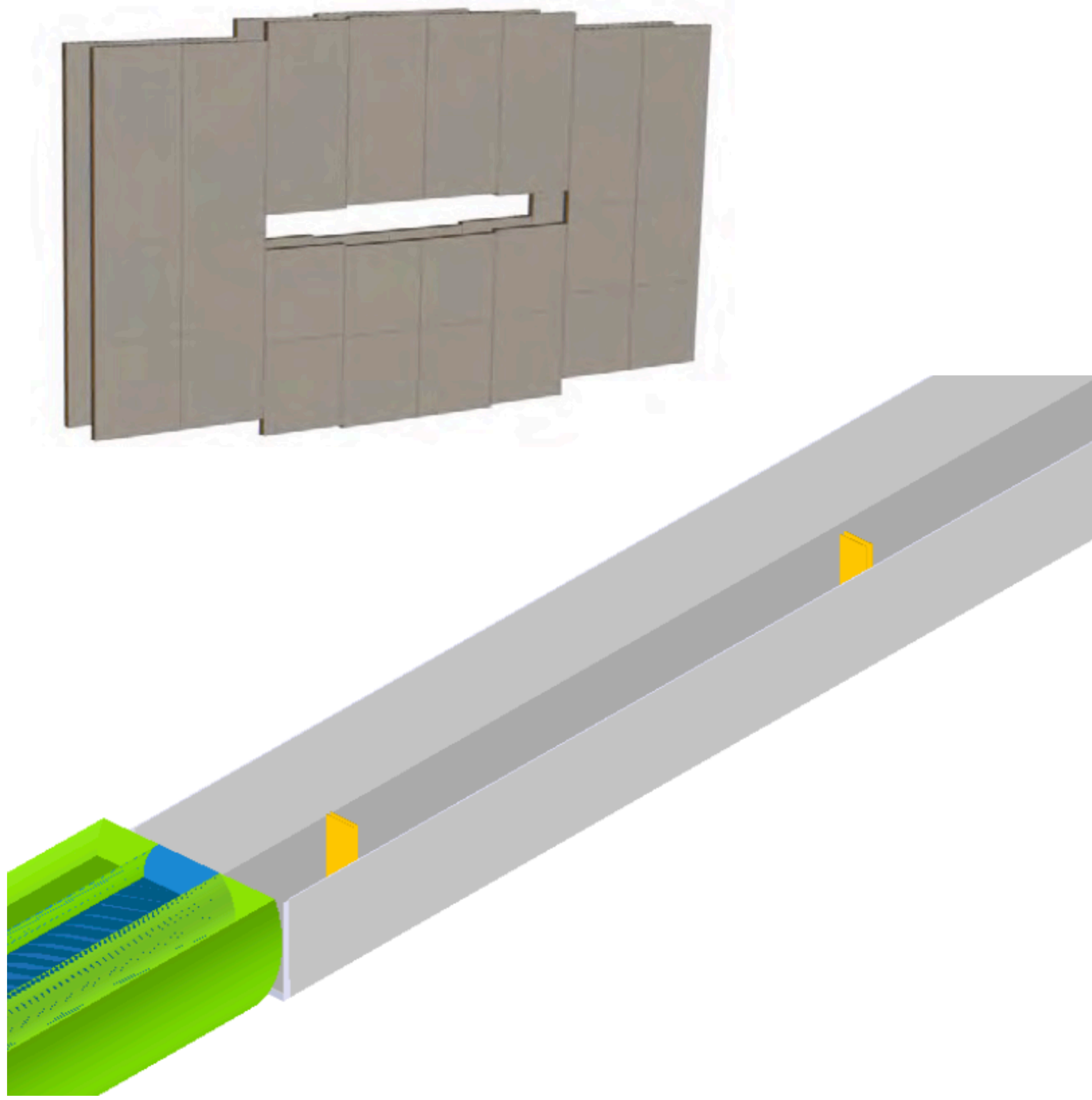
Tonko Ljubicic, Wei Li, Mike Matveev (Rice)
William Gu (JLab)
Satoshi Yano et al (Japan)
Tommy Tsang, Zhangbu Xu (Kent)
Zhenyu Ye (UIC/LBNL)

AC-LGAD applications at ePIC EIC

Six subsystems (BTOF, FTOF, B0 tracker, OMD, Roman Pots, Lumi mon so far will use AC-LGAD (1 using strip, 5 pixelated)







	Area (m^2)	Channel size (mm^2)	# of Channels	Timing Resolution	Spatial resolution	Material budget
Barrel TOF	10	0.5*10	2.4M	35 ps	30 μm in $r \cdot \varphi$	0.01 X_0
Forward TOF	1.4	0.5*0.5	5.6M	25 ps	30 μm in x and y	0.05 X_0
B0 tracker	0.07	0.5*0.5	0.28M	30 ps	20 μm in x and y	0.05 X_0
RPs/OMD	0.14/0.08	0.5*0.5	0.56M/0.32M	30 ps	140 μm in x and y	no strict req.
Lumi Tracker						

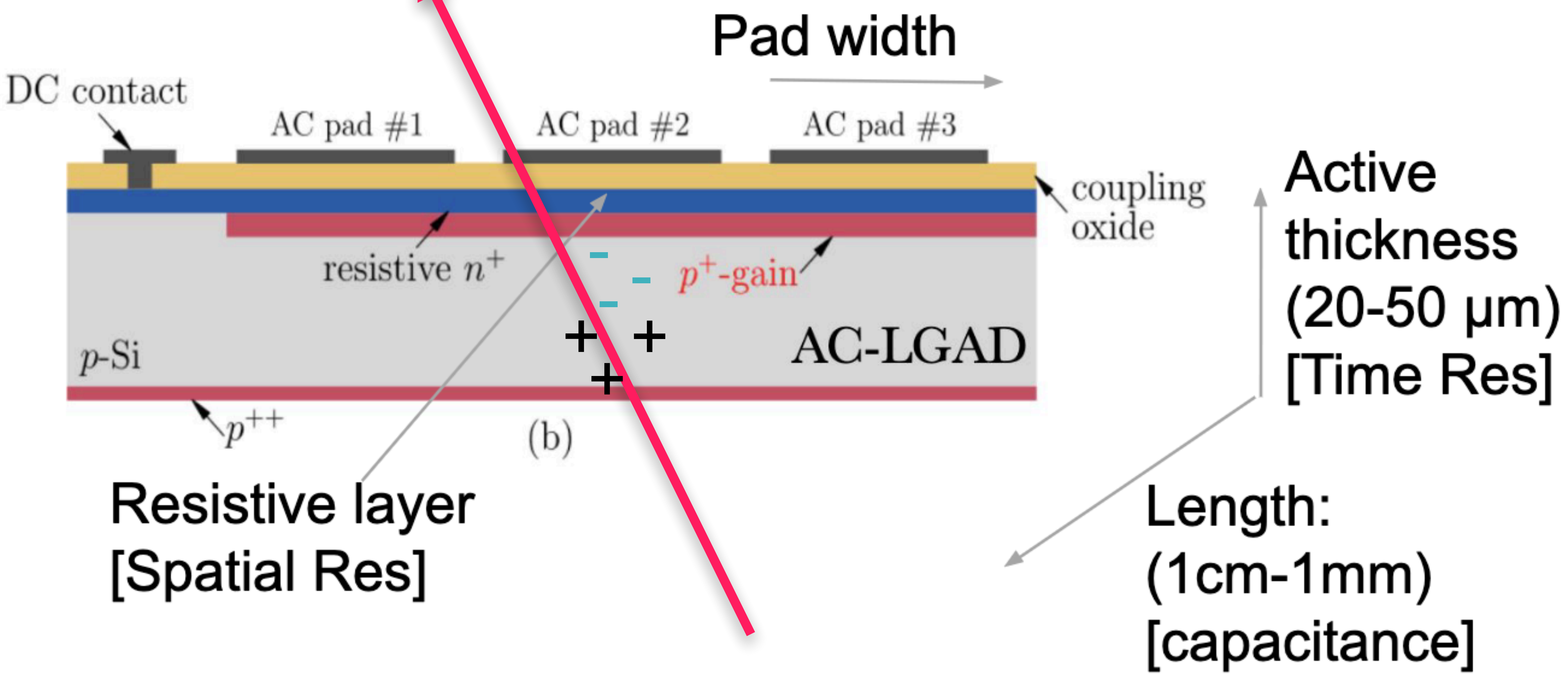
Exact dimension, sensor, dead area are under discussion:

BTOF: 128 staves (3.2x4 cm^2), FTOF: 736 sensors (1.6x1.6 cm^2)
Roman Pots: 128 (3.2x3.2 cm^2) units or 512 (1.6×1.6 cm^2) units

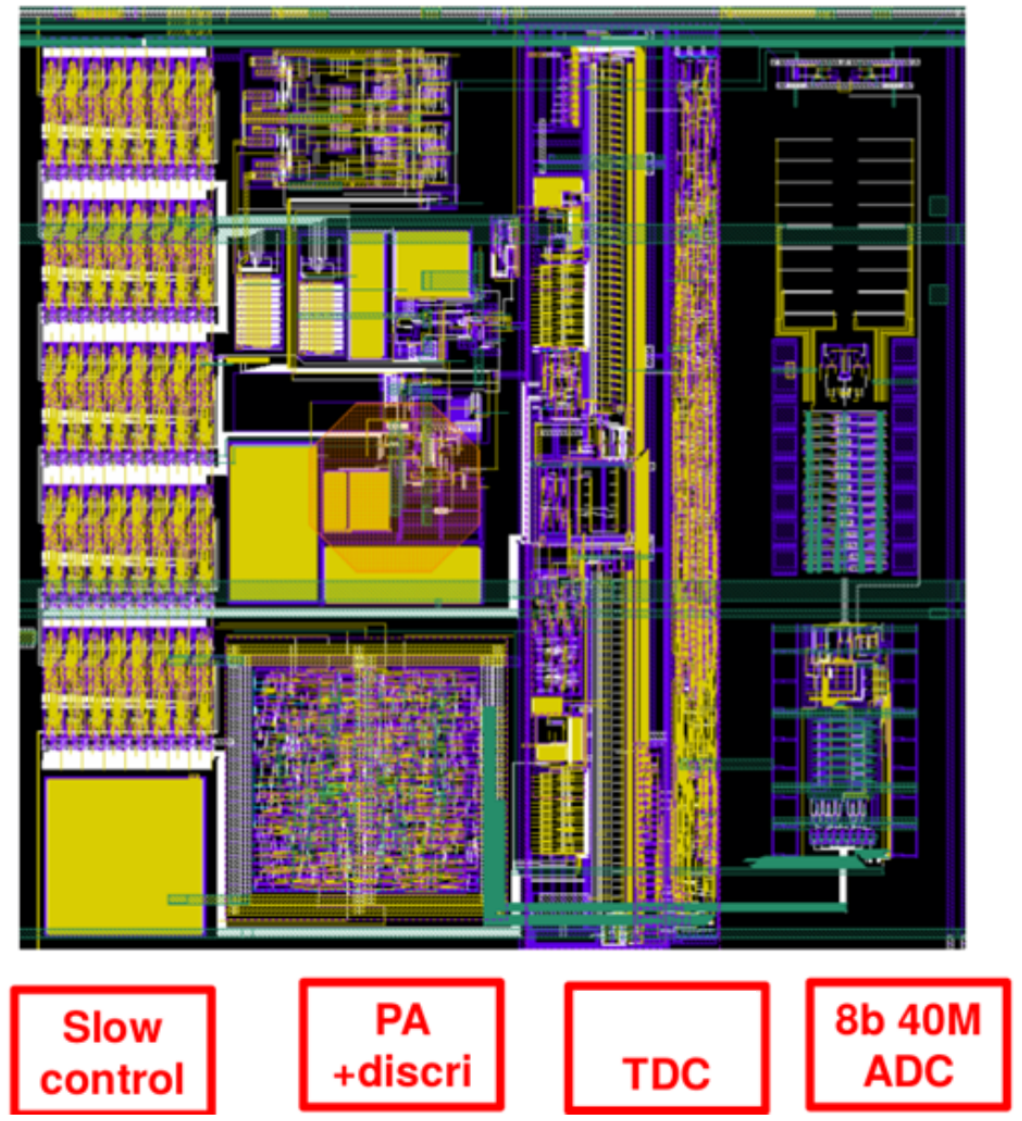
Off-Momentum detectors : 72 (3.2x3.2 cm^2) units or 288 (1.6×1.6 cm^2) units
BO tracking: 168 (3.2×3.2 cm^2) units or 672 (1.6×1.6 cm^2) units
Lumi-PS: 72 sensors (3.2×3.2 cm^2 units) or 288 (1.6×1.6 cm^2) units

AC-LGAD readout-chain (make it work)

Sensor



Front end options: EICROC/FCFD, fast, low-jitter, TDC, ADC enable

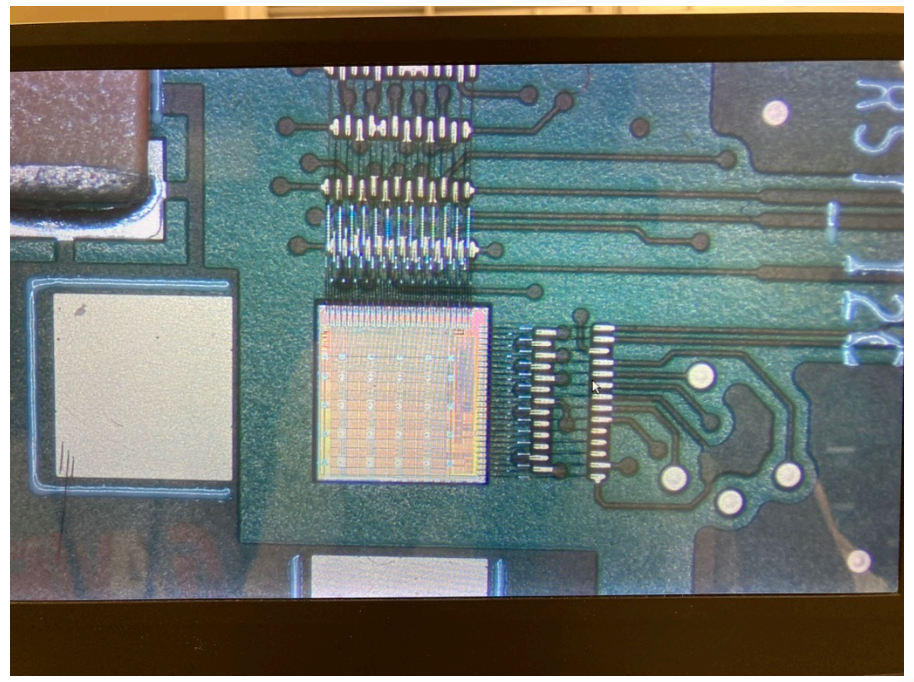


Now we have: EICROC0: 4x4
EICROC1 (2025): 16x8
EICROC (final): 32x32
10 bit TDC, 8 bit ADC

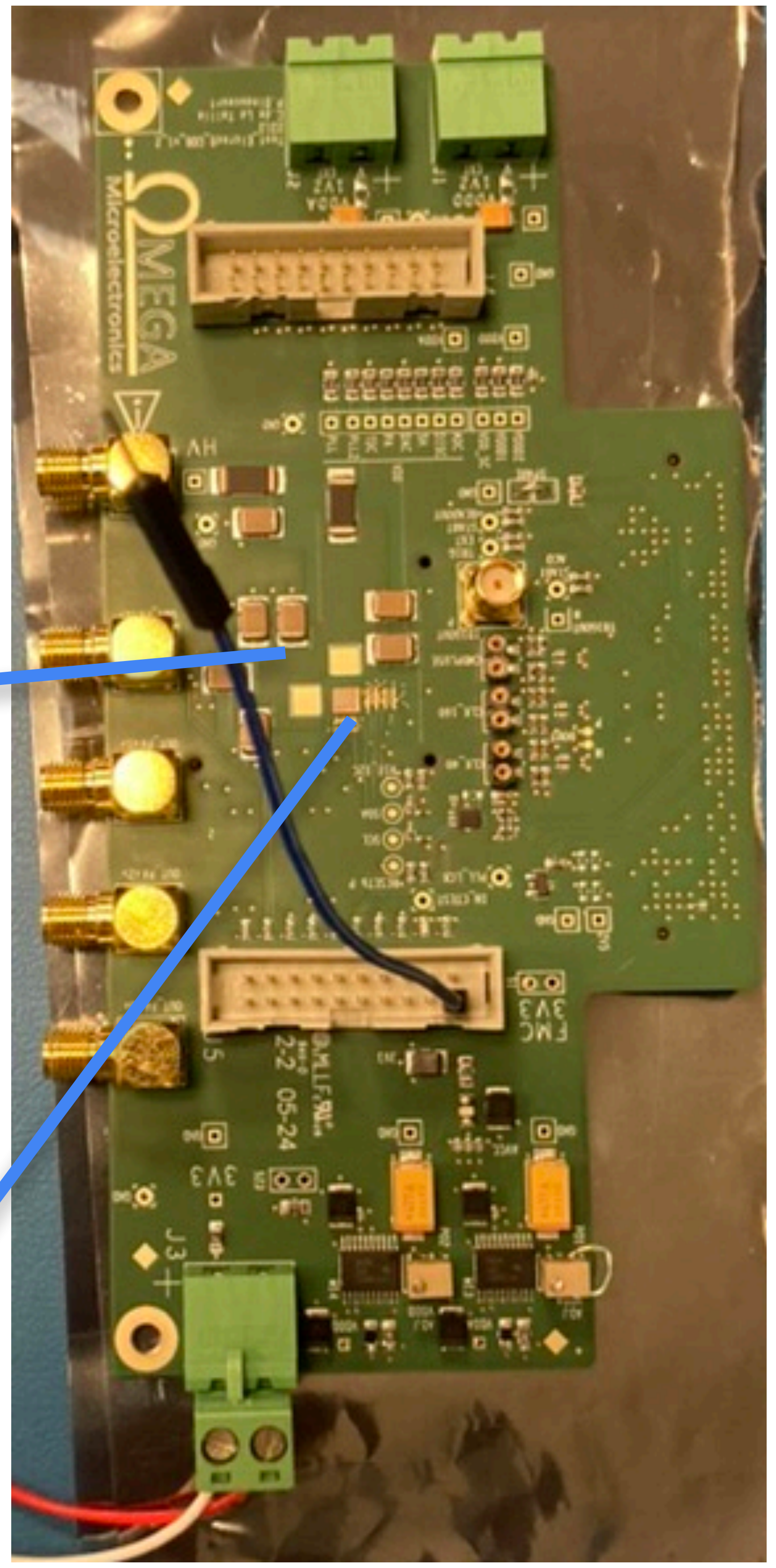
AC-LGAD: New tech, never used in any detector
very thin, fast, low noise, highly pixelated

BNL has lab that produces AC-LGAD sensors, HPK Japan can produce it, Taiwan can mass produce

Now we have: BNL 500 µm, 4x4 sensor

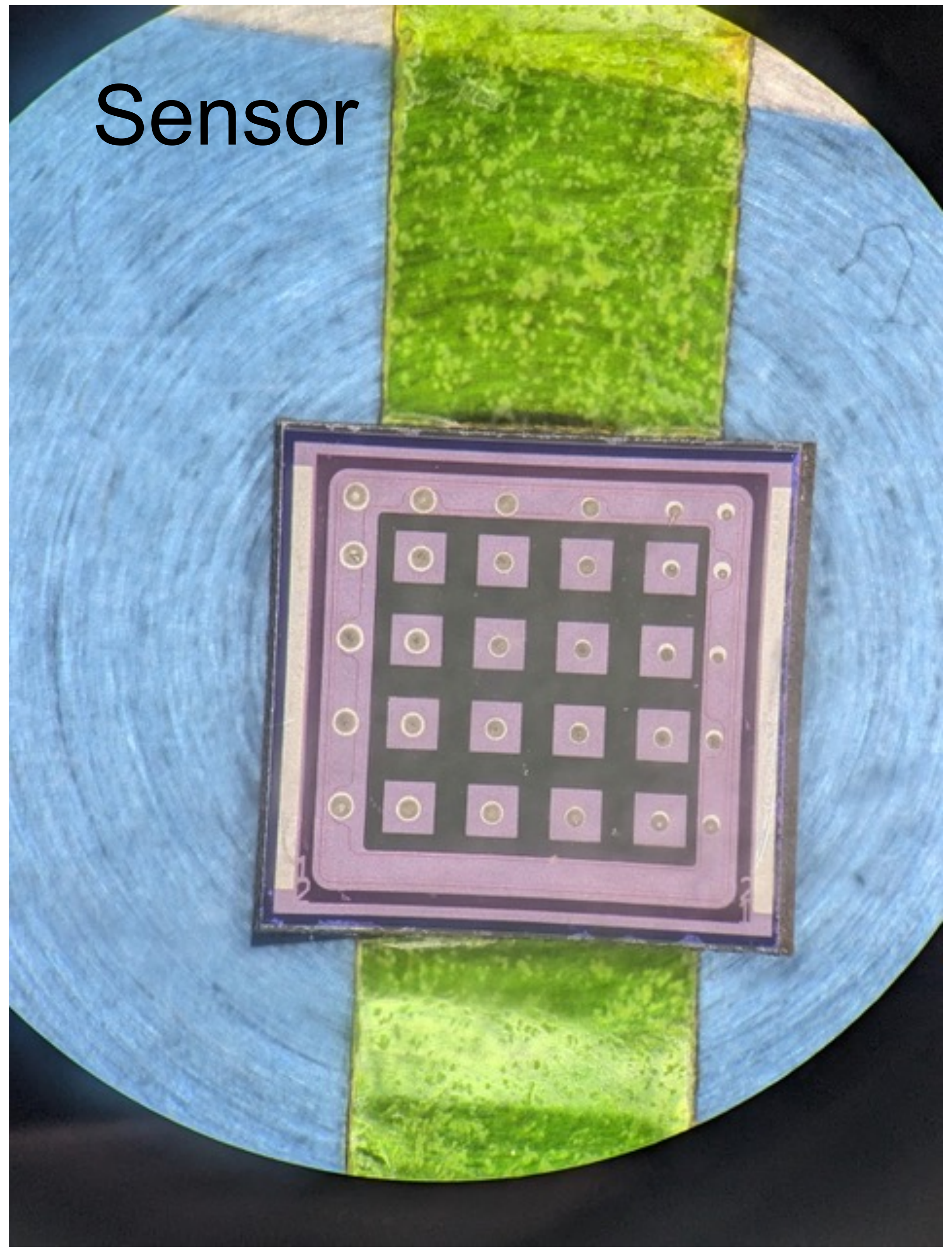


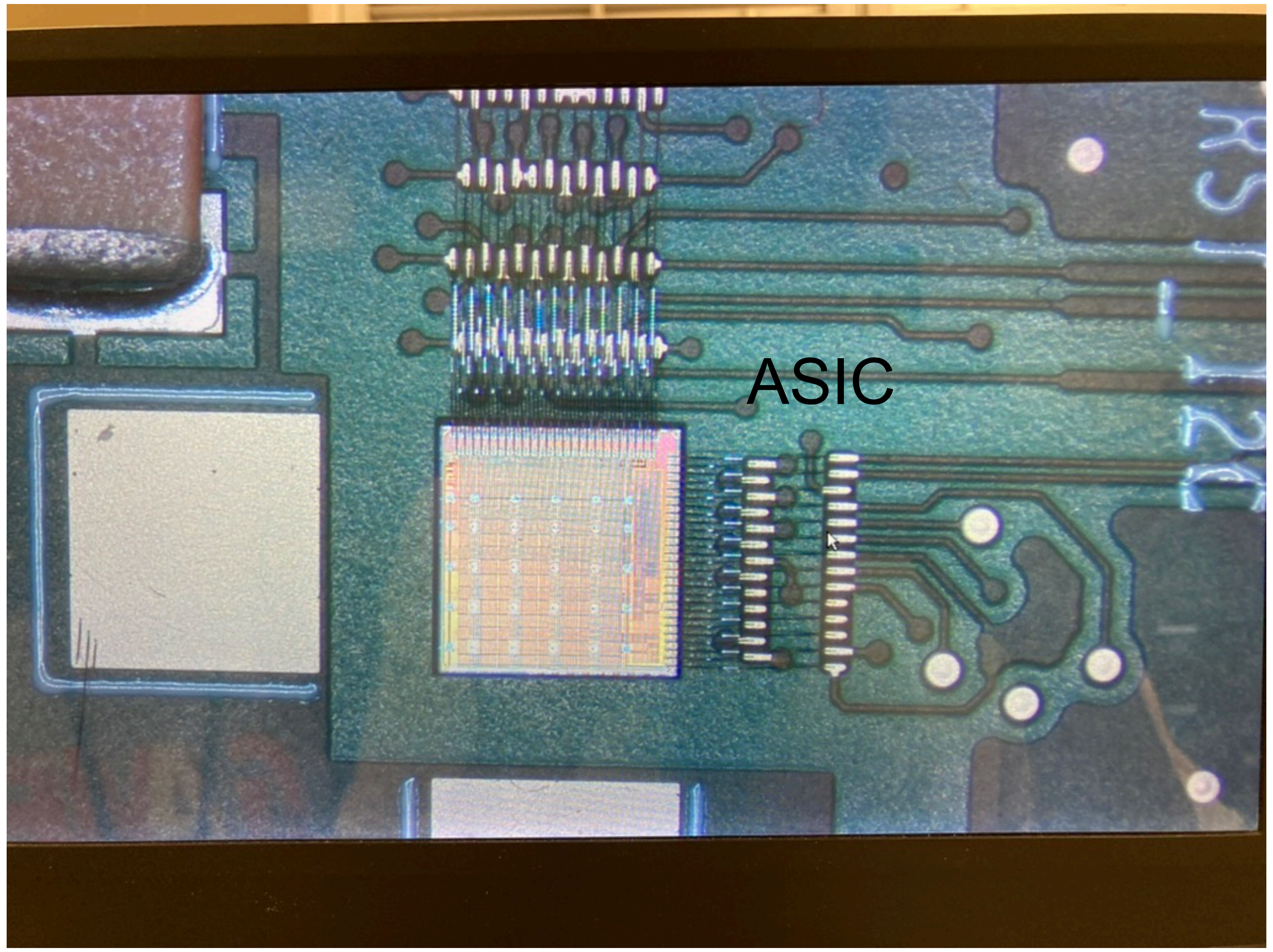
Slot for ASIC

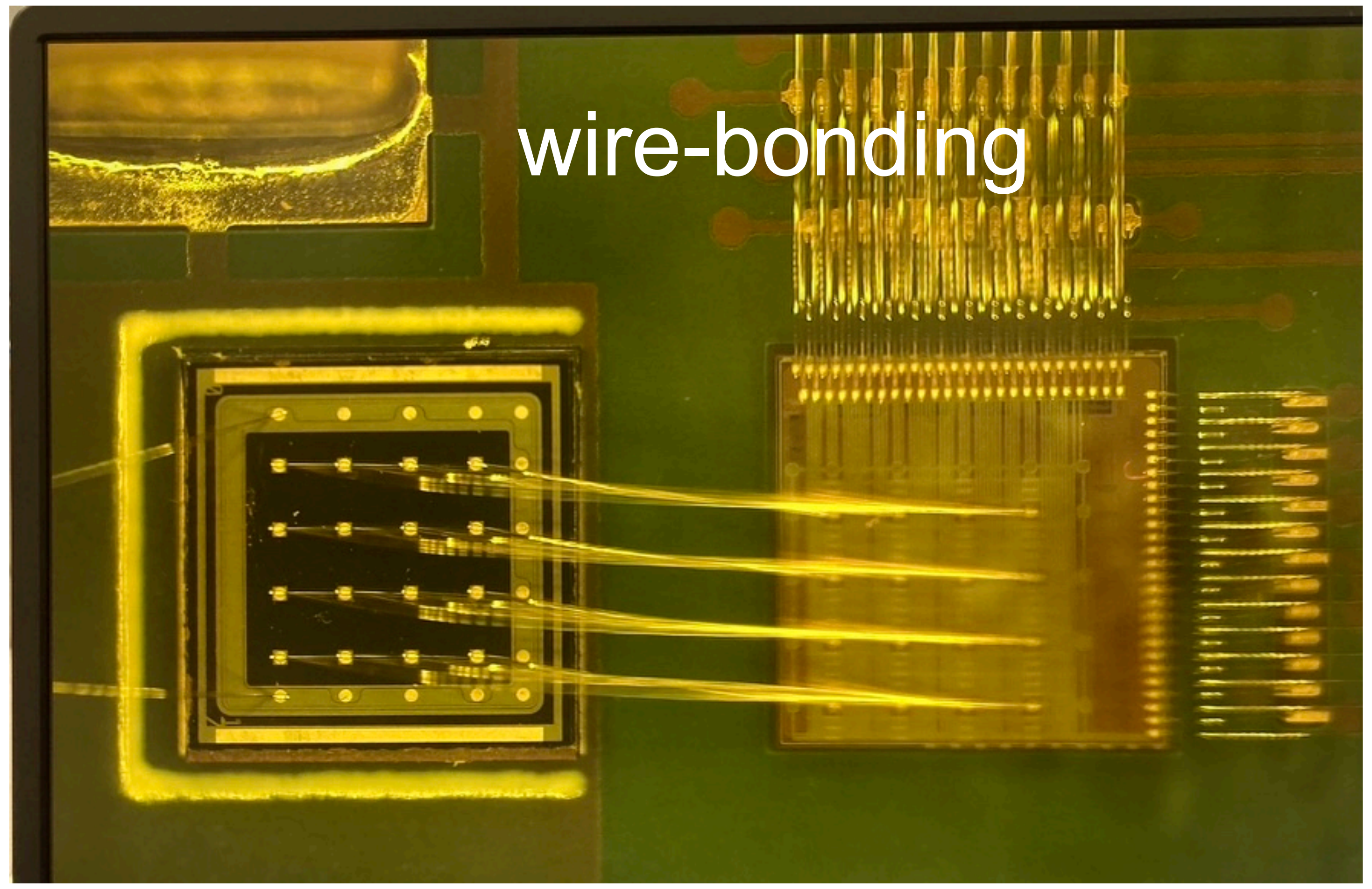


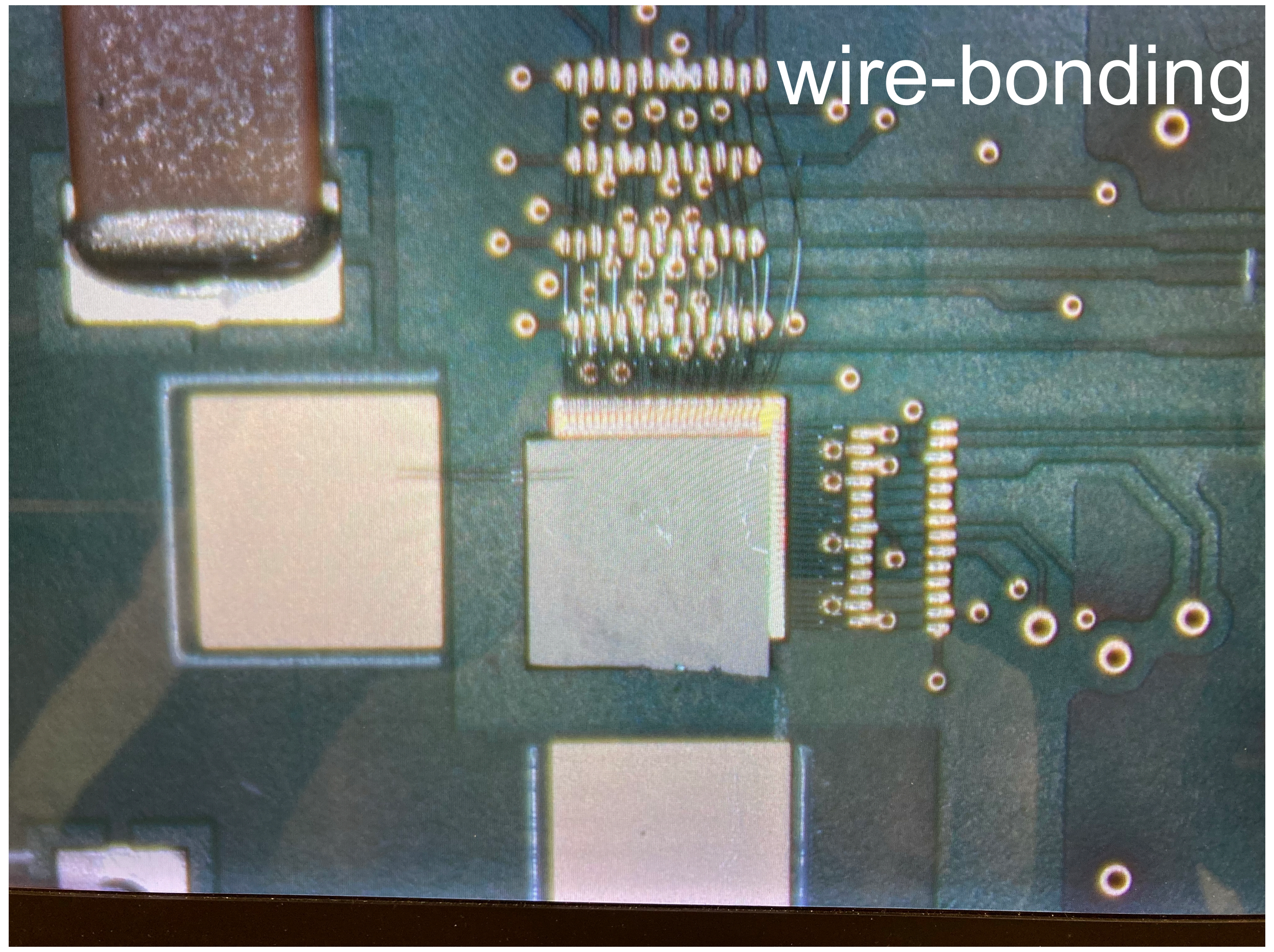
Carrier-board

Sensor-ASIC bonding



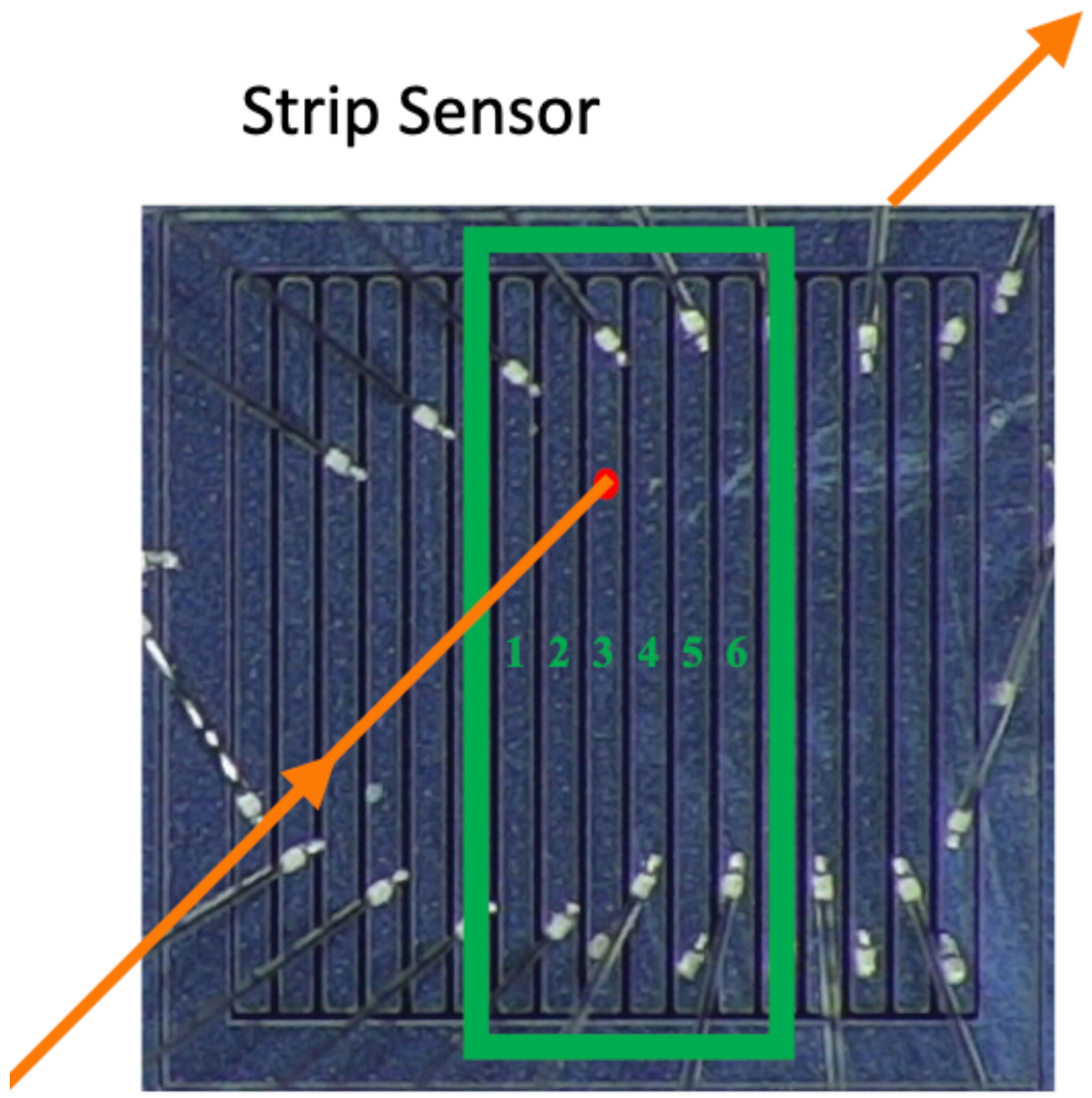




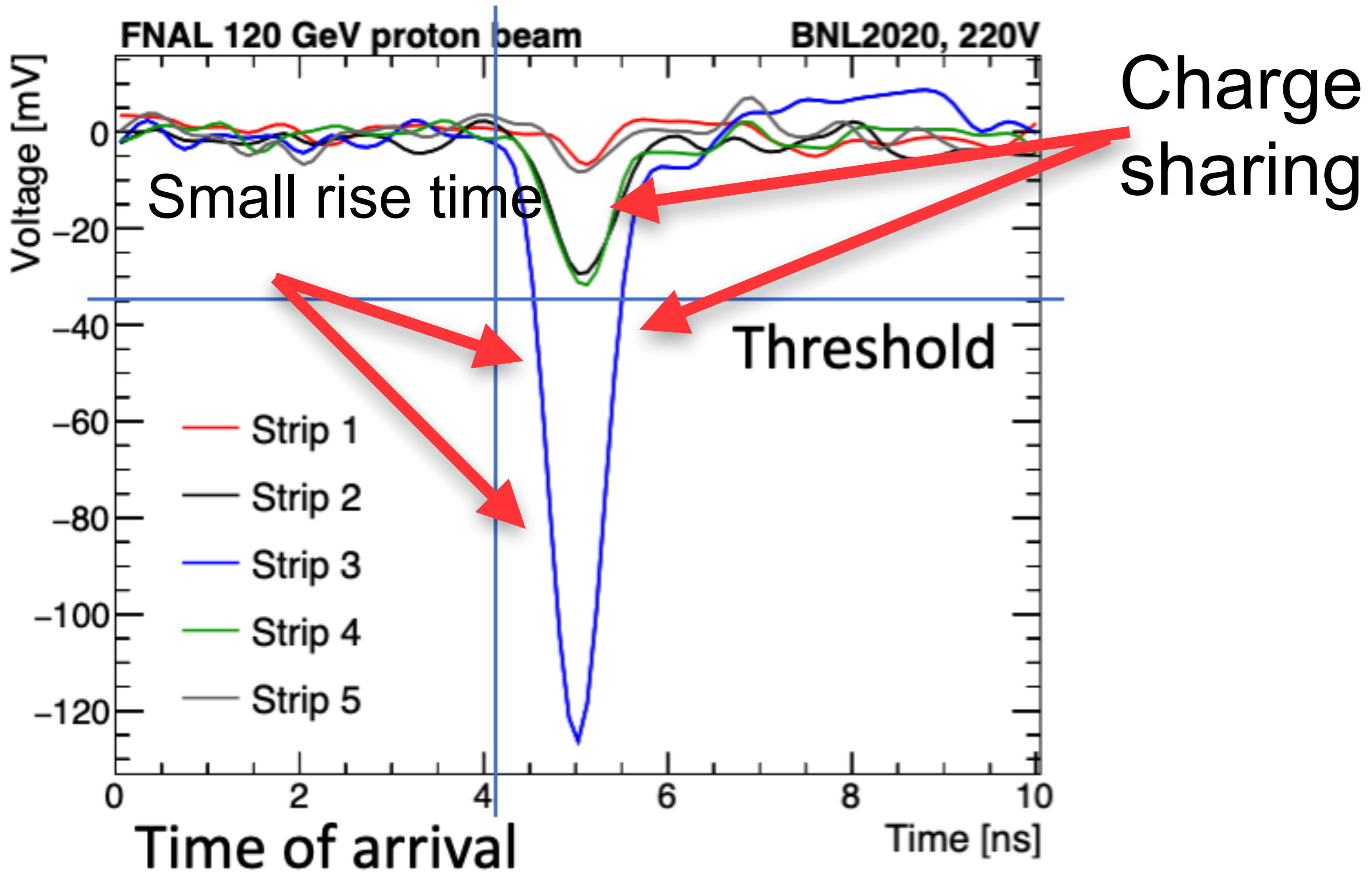


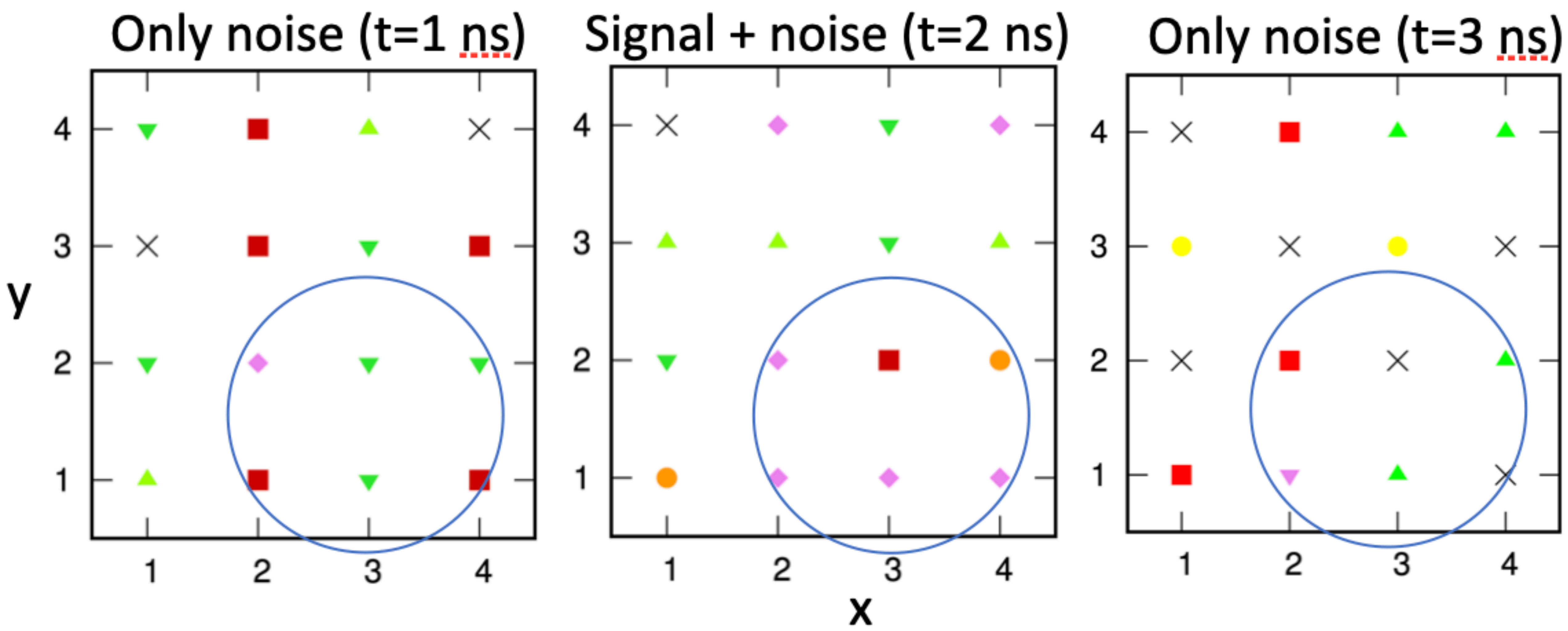
AC-LGAD based systems: pros, cons

Strip Sensor



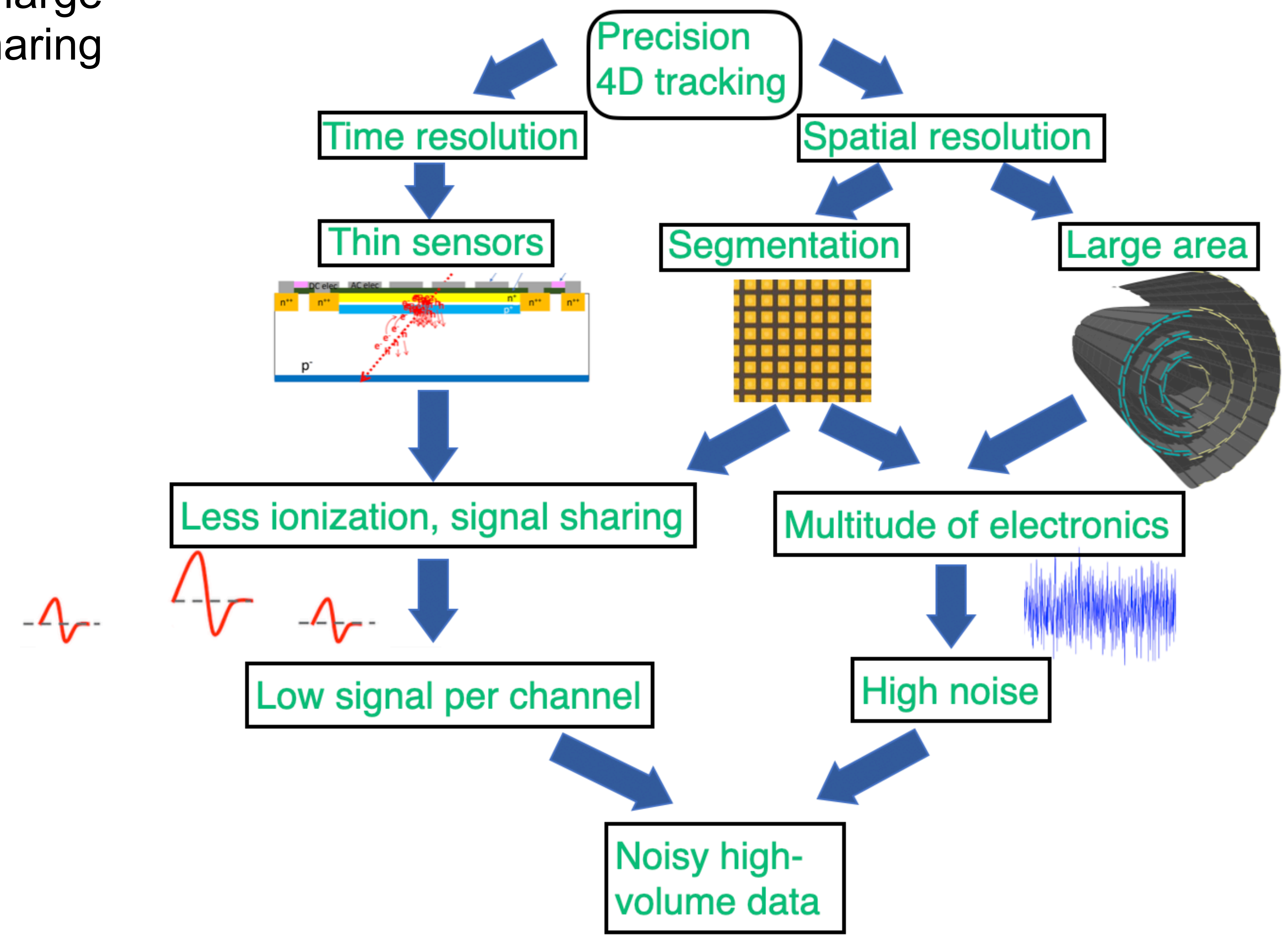
Analog signal





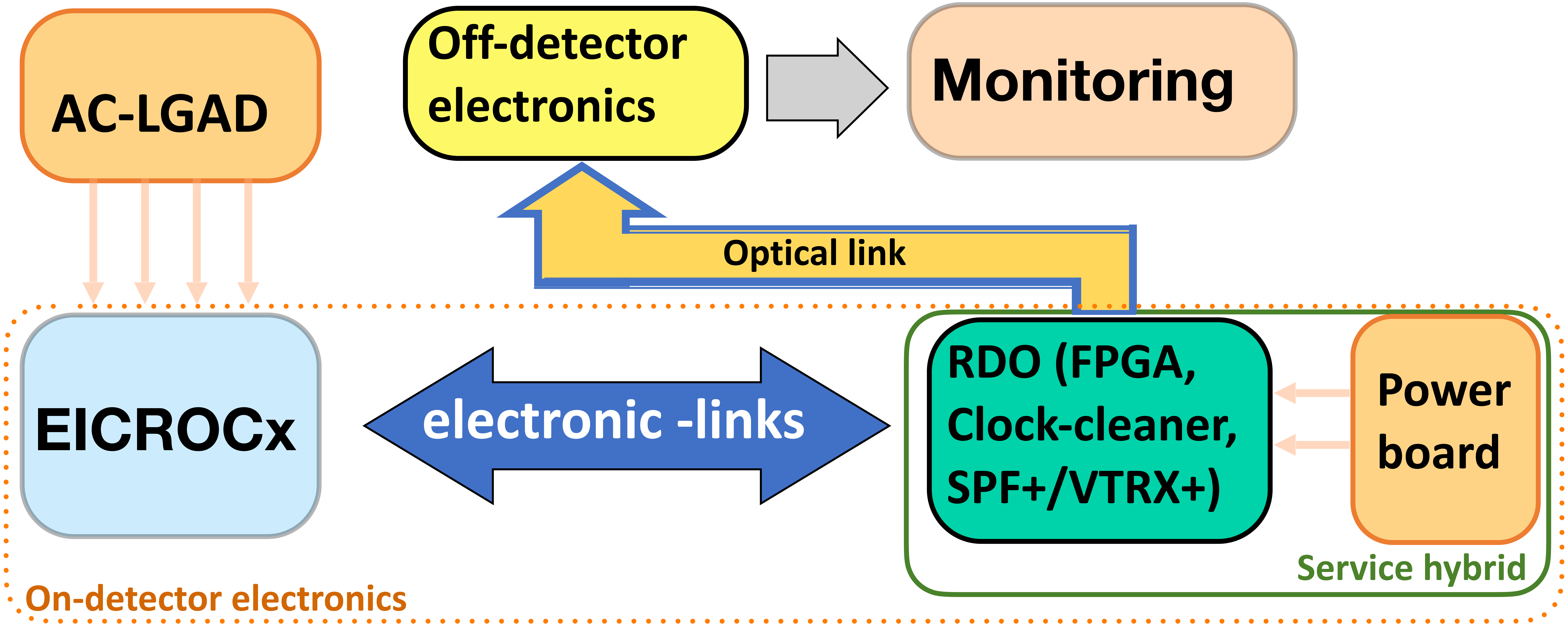
Clustering with time-compatible points

Pros: Small rise time+small jitter —> fast timing, charge sharing —> small spatial resolution



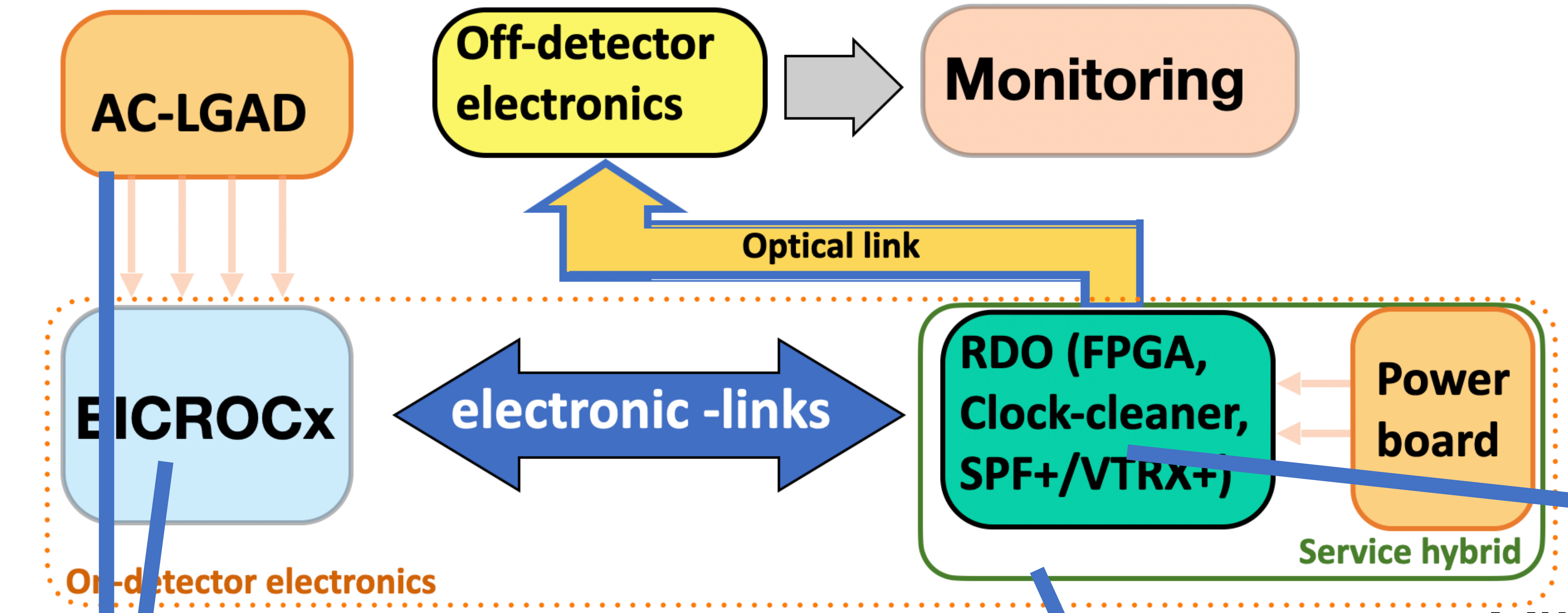
Cons: Small gain, small signal, noise dominated

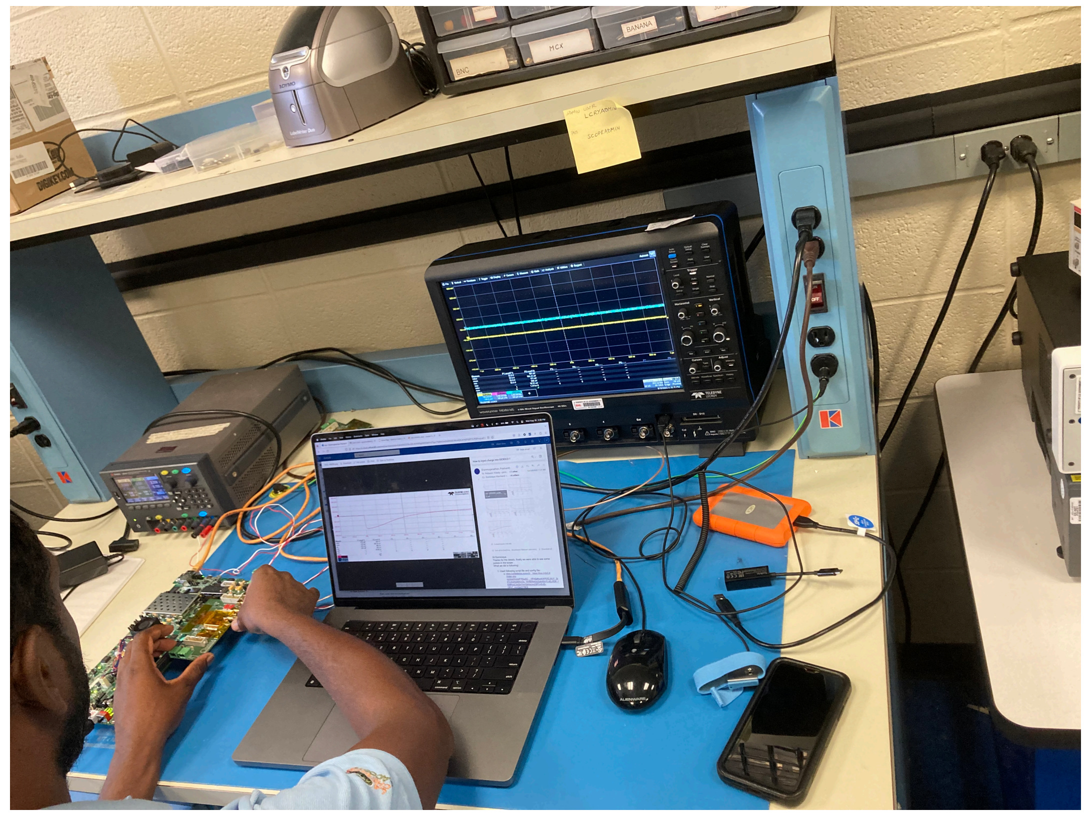
Readout chain of AC-LGAD based systems*



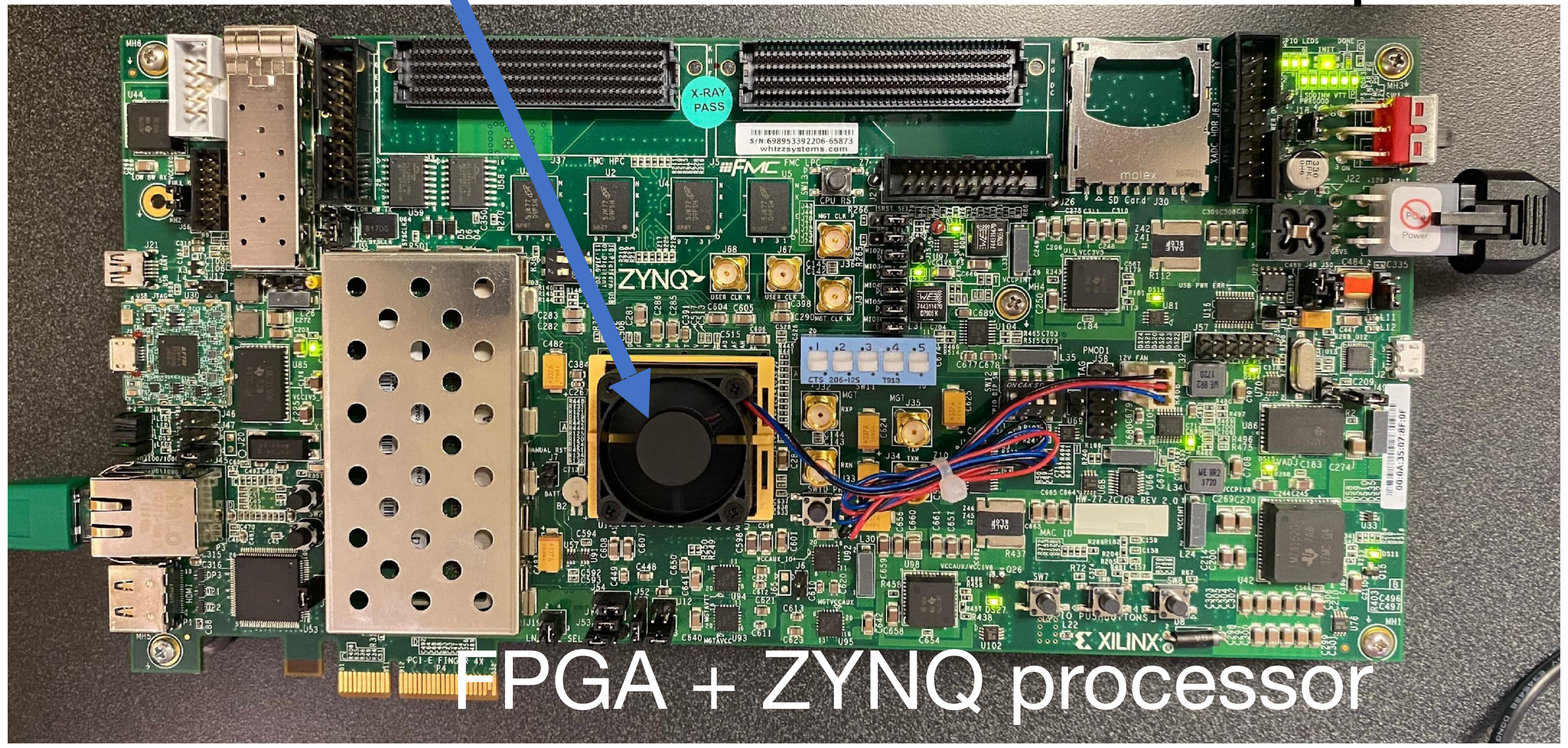
* For systems in vacuum like Roman Pots, B0 systems service hybrid maybe meter(s) away, sensor+ASIC+connector (flex board)

All the elements at BNL

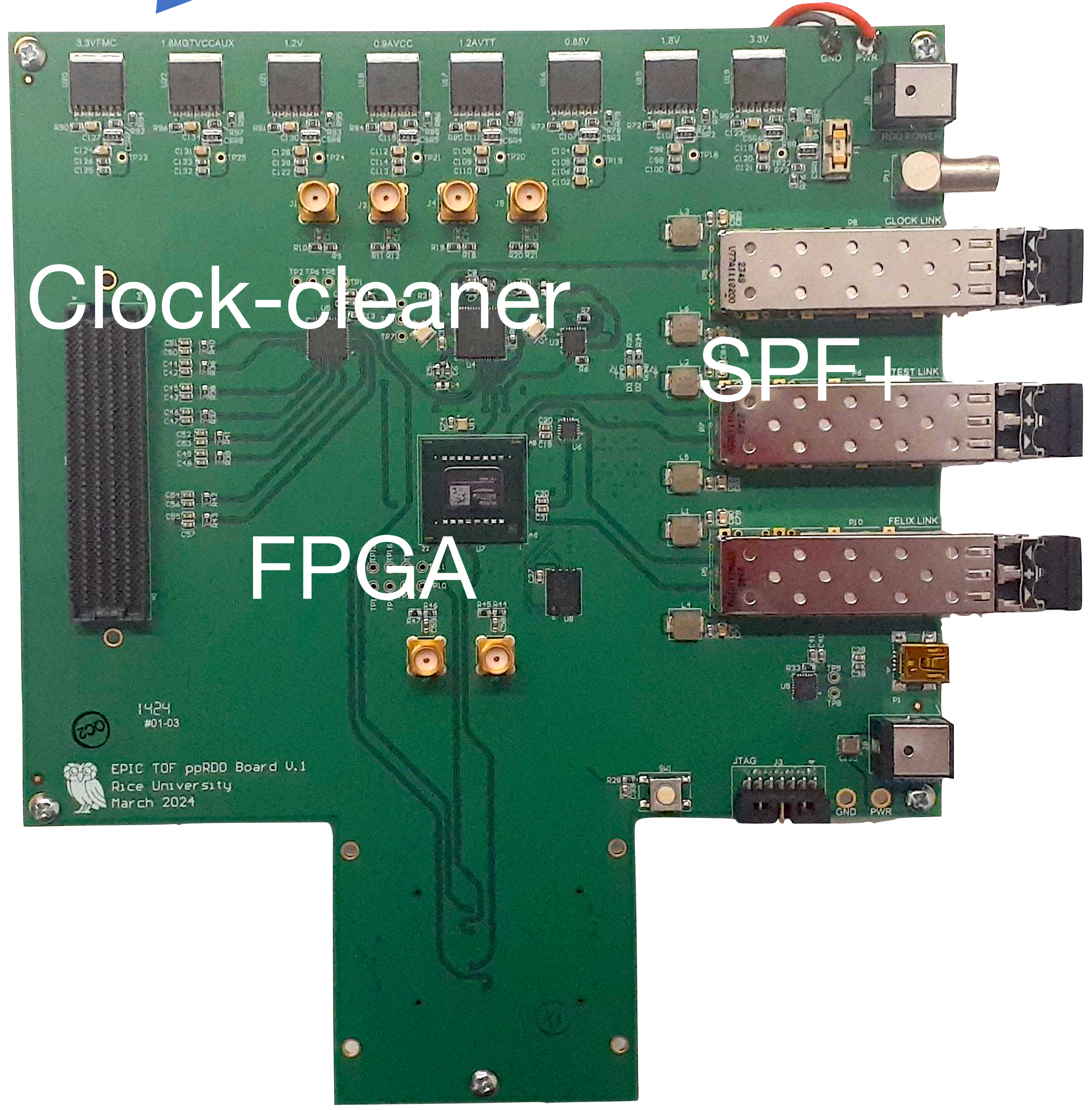




Xilinx development kit

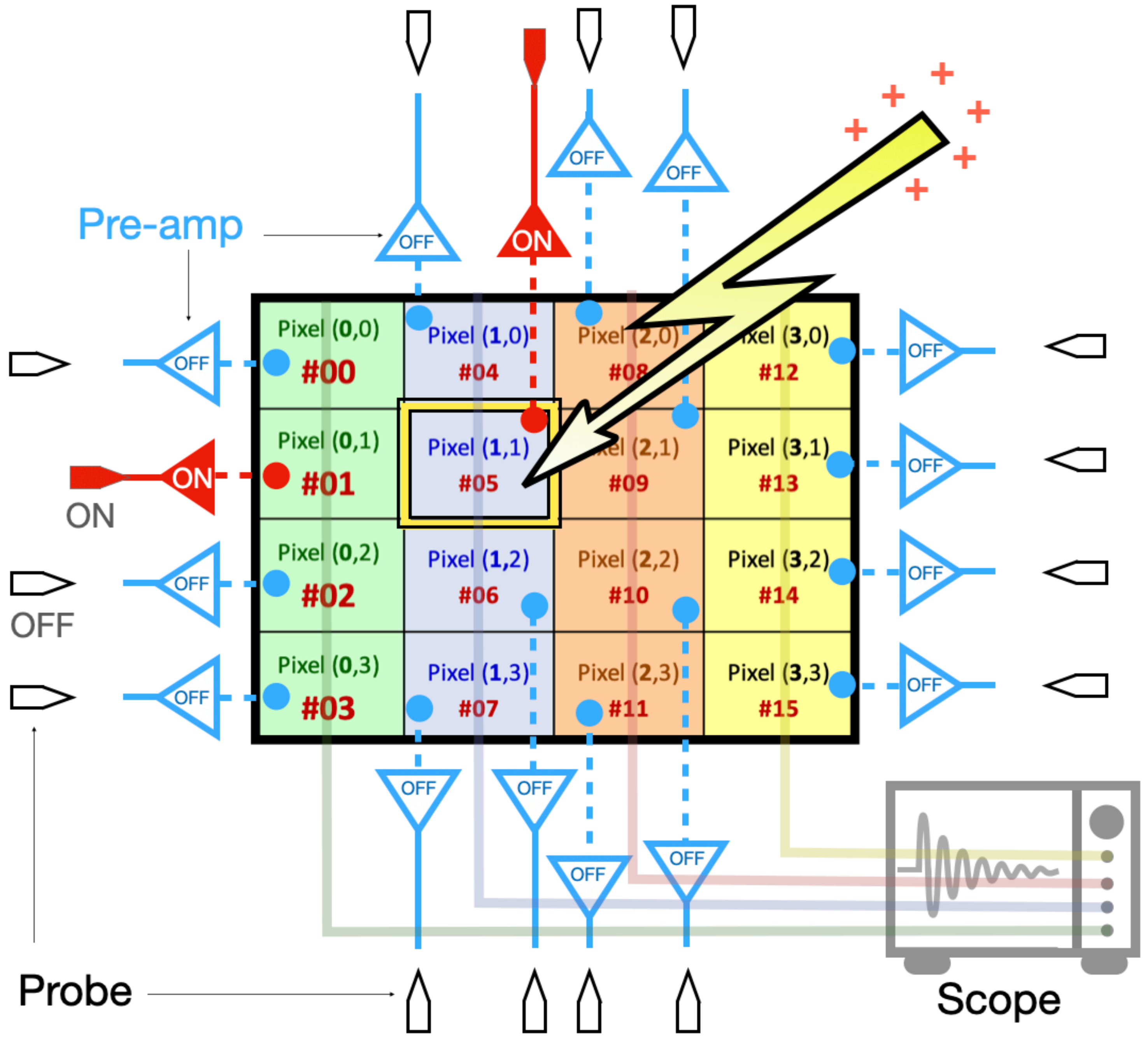


pre-prototypeRDO (for ePIC)

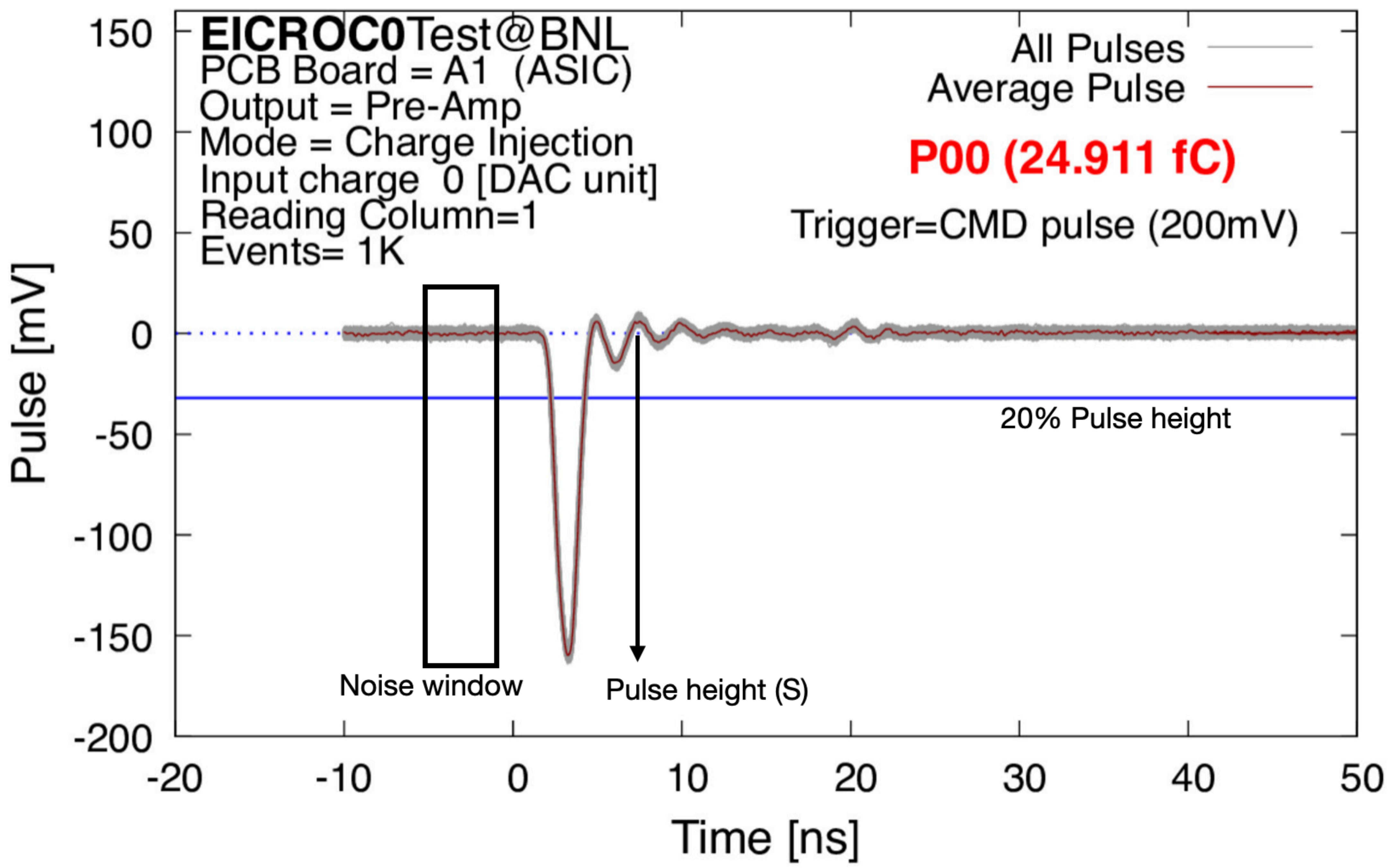


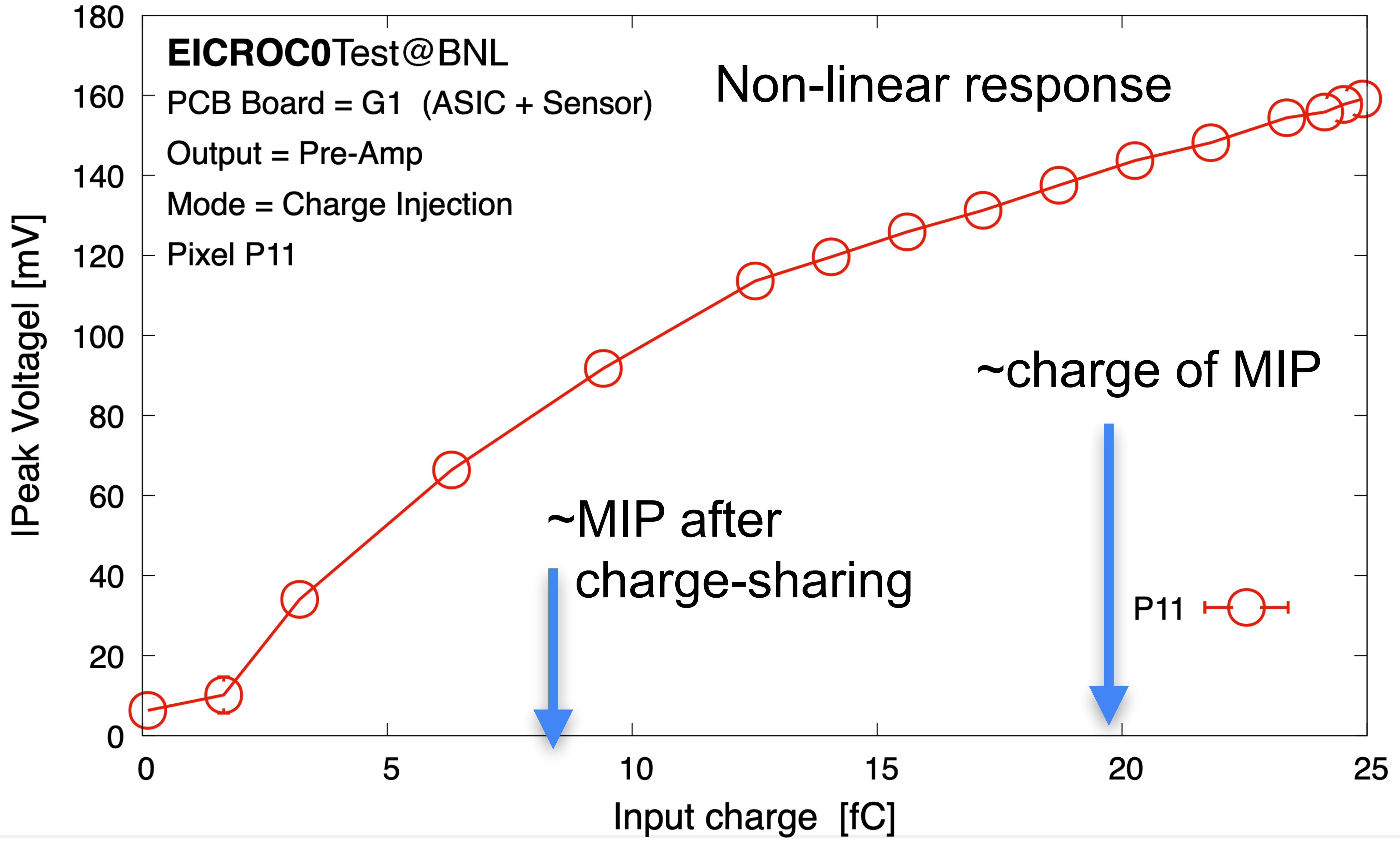
Key development and optimization of the readout chain:
Compatibility with AC-LGAD pixel sensor integration with wire and bump-bonded ASIC, measurement of jitter from ASIC, charge-injection, cross-talk, radiation source/laser, TDC/ADC clock cleaning, clock phase, jitter measurements in various environments

ASIC focused Measurements with charge injection: pre-Amp

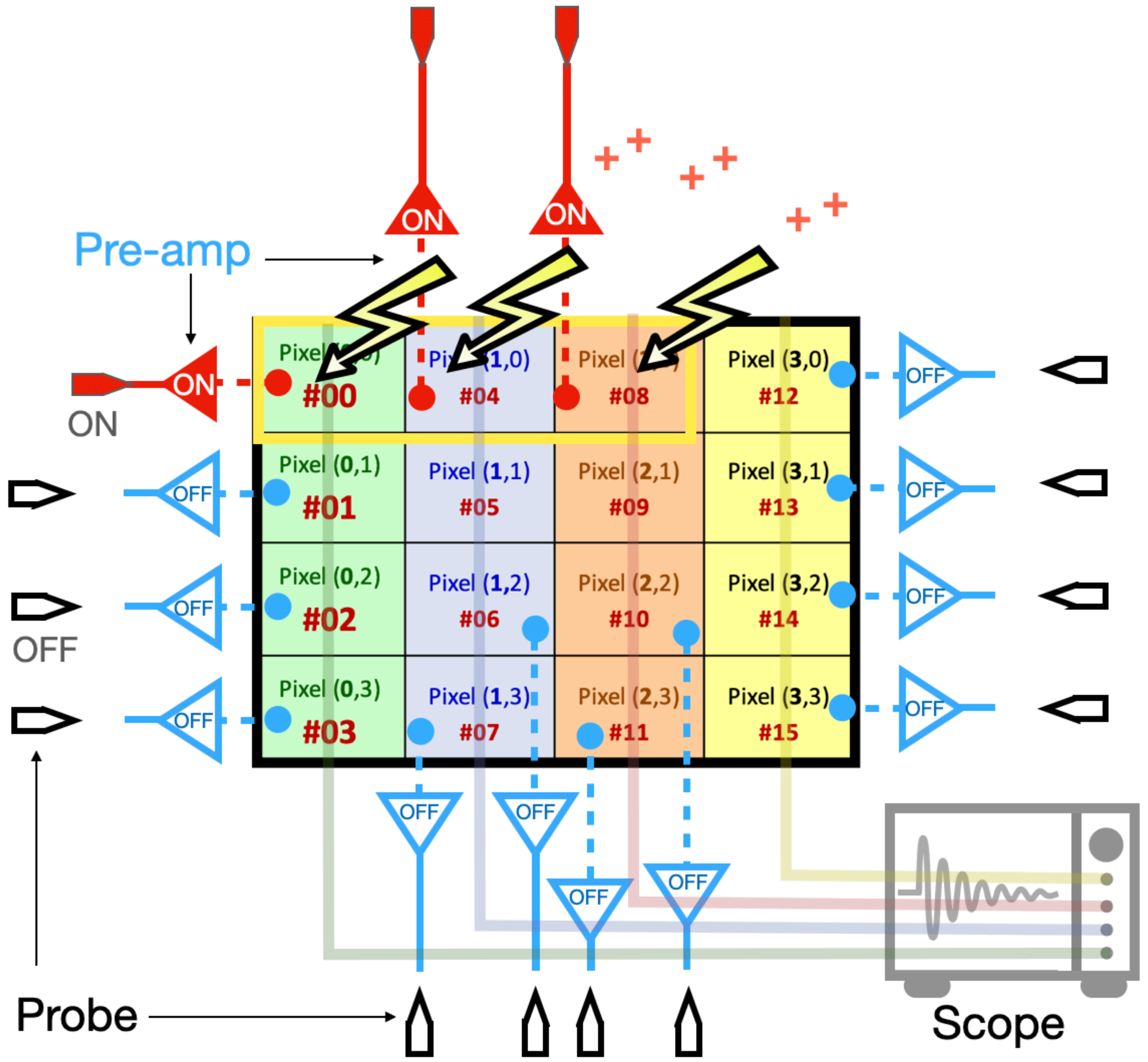


Inject internally charge <25 fC into ASIC to study the characteristic features

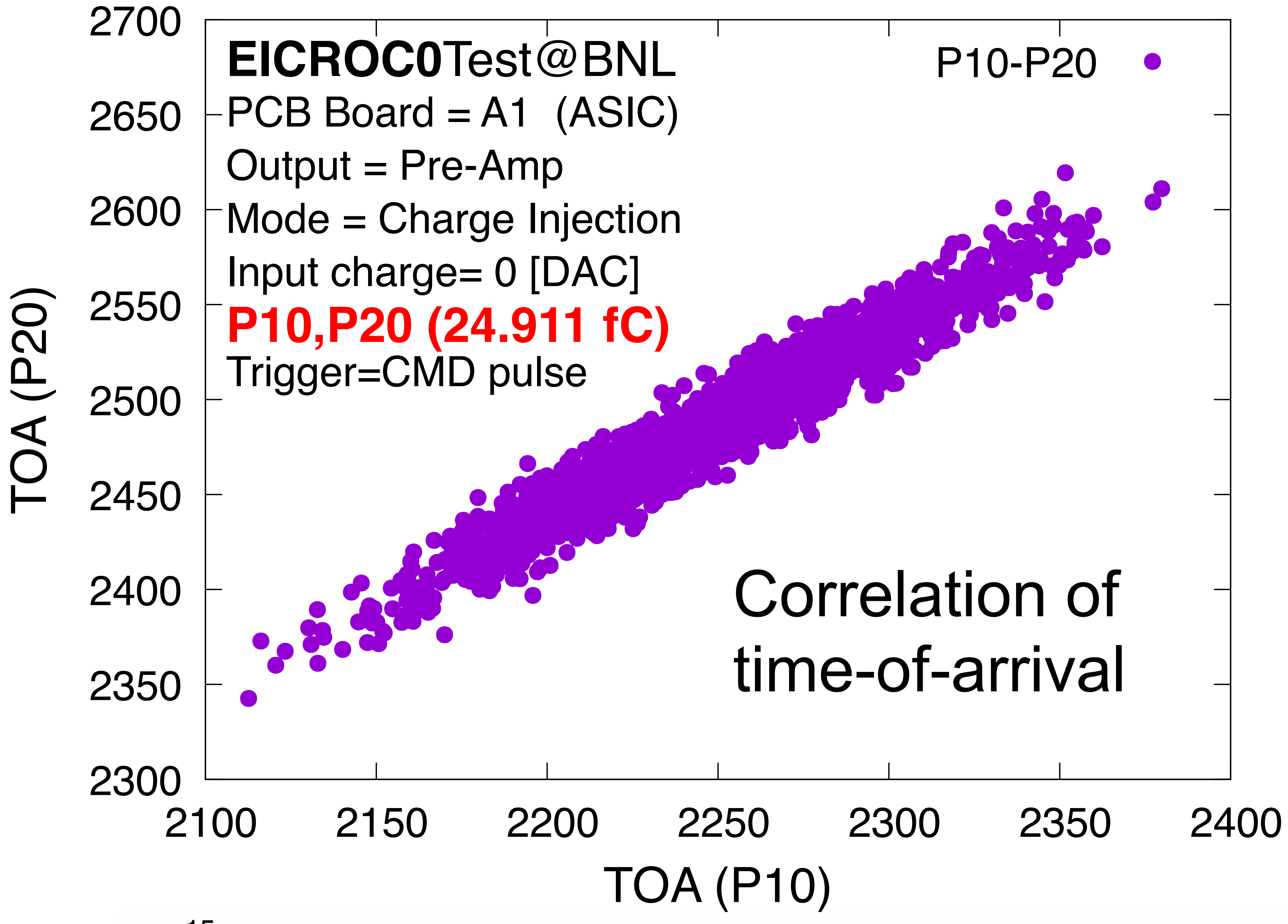


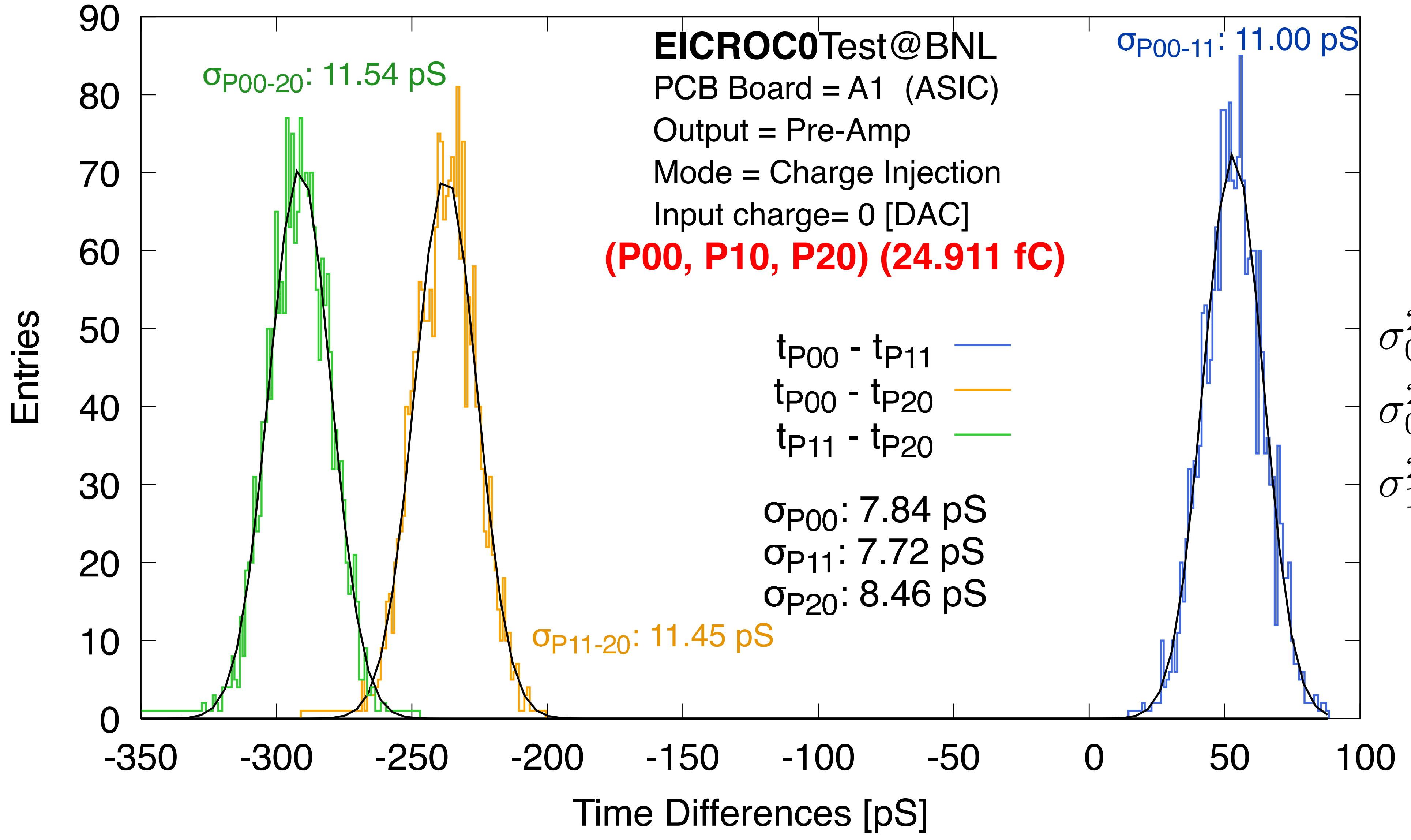


Jitter measurements

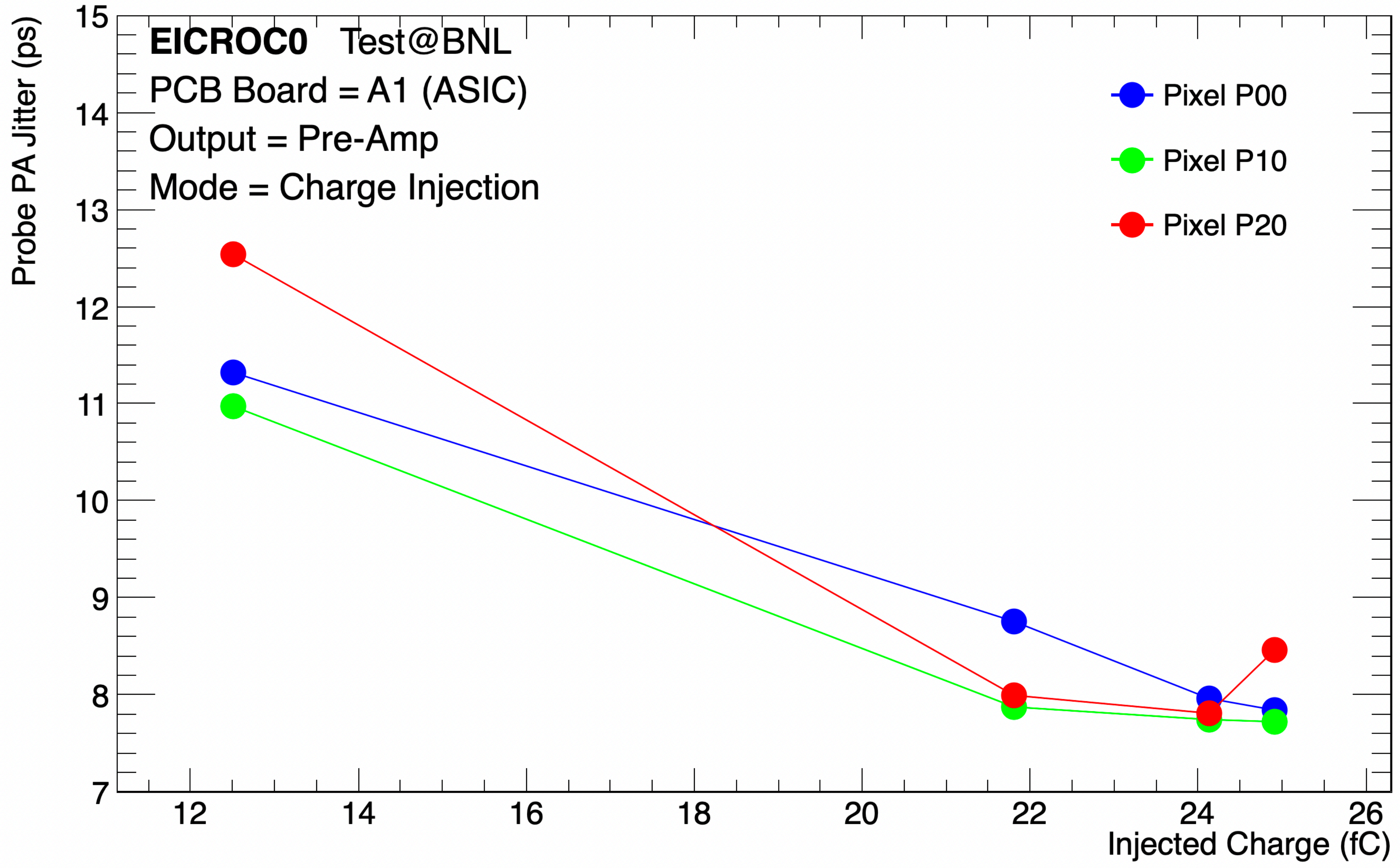


Synchronized charge injection on three pixel



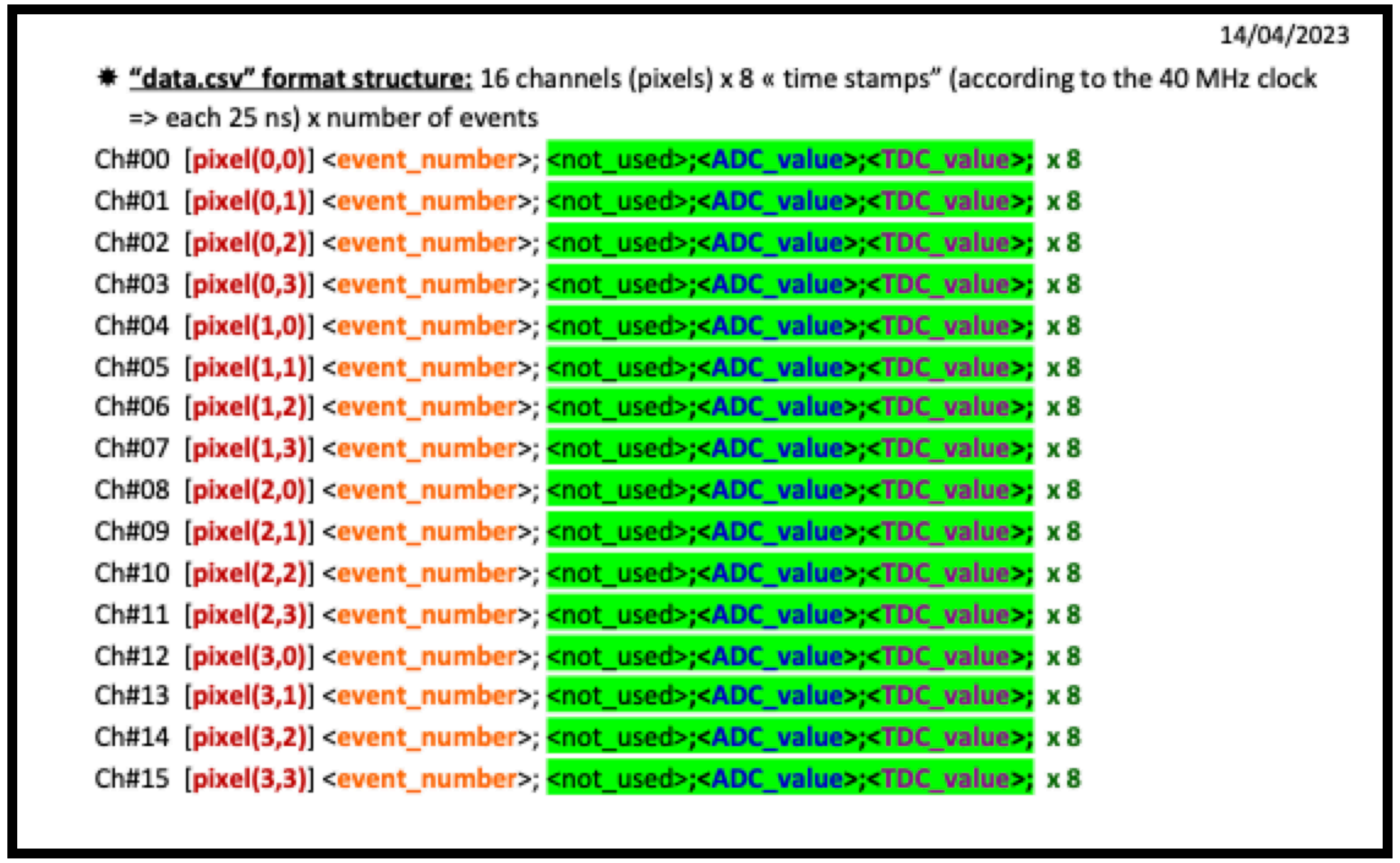


$$\sigma^2_{00-10} = \sigma^2_{00} + \sigma^2_{10}$$
$$\sigma^2_{00-20} = \sigma^2_{00} + \sigma^2_{20}$$
$$\sigma^2_{10-20} = \sigma^2_{10} + \sigma^2_{20}$$



ASIC jitter measured to be ~8 pS

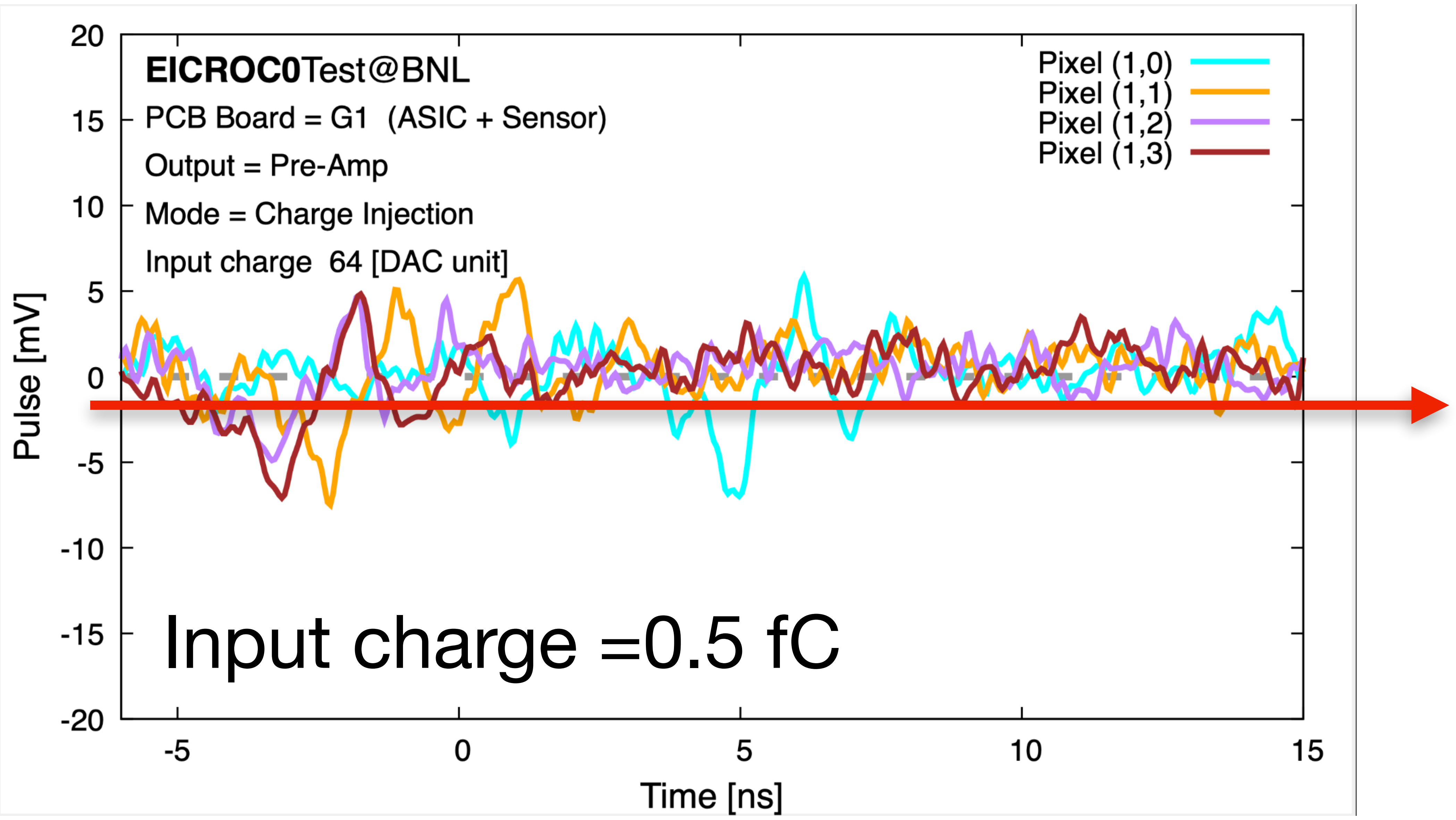
ASIC measurements: ADC/TDC, S-curve, noise/threshold scan



14/04/2023

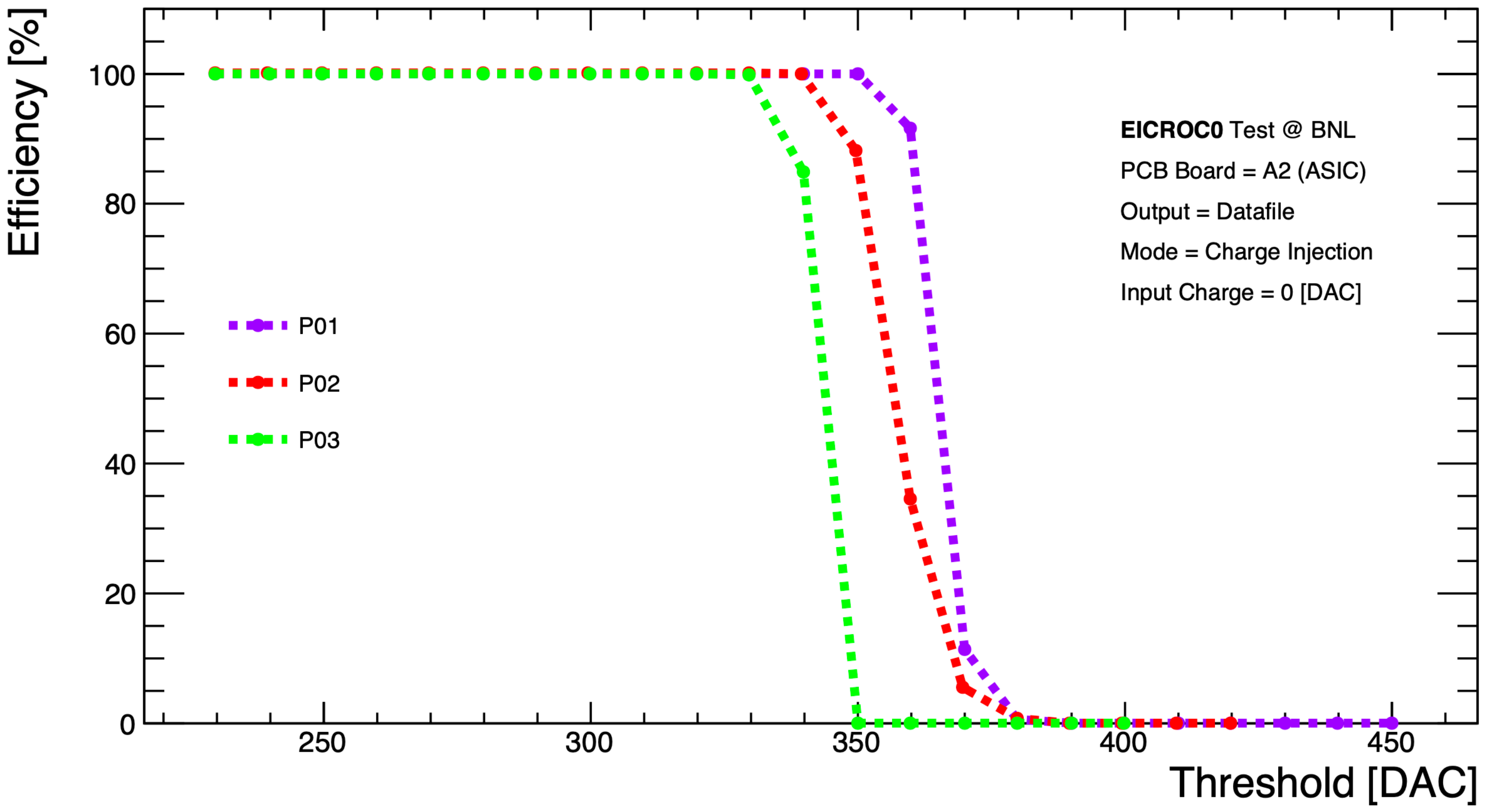
* **"data.csv" format structure:** 16 channels (pixels) x 8 « time stamps" (according to the 40 MHz clock => each 25 ns) x number of events

Ch#00 [pixel(0,0)] <event_number>; <not_used>;<ADC_value>;<TDC_value>; x 8
Ch#01 [pixel(0,1)] <event_number>; <not_used>;<ADC_value>;<TDC_value>; x 8
Ch#02 [pixel(0,2)] <event_number>; <not_used>;<ADC_value>;<TDC_value>; x 8
Ch#03 [pixel(0,3)] <event_number>; <not_used>;<ADC_value>;<TDC_value>; x 8
Ch#04 [pixel(1,0)] <event_number>; <not_used>;<ADC_value>;<TDC_value>; x 8
Ch#05 [pixel(1,1)] <event_number>; <not_used>;<ADC_value>;<TDC_value>; x 8
Ch#06 [pixel(1,2)] <event_number>; <not_used>;<ADC_value>;<TDC_value>; x 8
Ch#07 [pixel(1,3)] <event_number>; <not_used>;<ADC_value>;<TDC_value>; x 8
Ch#08 [pixel(2,0)] <event_number>; <not_used>;<ADC_value>;<TDC_value>; x 8
Ch#09 [pixel(2,1)] <event_number>; <not_used>;<ADC_value>;<TDC_value>; x 8
Ch#10 [pixel(2,2)] <event_number>; <not_used>;<ADC_value>;<TDC_value>; x 8
Ch#11 [pixel(2,3)] <event_number>; <not_used>;<ADC_value>;<TDC_value>; x 8
Ch#12 [pixel(3,0)] <event_number>; <not_used>;<ADC_value>;<TDC_value>; x 8
Ch#13 [pixel(3,1)] <event_number>; <not_used>;<ADC_value>;<TDC_value>; x 8
Ch#14 [pixel(3,2)] <event_number>; <not_used>;<ADC_value>;<TDC_value>; x 8
Ch#15 [pixel(3,3)] <event_number>; <not_used>;<ADC_value>;<TDC_value>; x 8

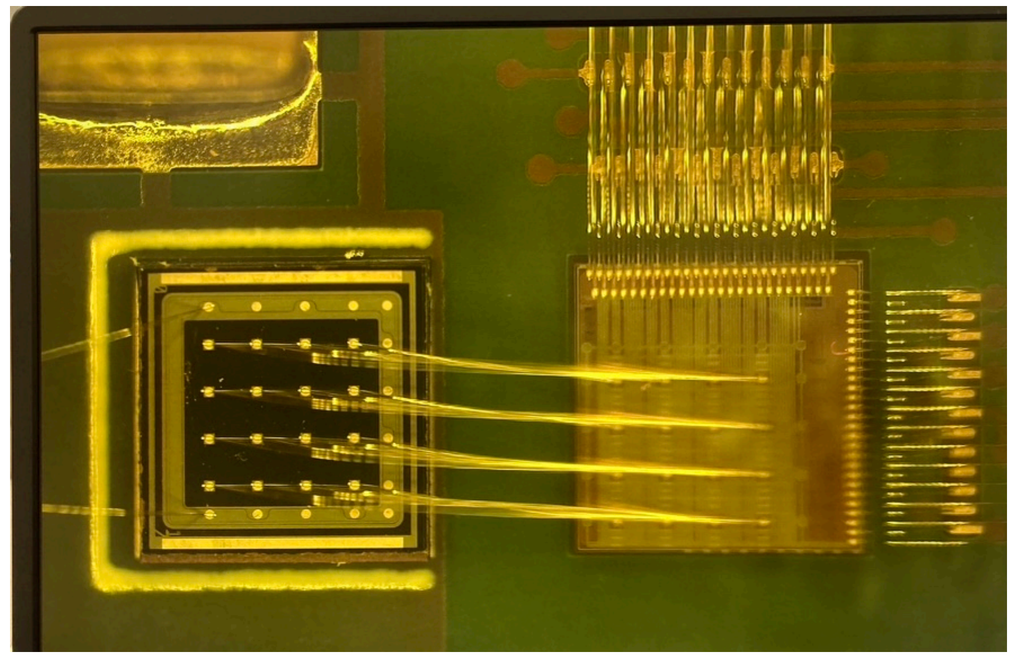


Threshold scan

Threshold on signal

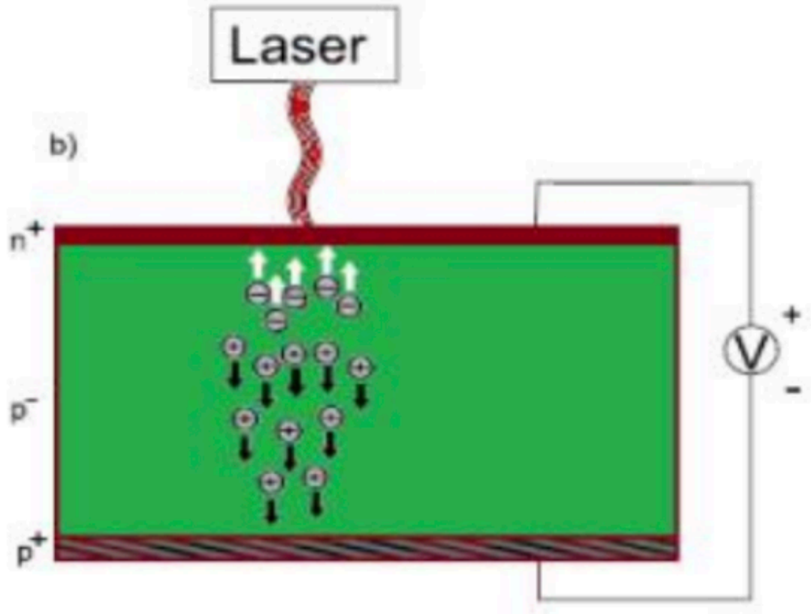


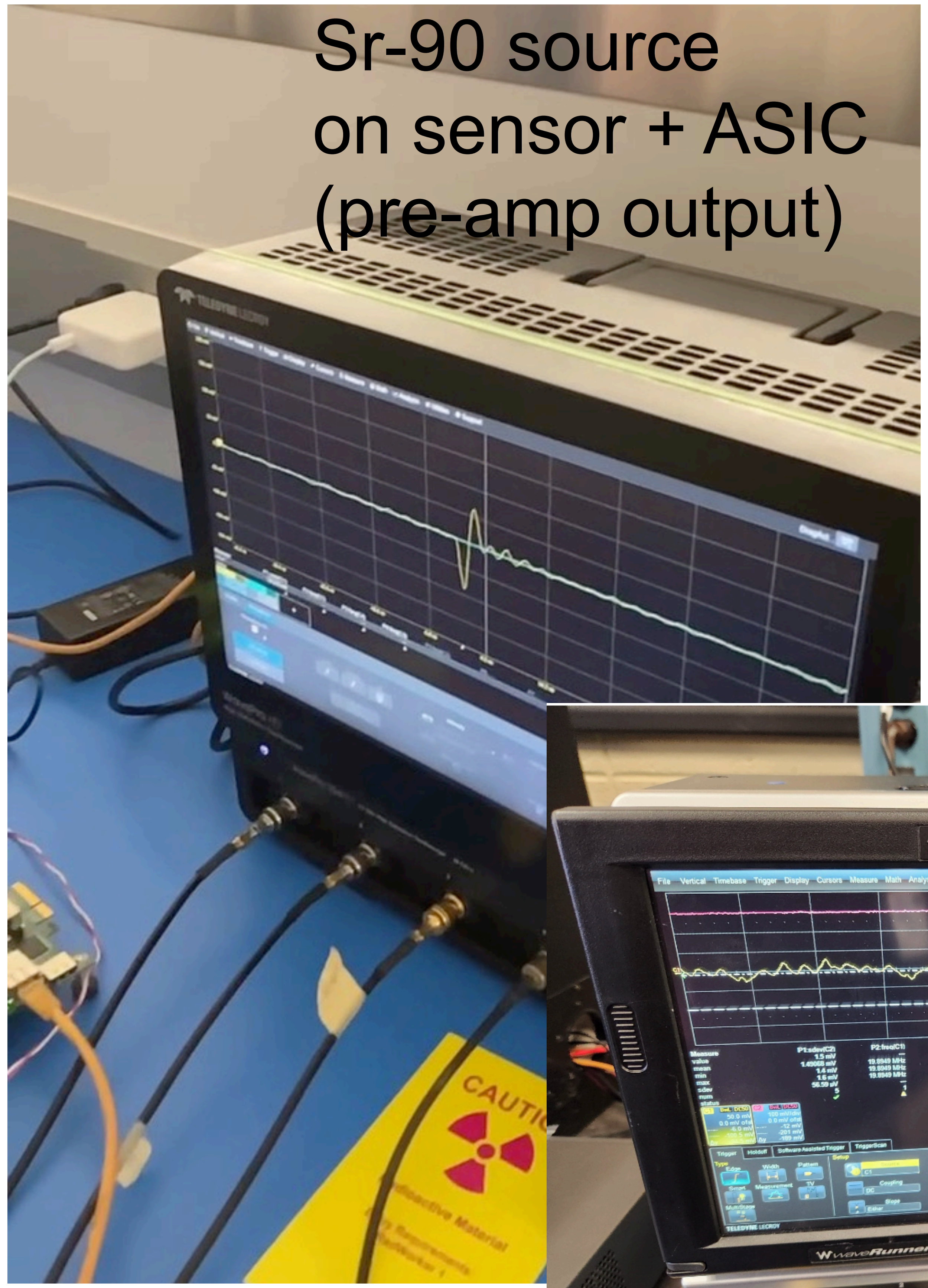
Measurements with charge injection, laser & source



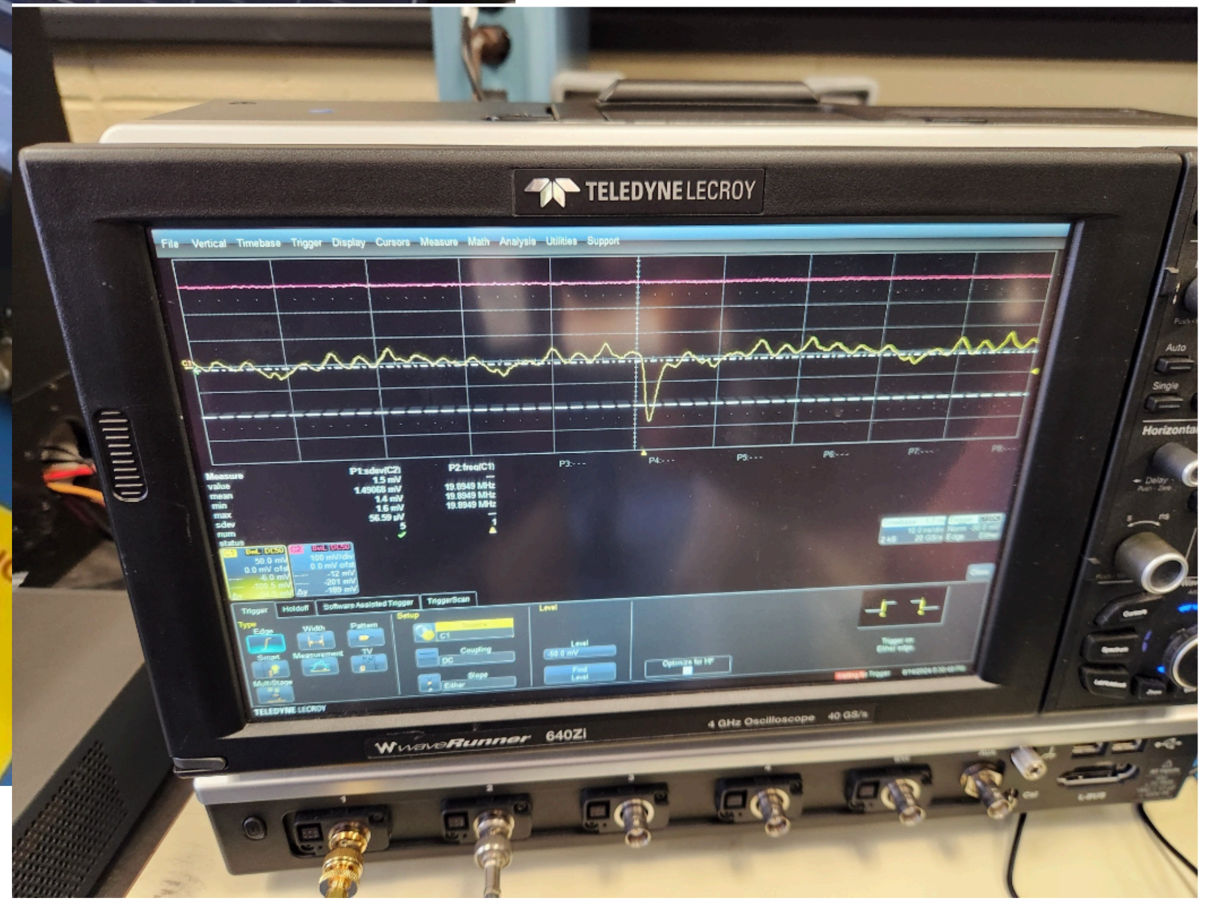
We use a wire-bonded sensor

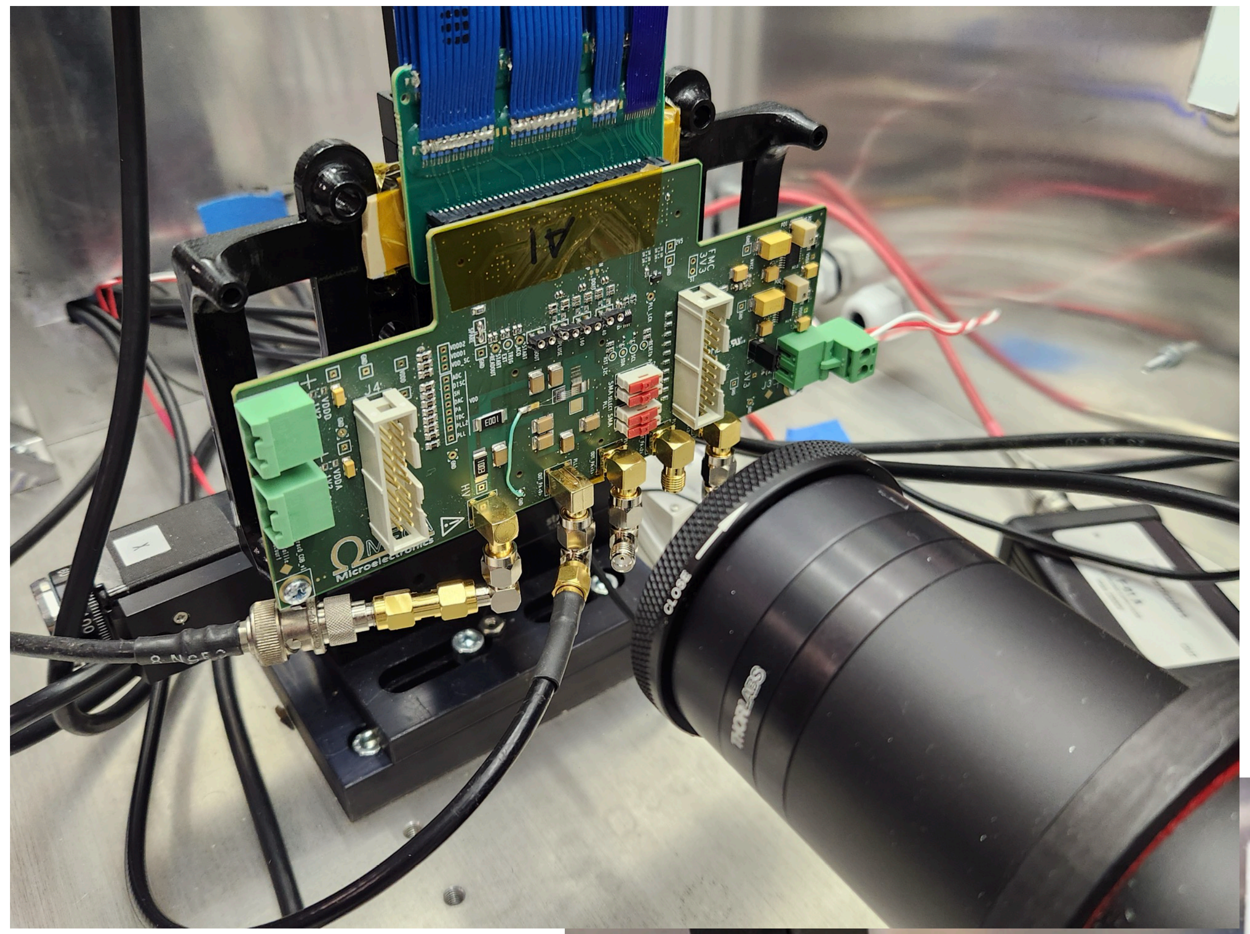
TCT (Transient Current Technique) laser scan to map out charge

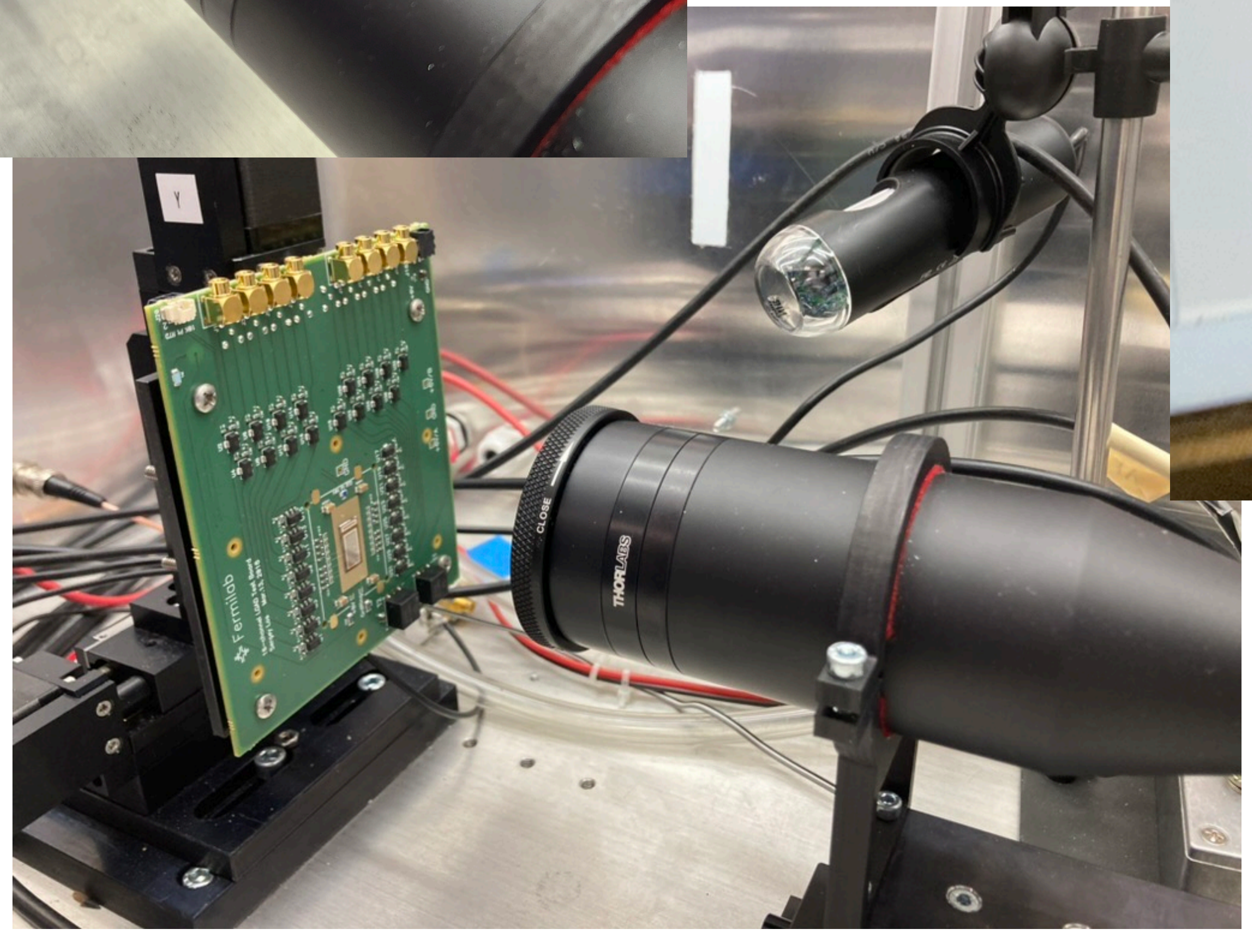


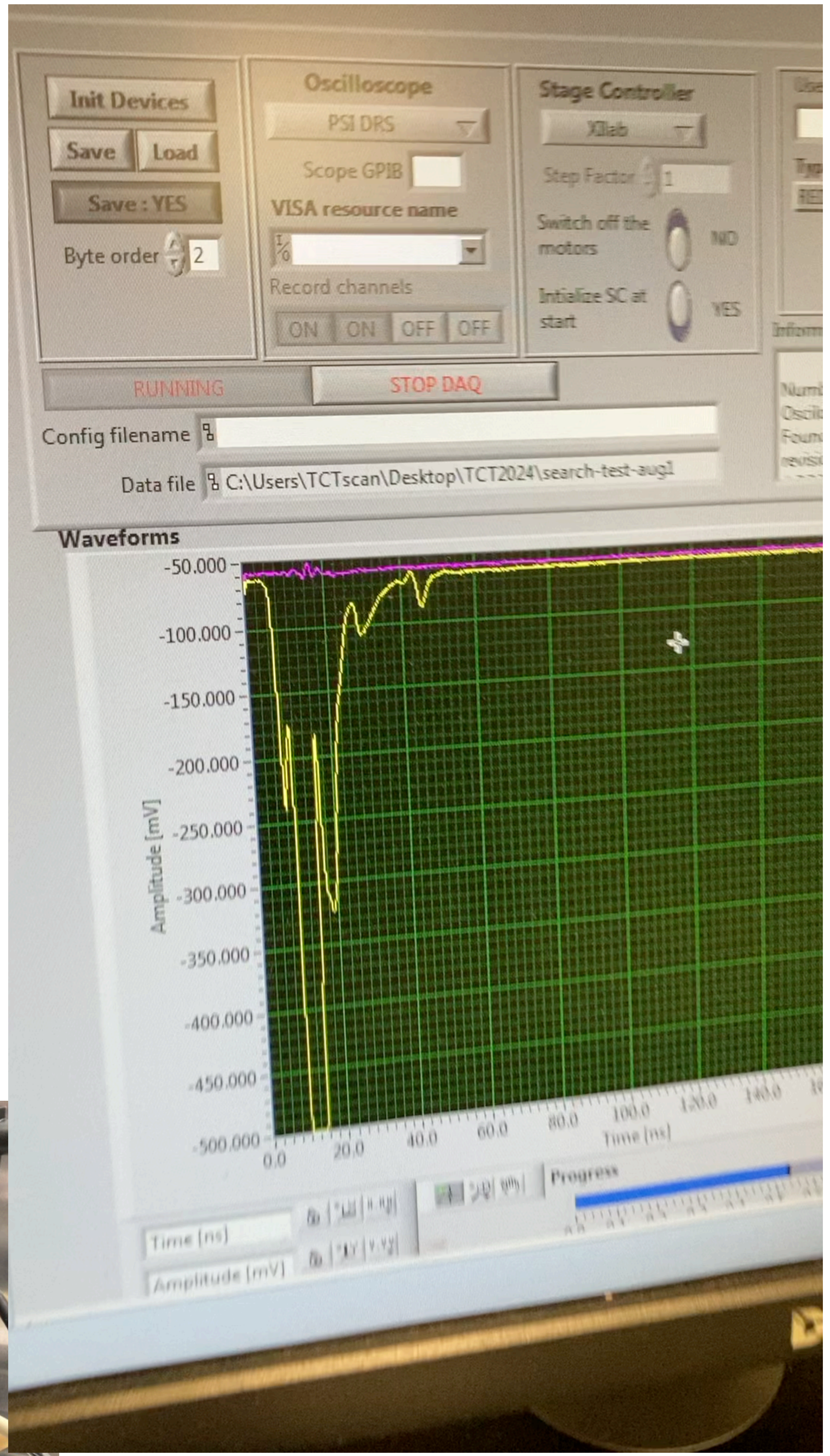


Sr-90 source
on sensor + ASIC
(pre-amp output)



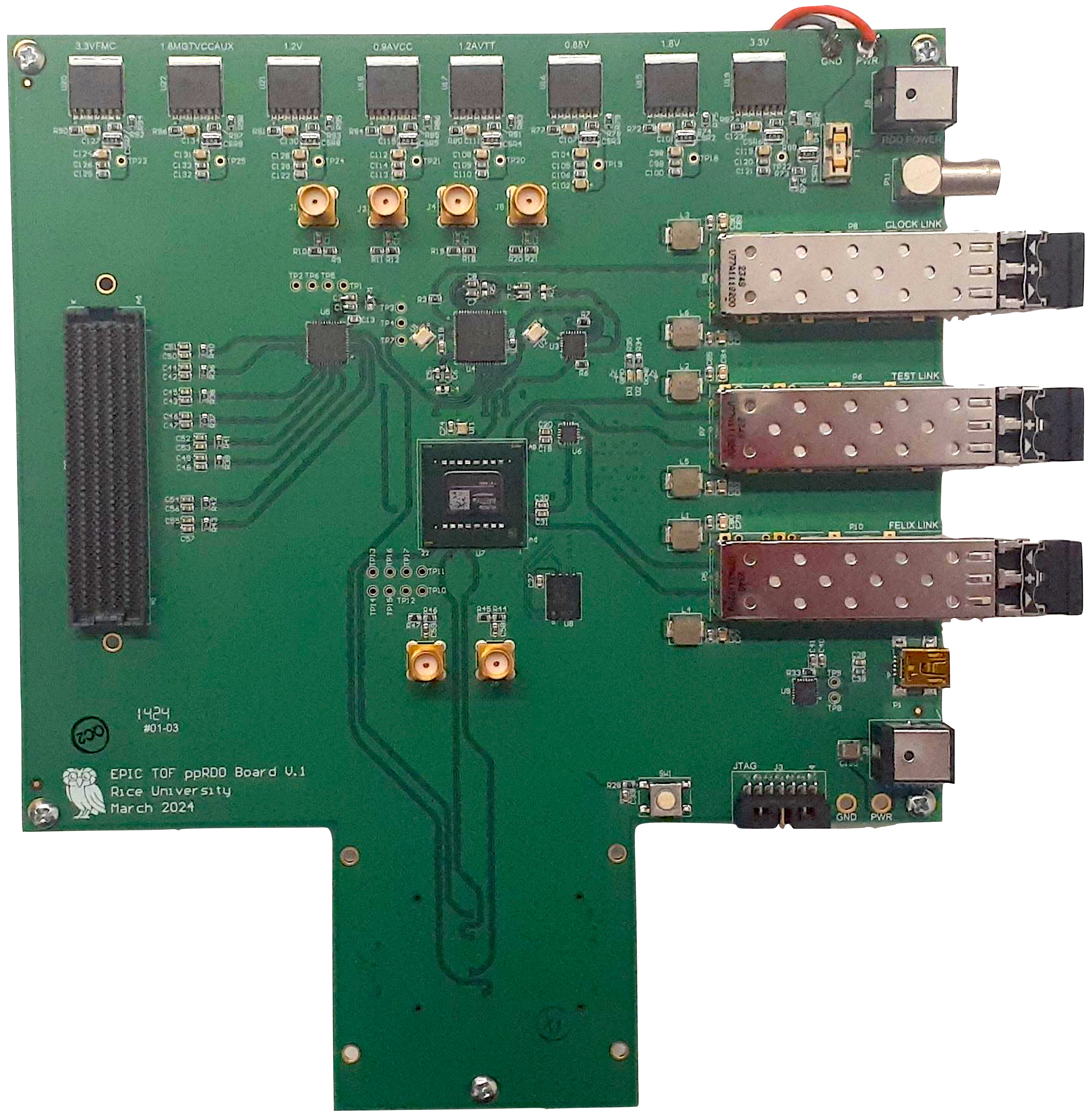


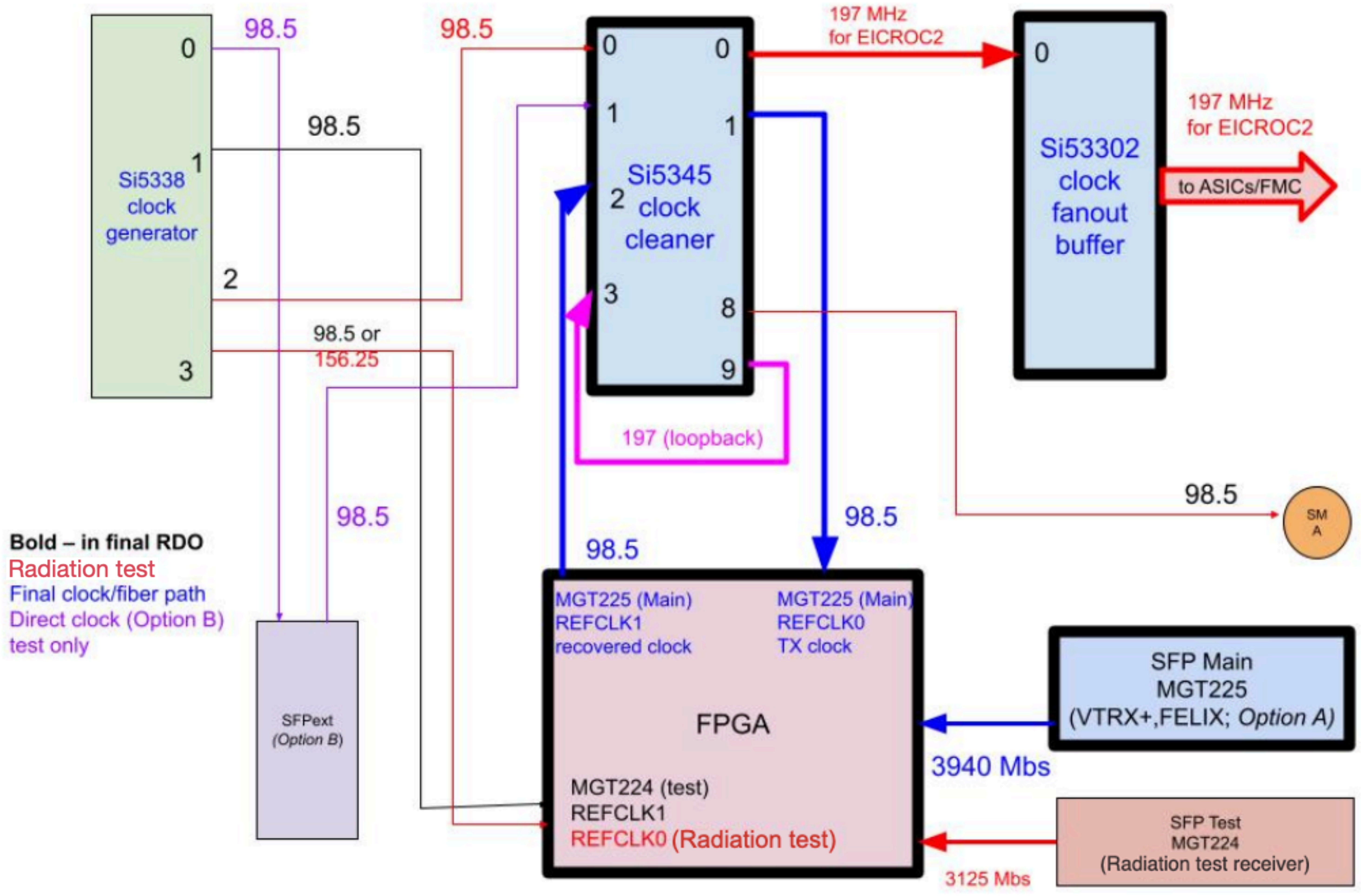




data analysis ongoing

pre-prototyping readout board: clock cleaner

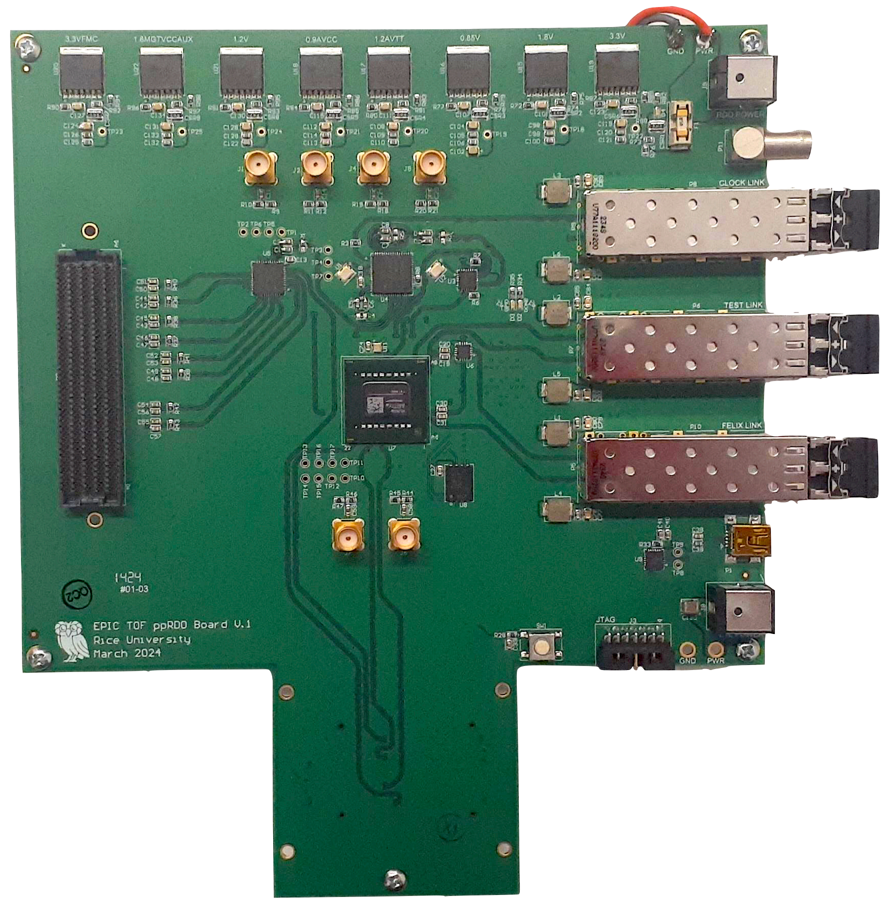


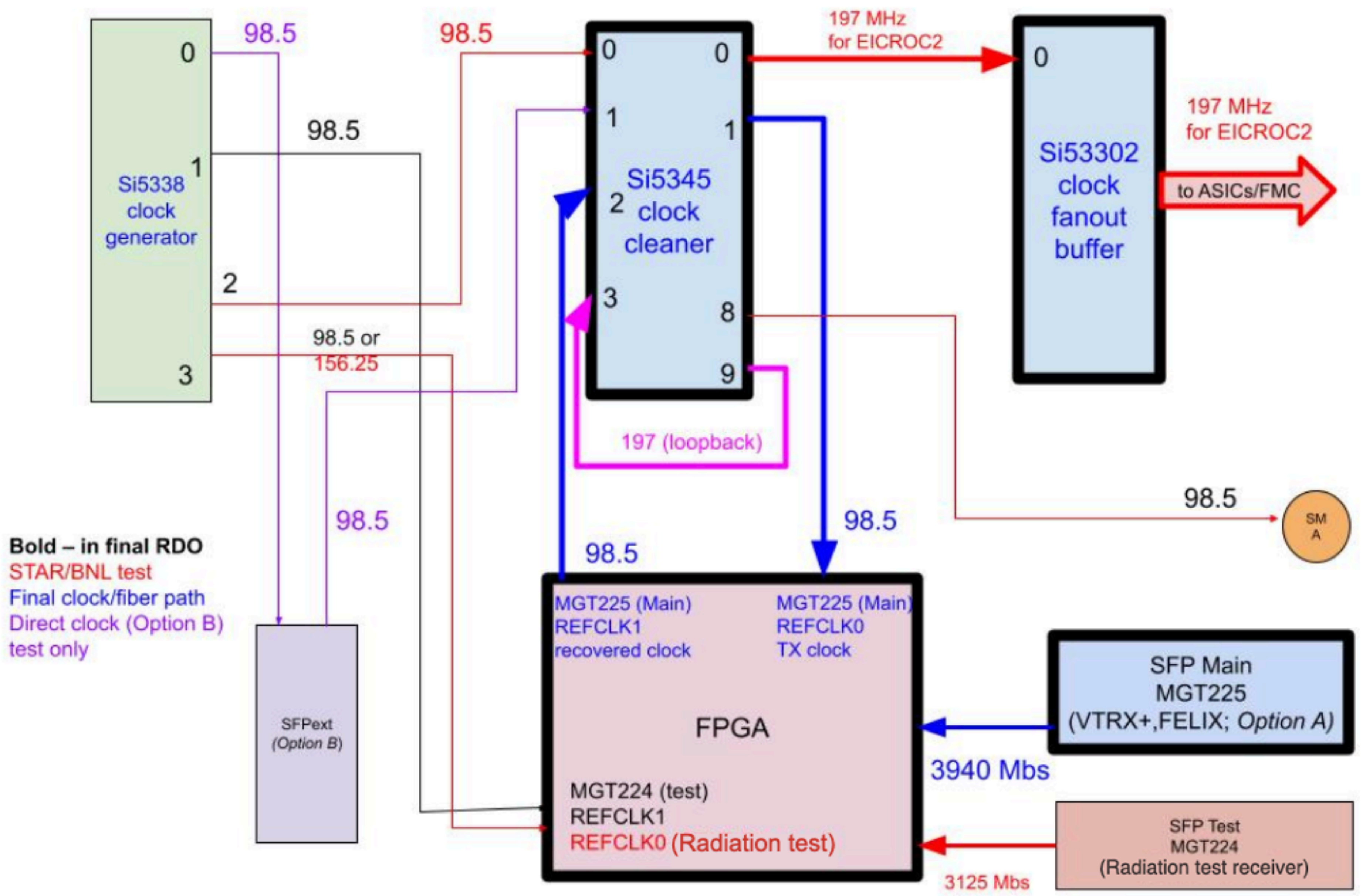


LV power line of 4-5V, 4A
bias, 98.5 MHz input/output clock

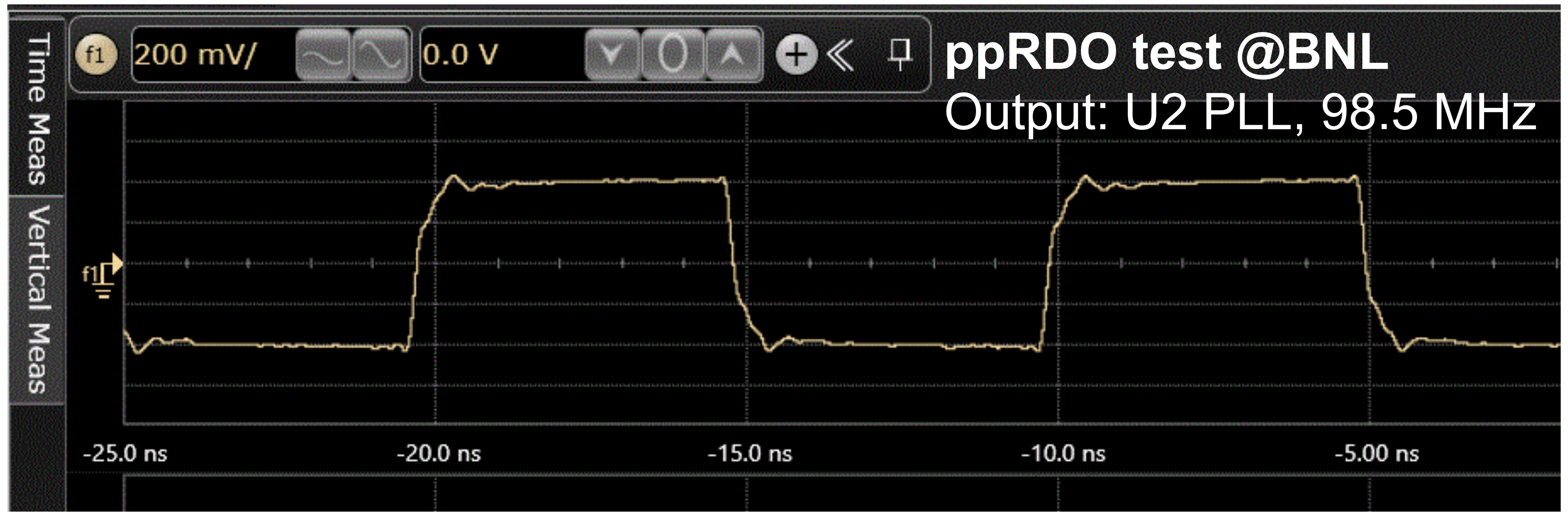
Goal: Perform assessment of clock cleaning, clock phase stability, single event upset of FPGA, clock cleaner & transceiver, insertion delay

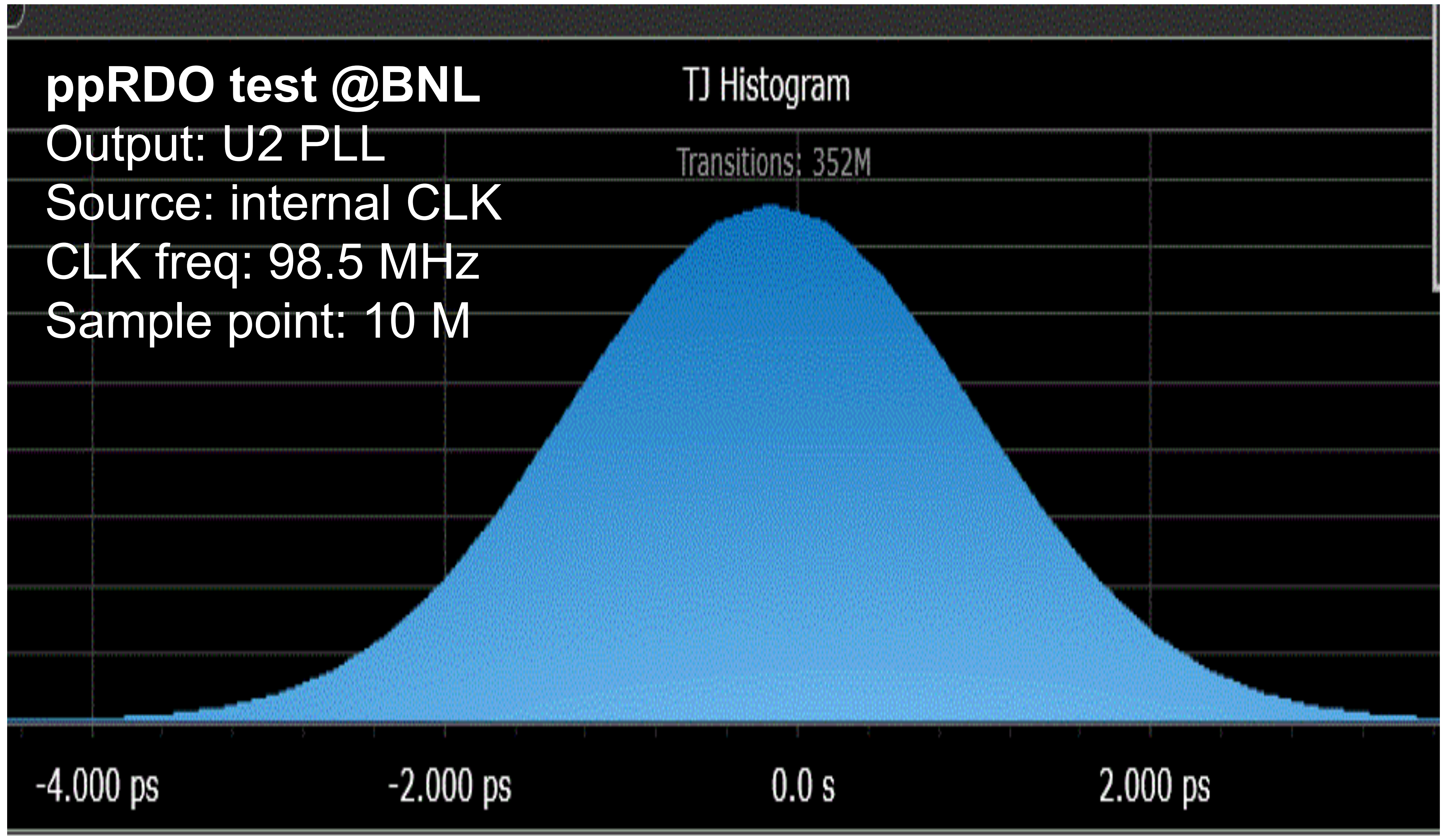
pre-prototyping readout board: clock cleaner





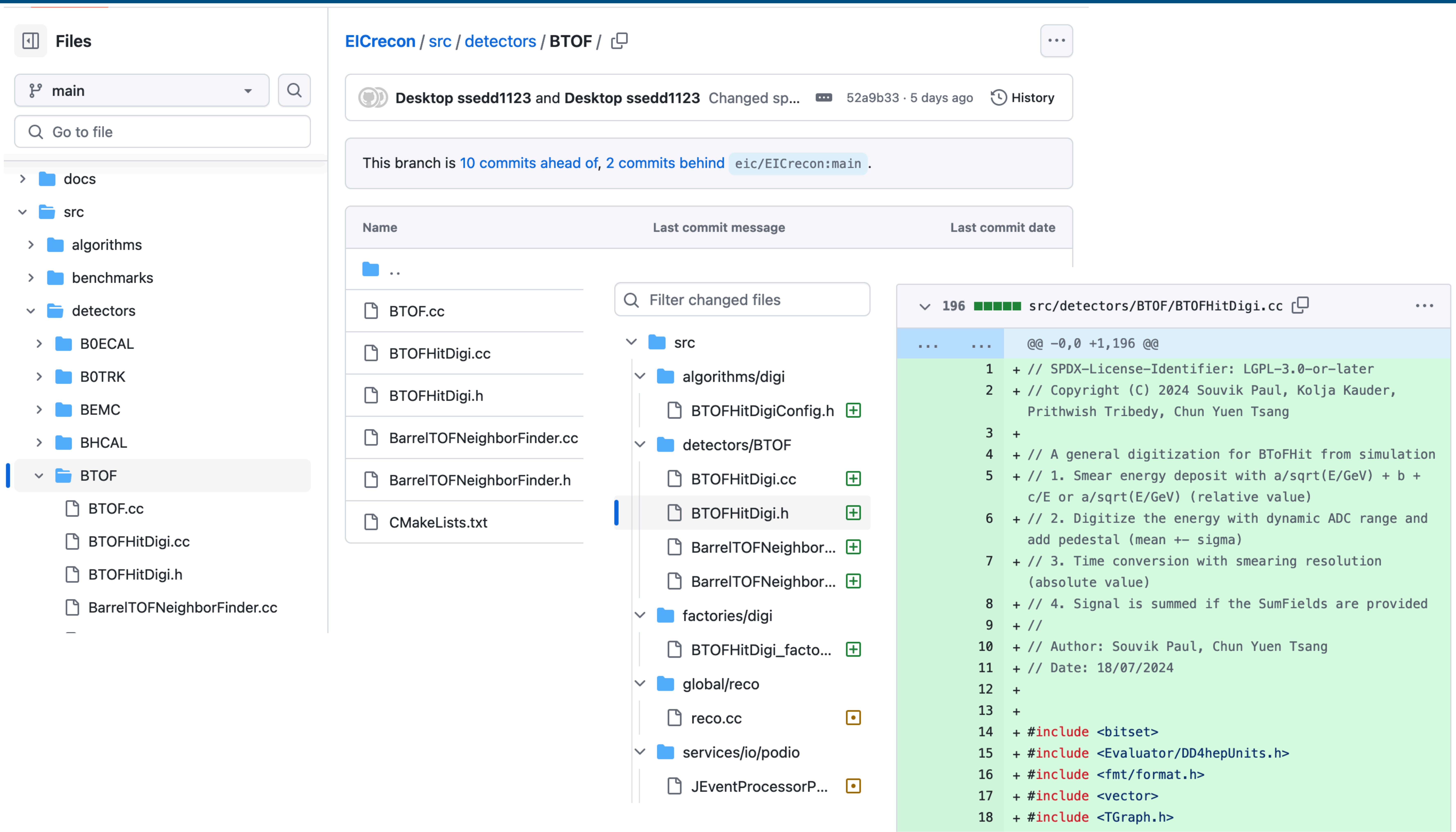
PLL output 98.5 MHz clock distribution

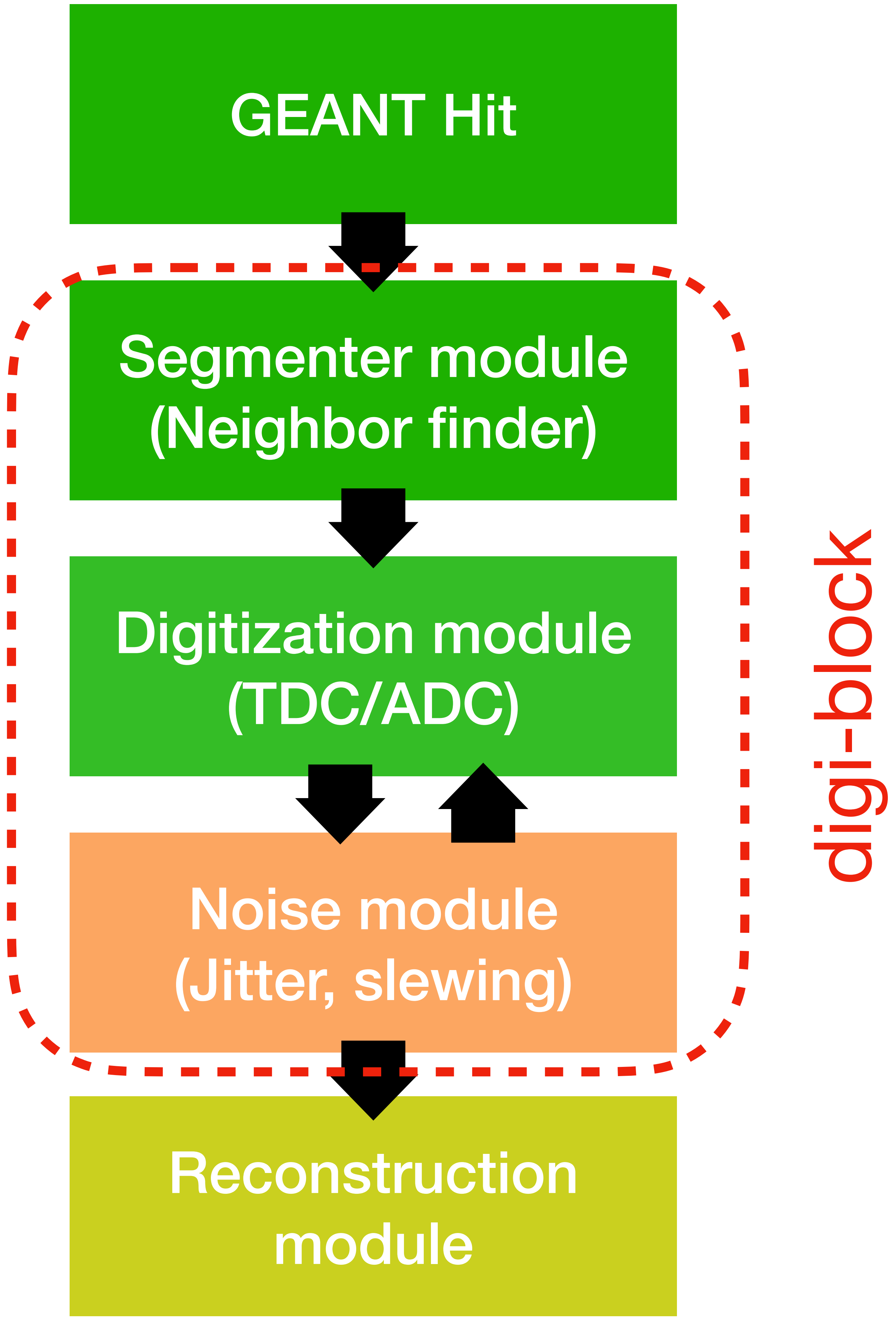




Clock jitter ~1.12 pS, deterministic jitter is 770 fS

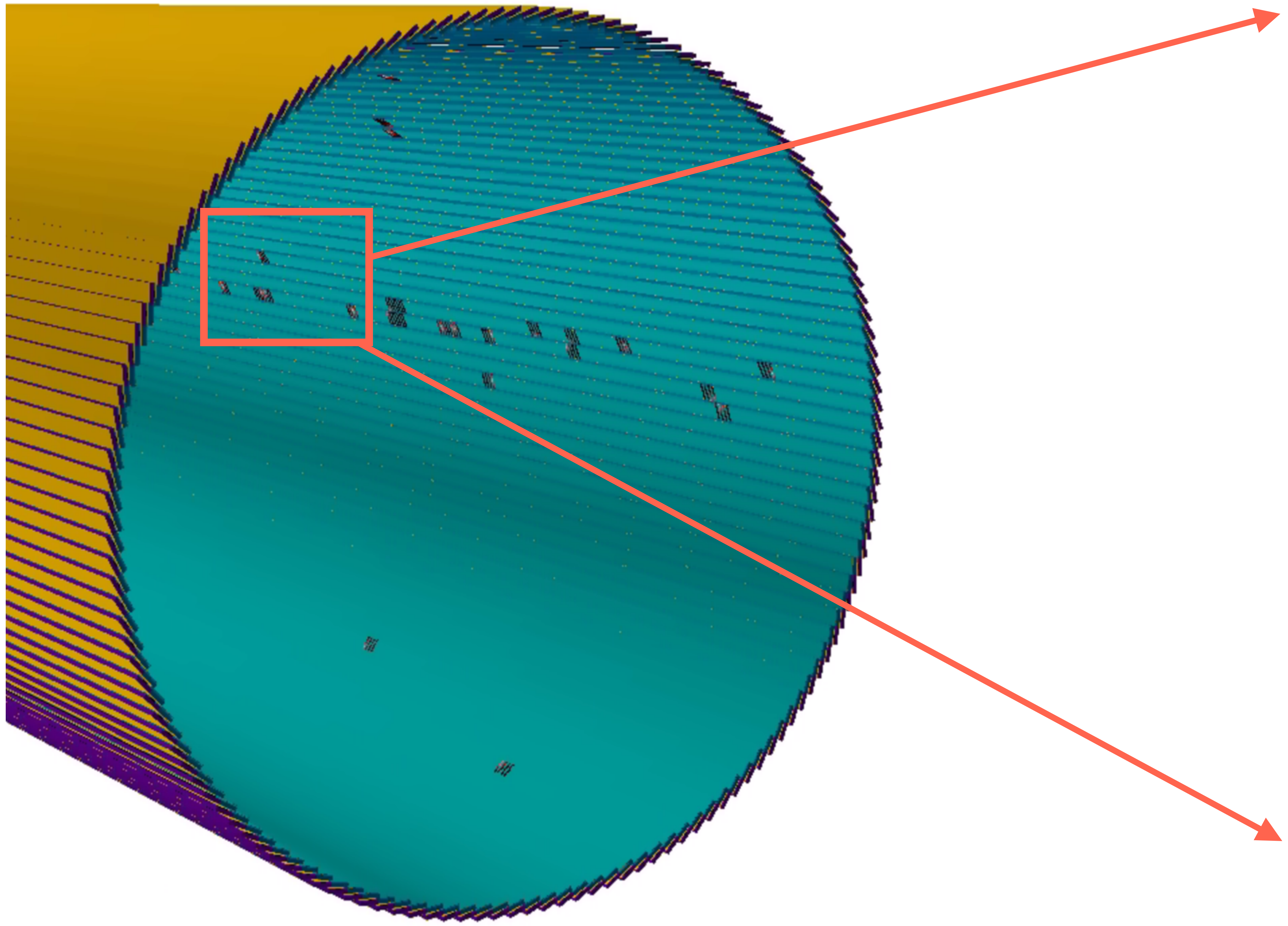
Quick summary of the current status





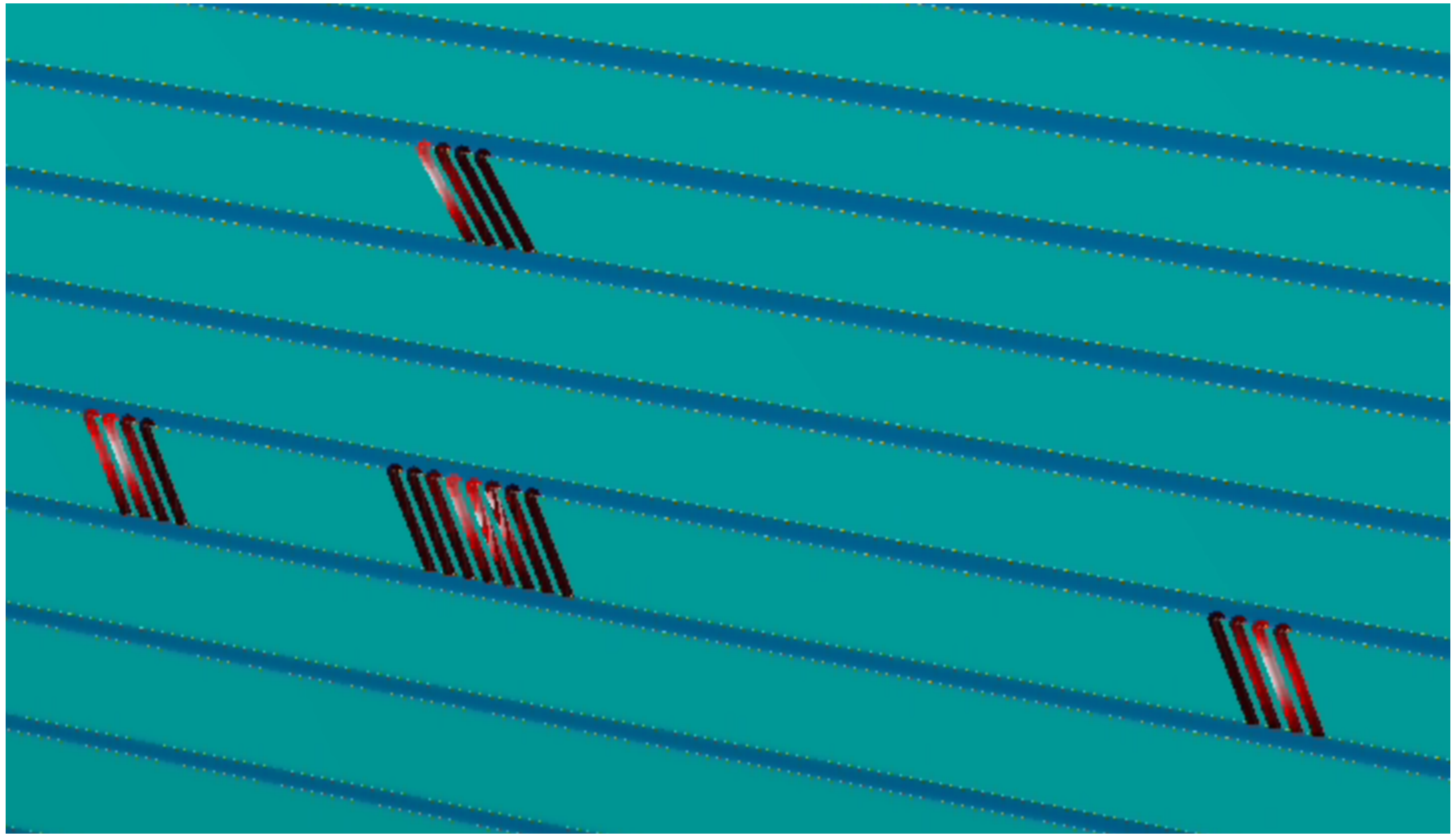
Recently we finished first implementation of the digitization model for AC-LGAD-based BTOF — work on other subsystems, FTOF and B0, is ongoing.

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

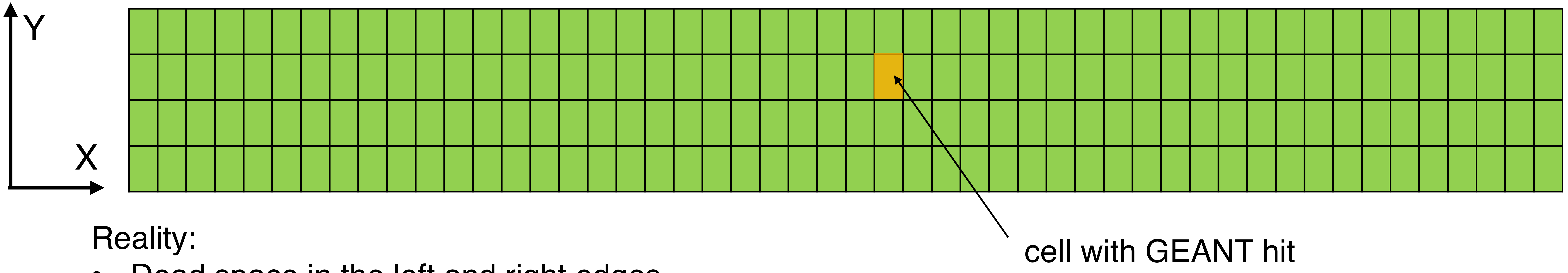
TOFBarrelADCTDC.cellID = 18425352185949725020, 18425070710973014364, 18424789235996303708, 18424507761019593052, 18424507782494429532...

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

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

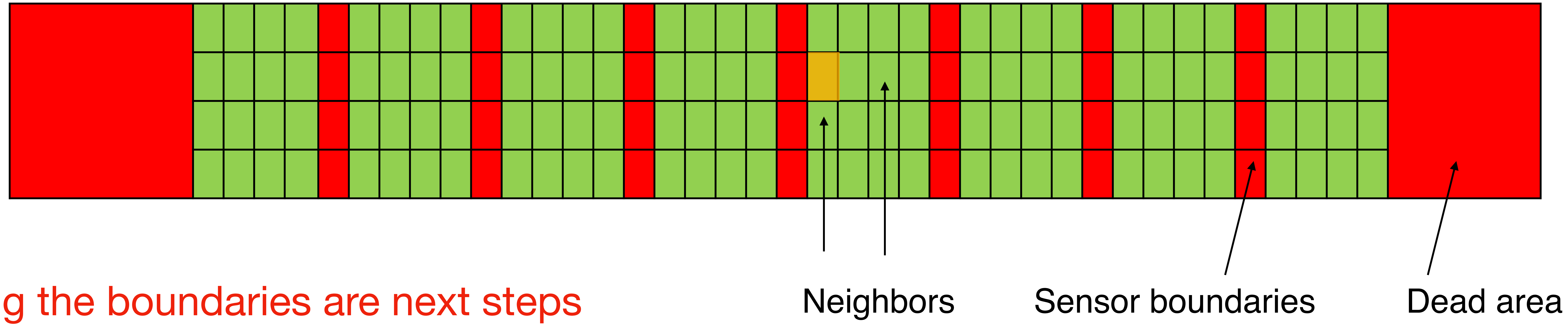
Original EICrecon:

- Pixels (cells) are populated in a regular grid from left edge to the right edge
- Original Y-direction pitch was 100 µm instead of 500 µm, X-direction no dead space



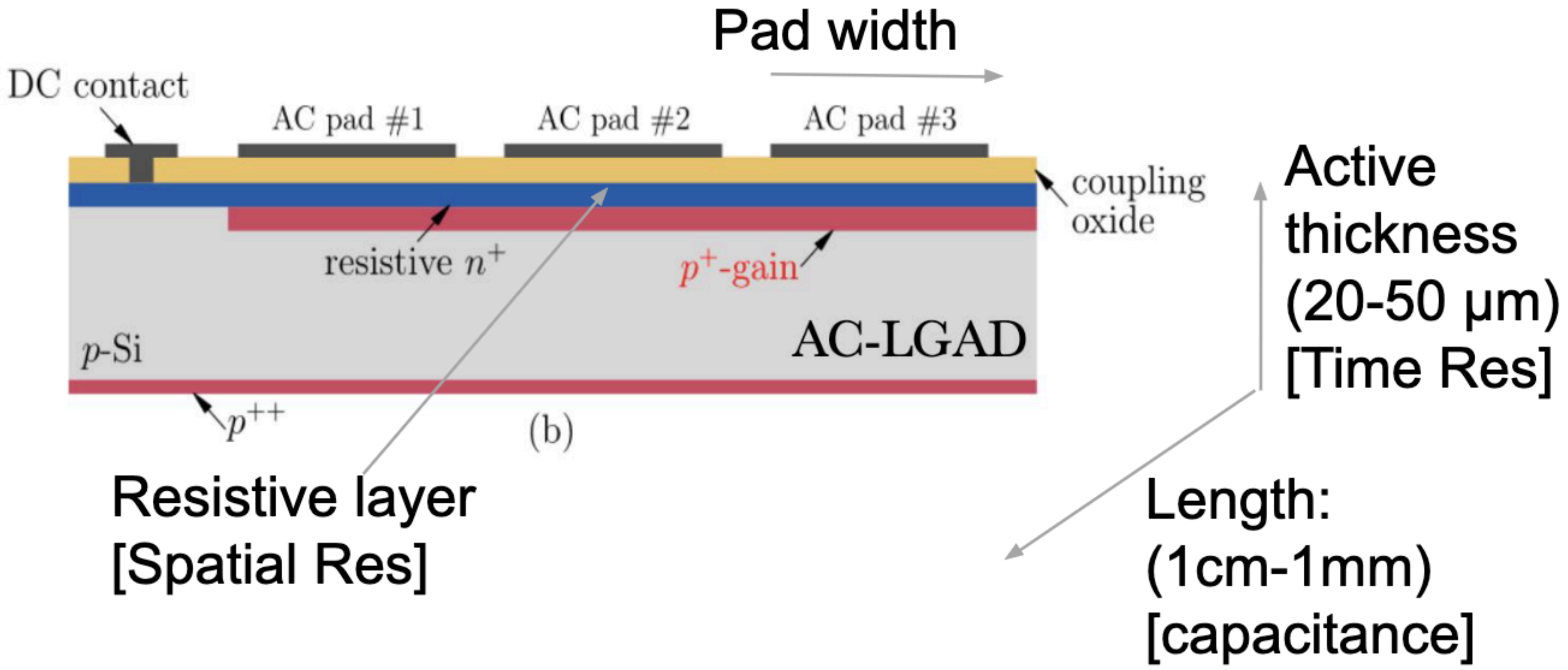
Reality:

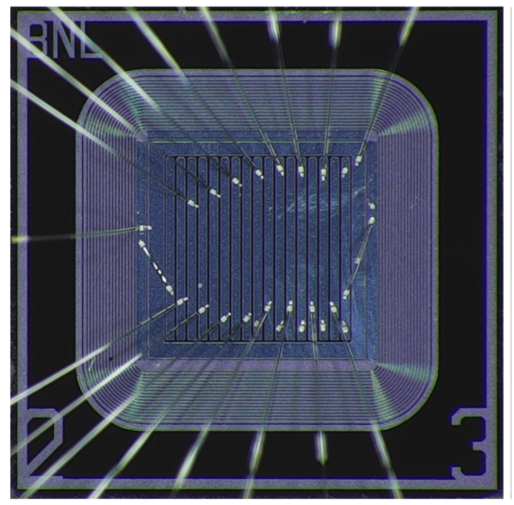
- Dead space in the left and right edges.
- Dead space between every nth cell.

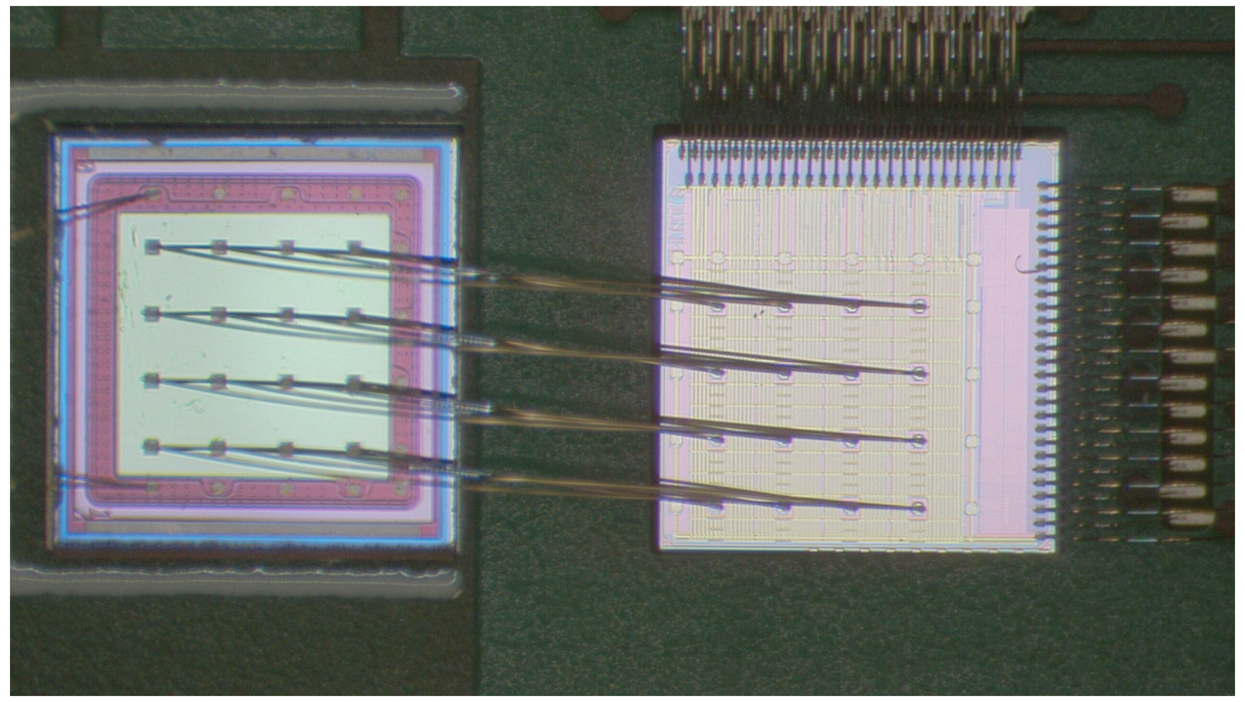


Finding the boundaries are next steps

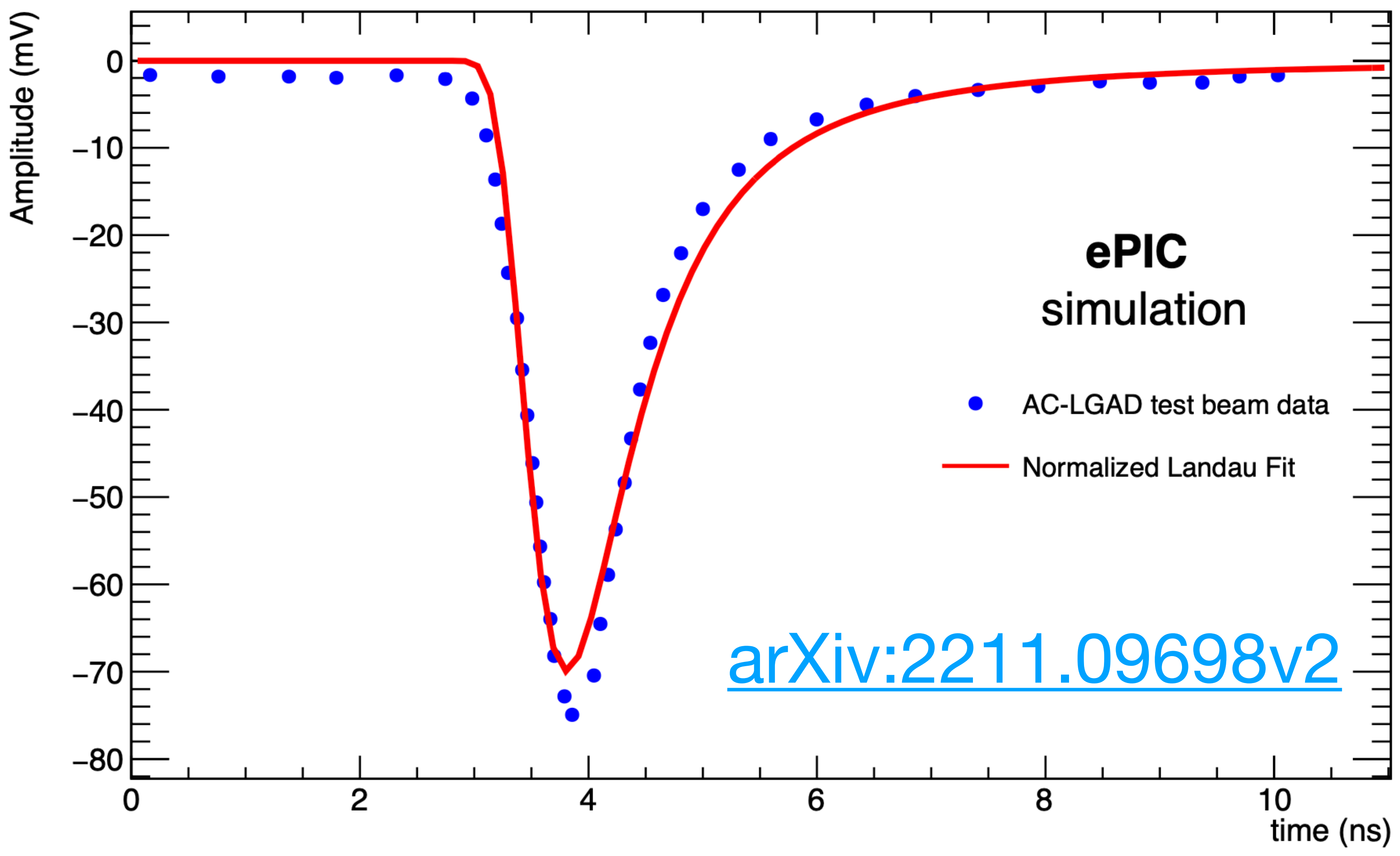
Input from sensor+asic+RDO

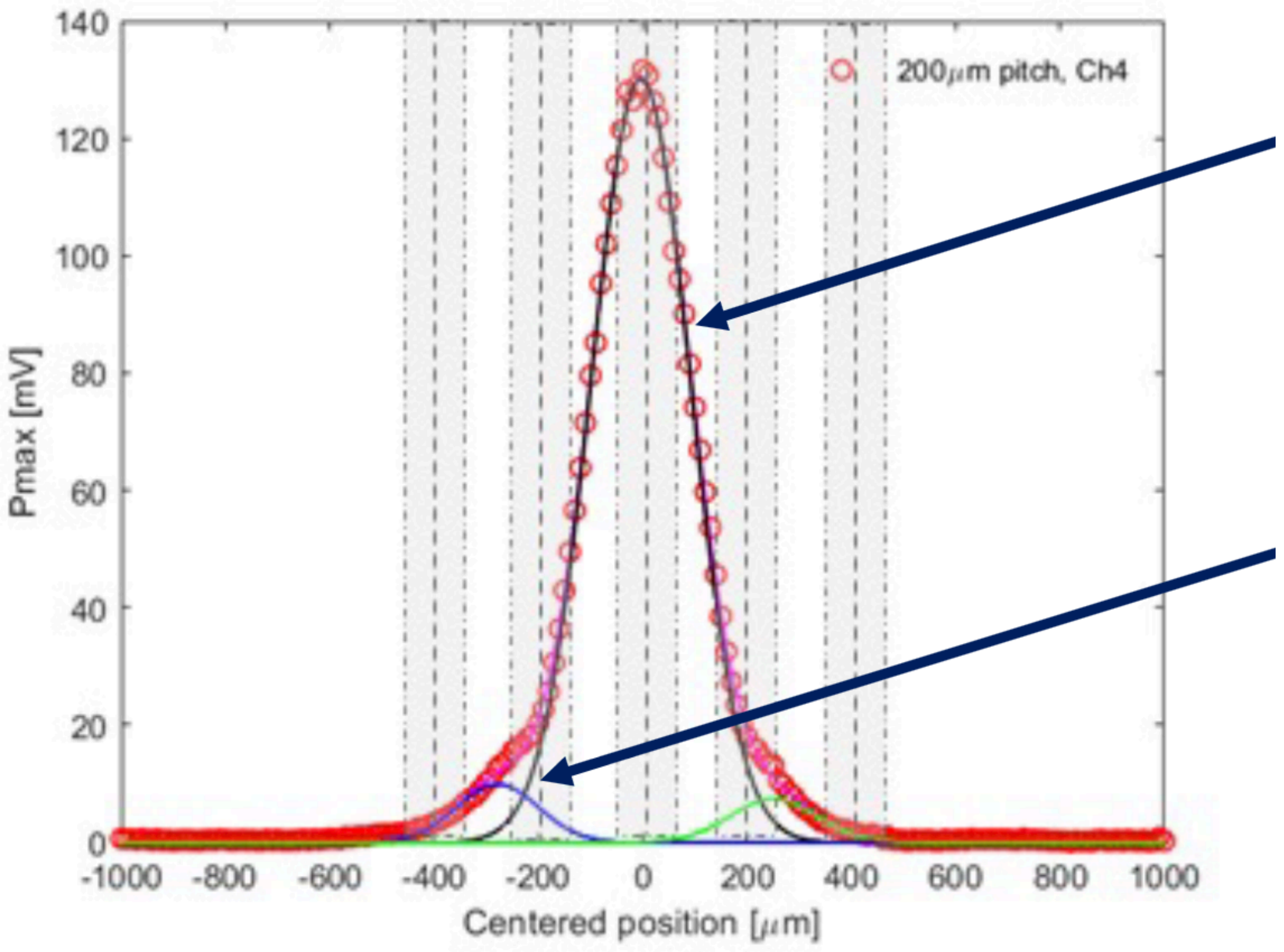


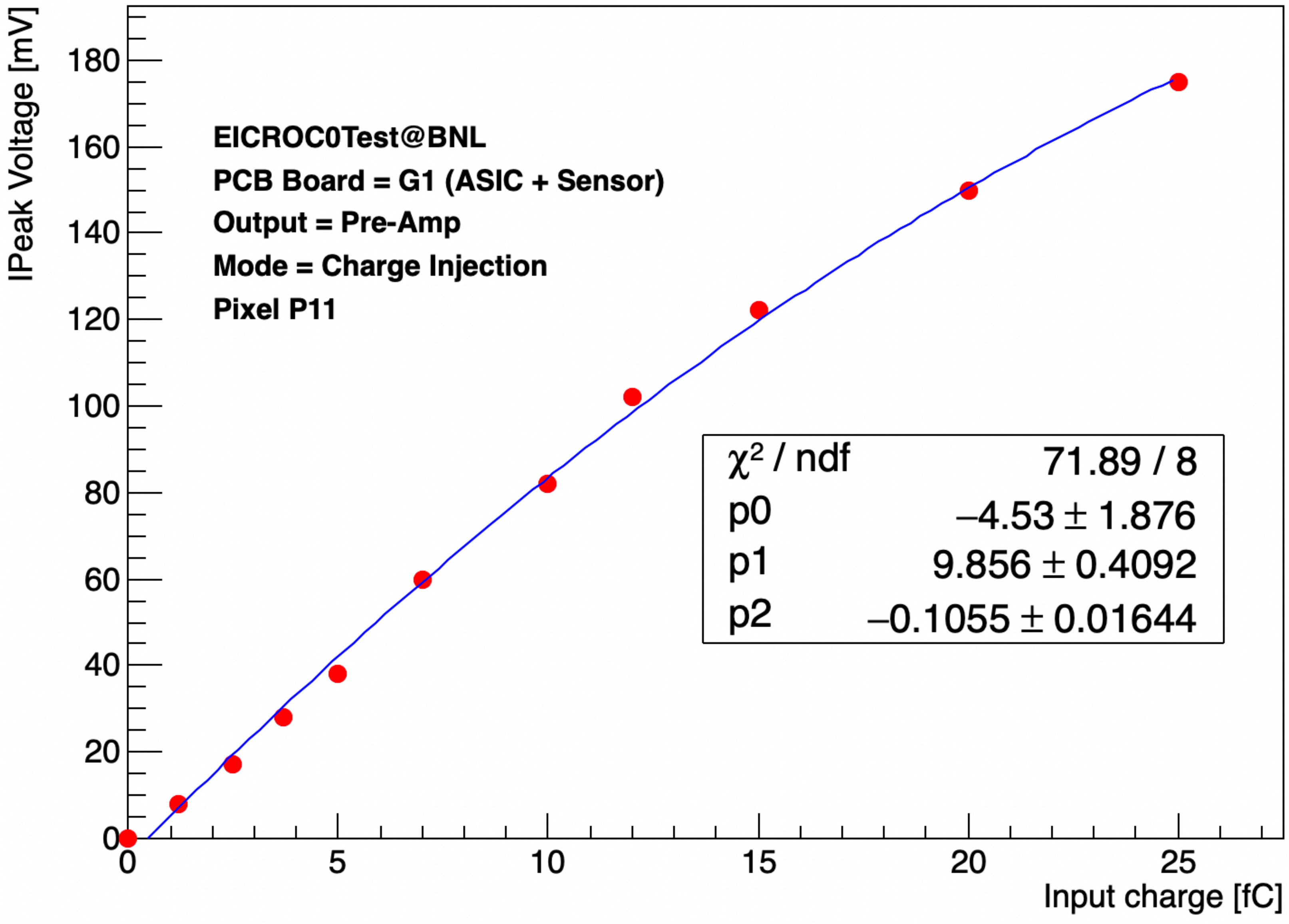




AC-LGAD EICROC0





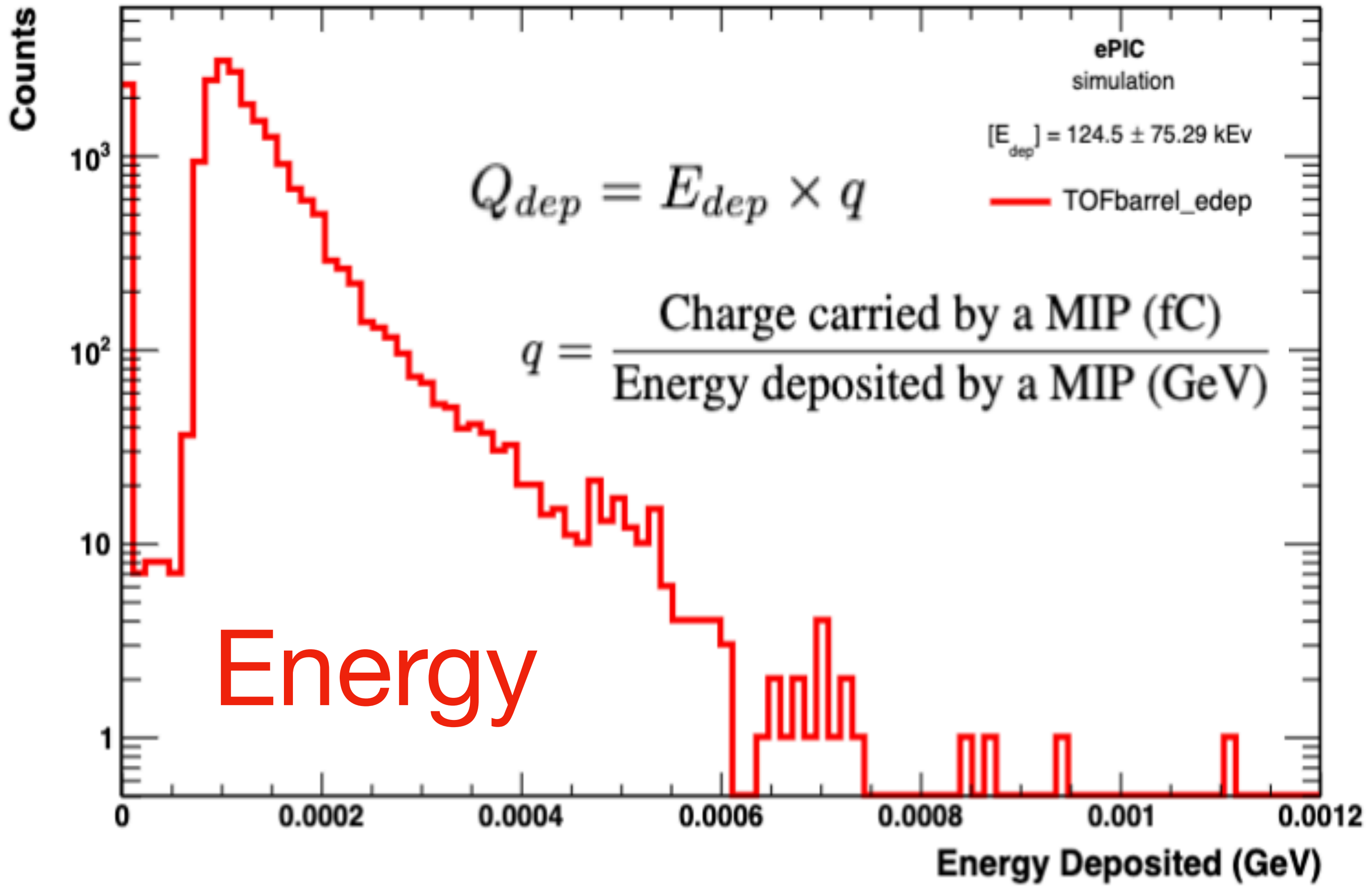


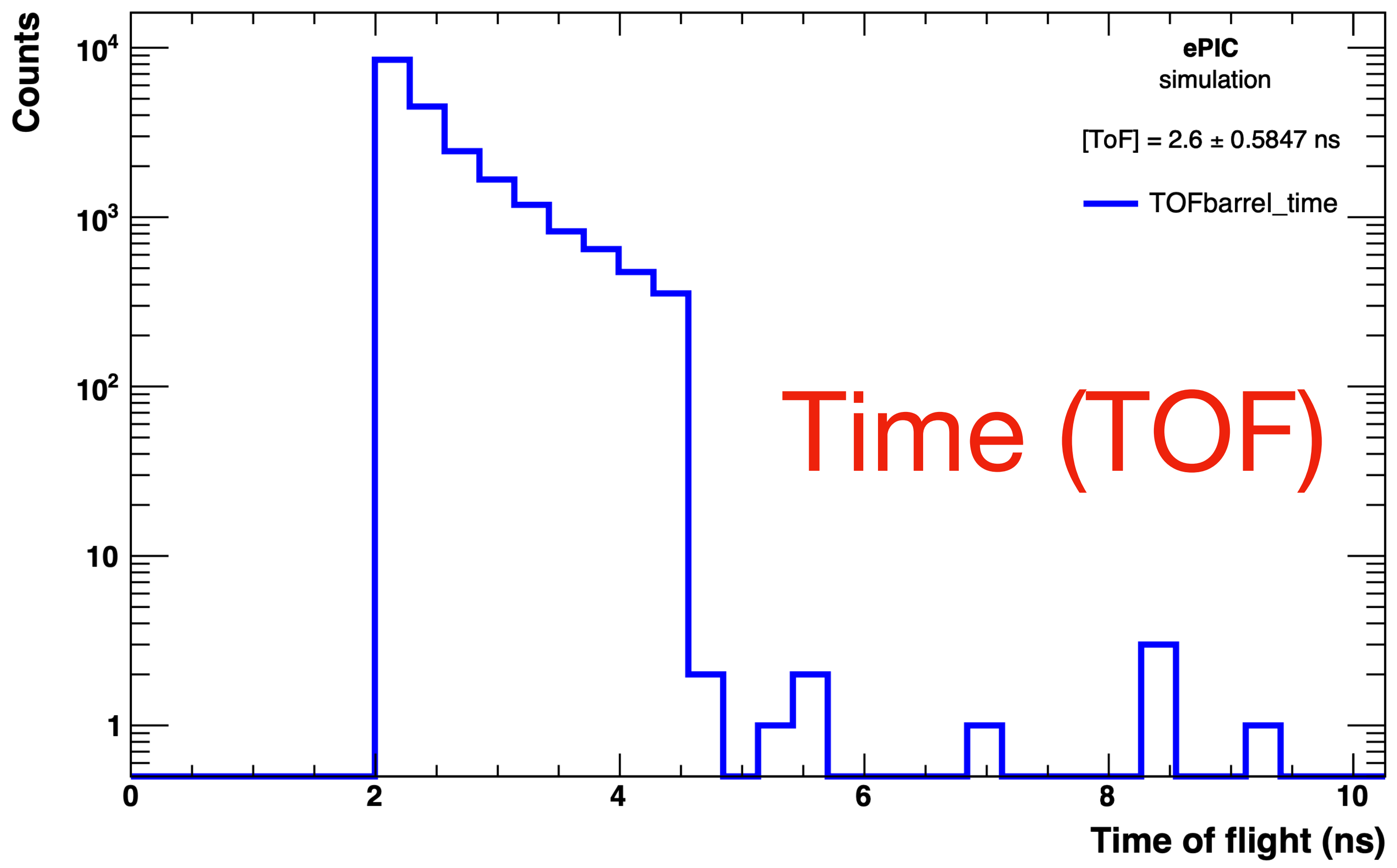
Input from hardware on signal shape, charge spread, pre-Amp output

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

Event Generation & Transport:

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



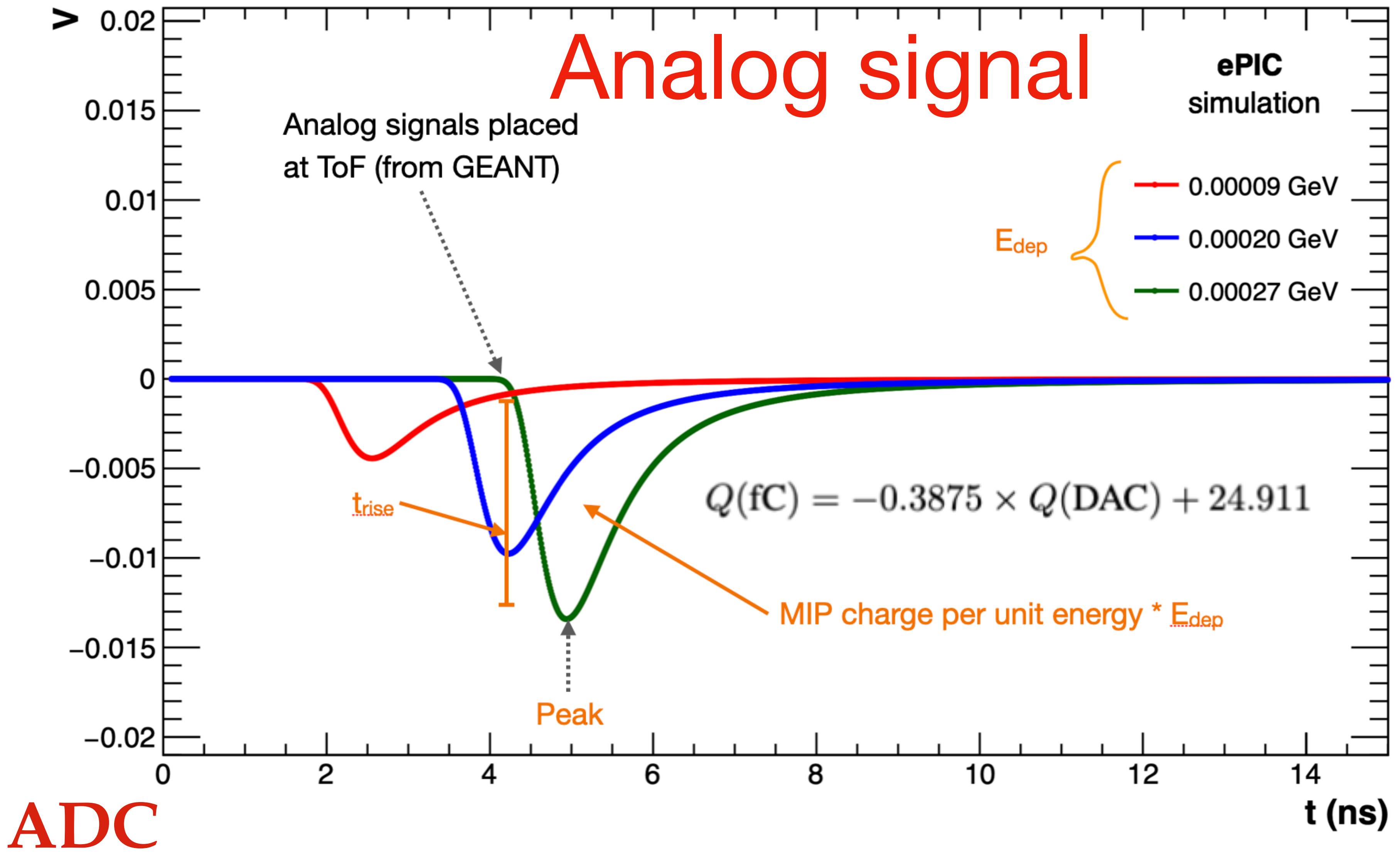


GEANT input:

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

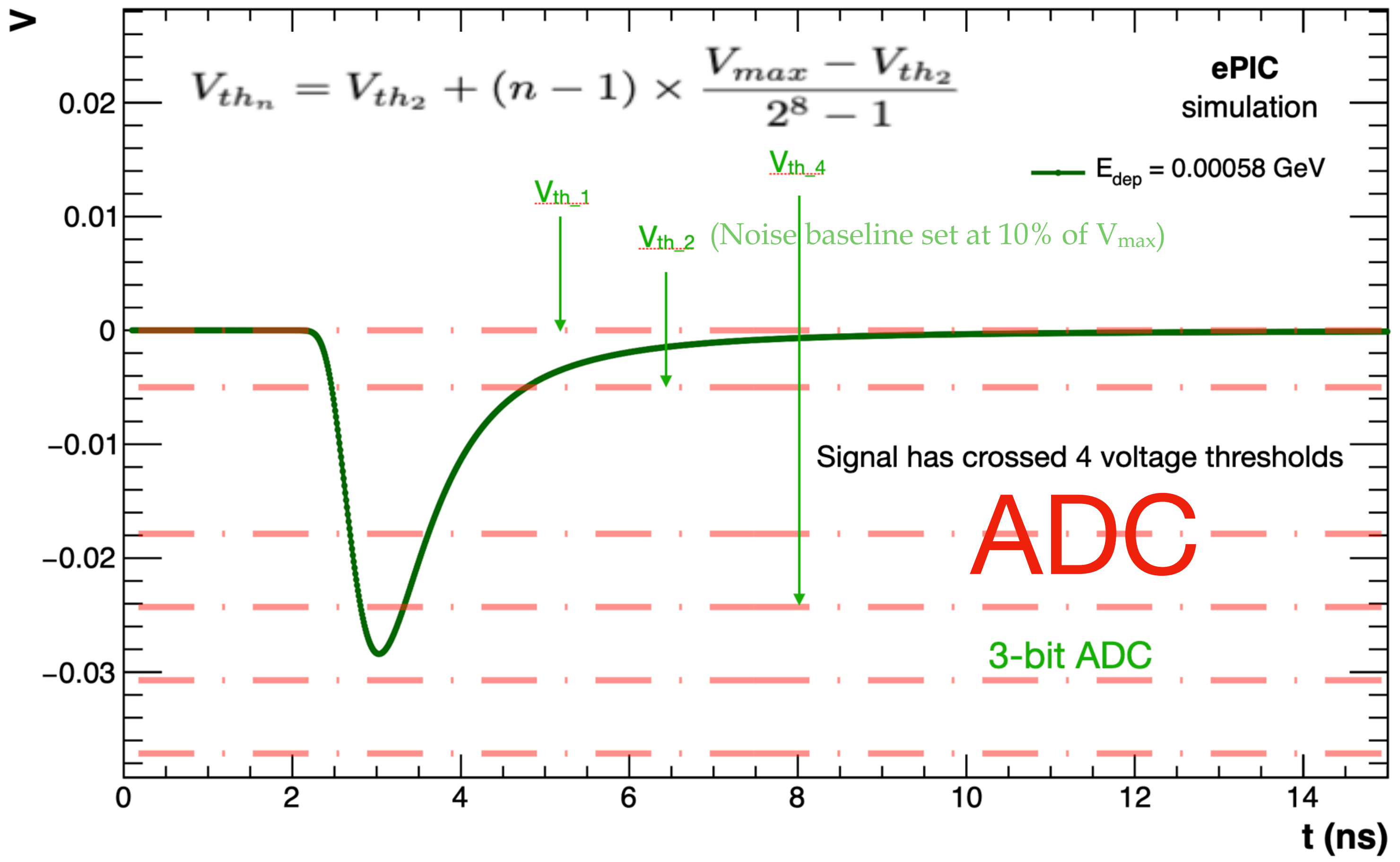
Data-driven input:

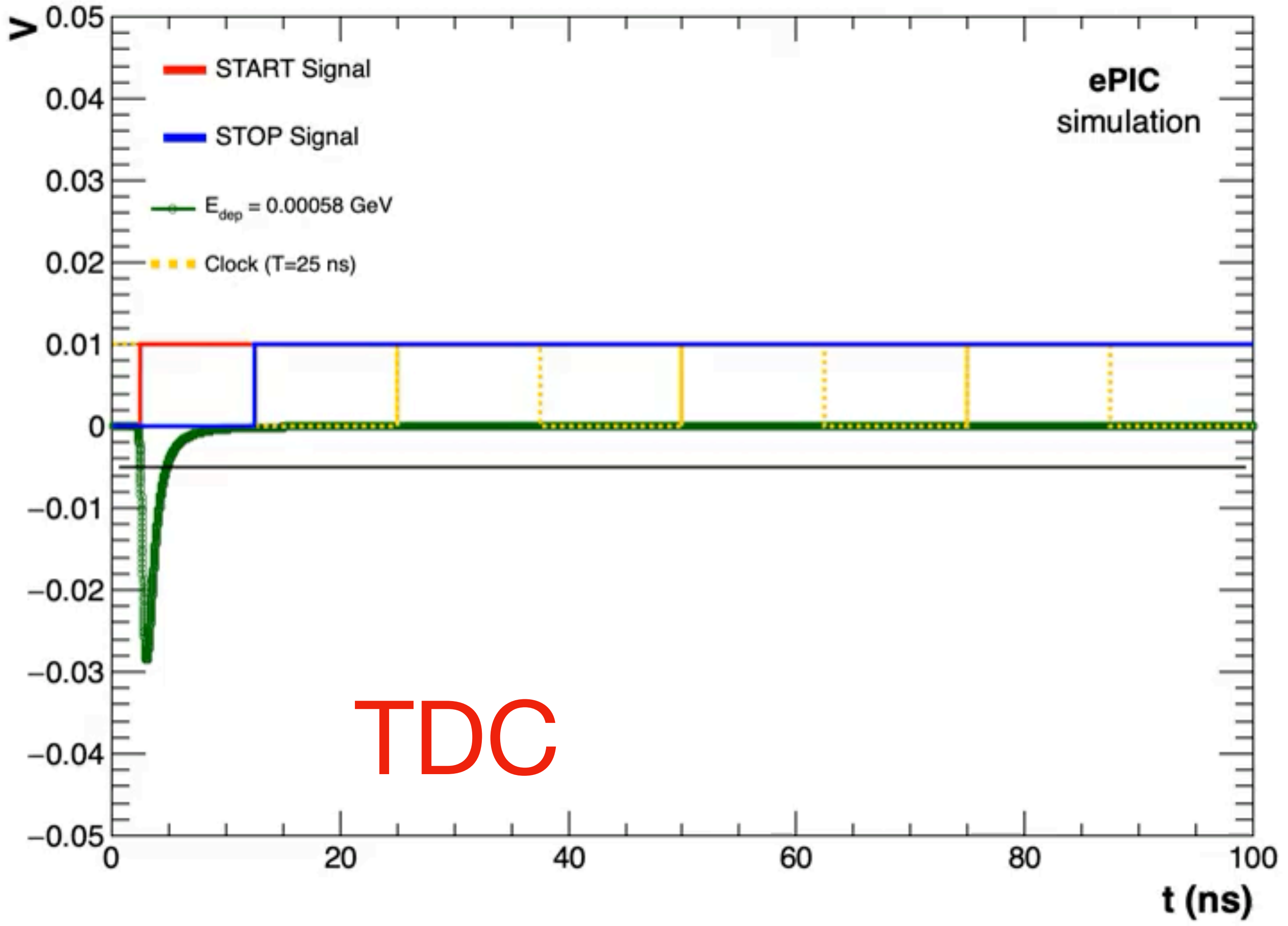
- Analog signal parameterized by Landau distribution
- Risetime ~ 450 ps
- Shape width ~294 ps.



Voltage thresholds ⟶ **8-bit ADC**

CLK + START/STOP ⟶ **10-bit TDC**

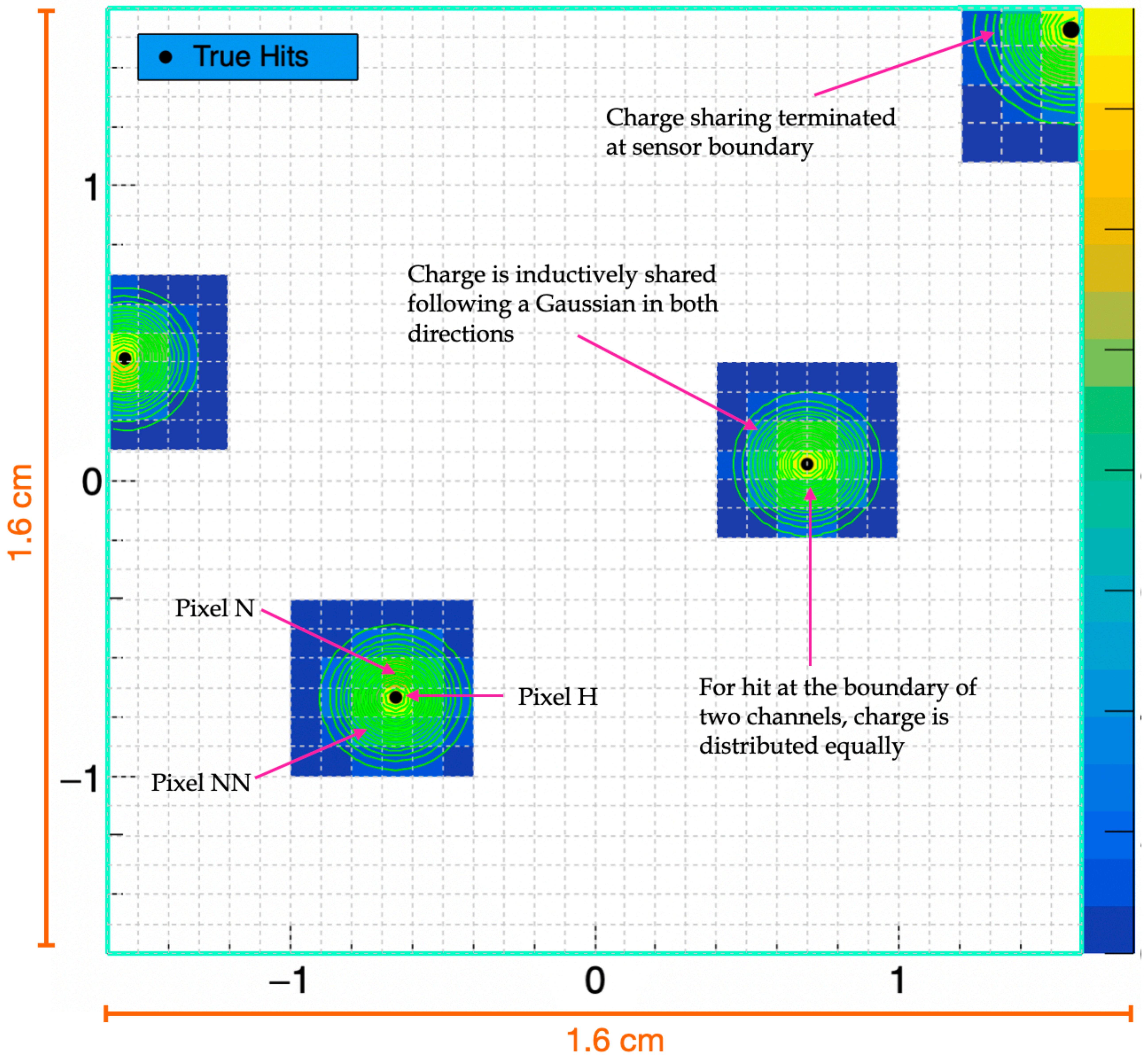




Energy Deposited ⟶ Charge ⟶ Peak of Signal ⟶ ADC

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

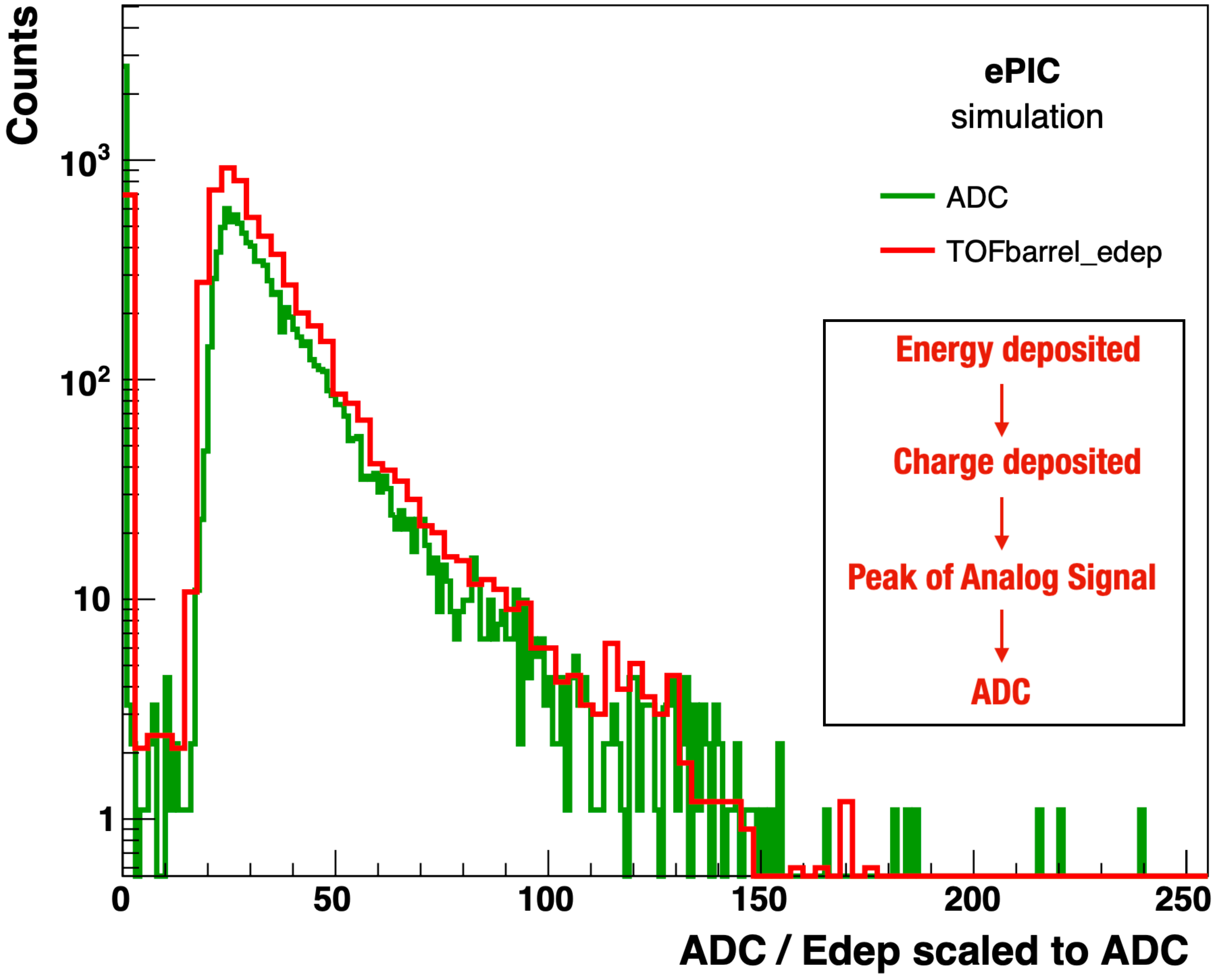
Charge sharing: Pixel geometry



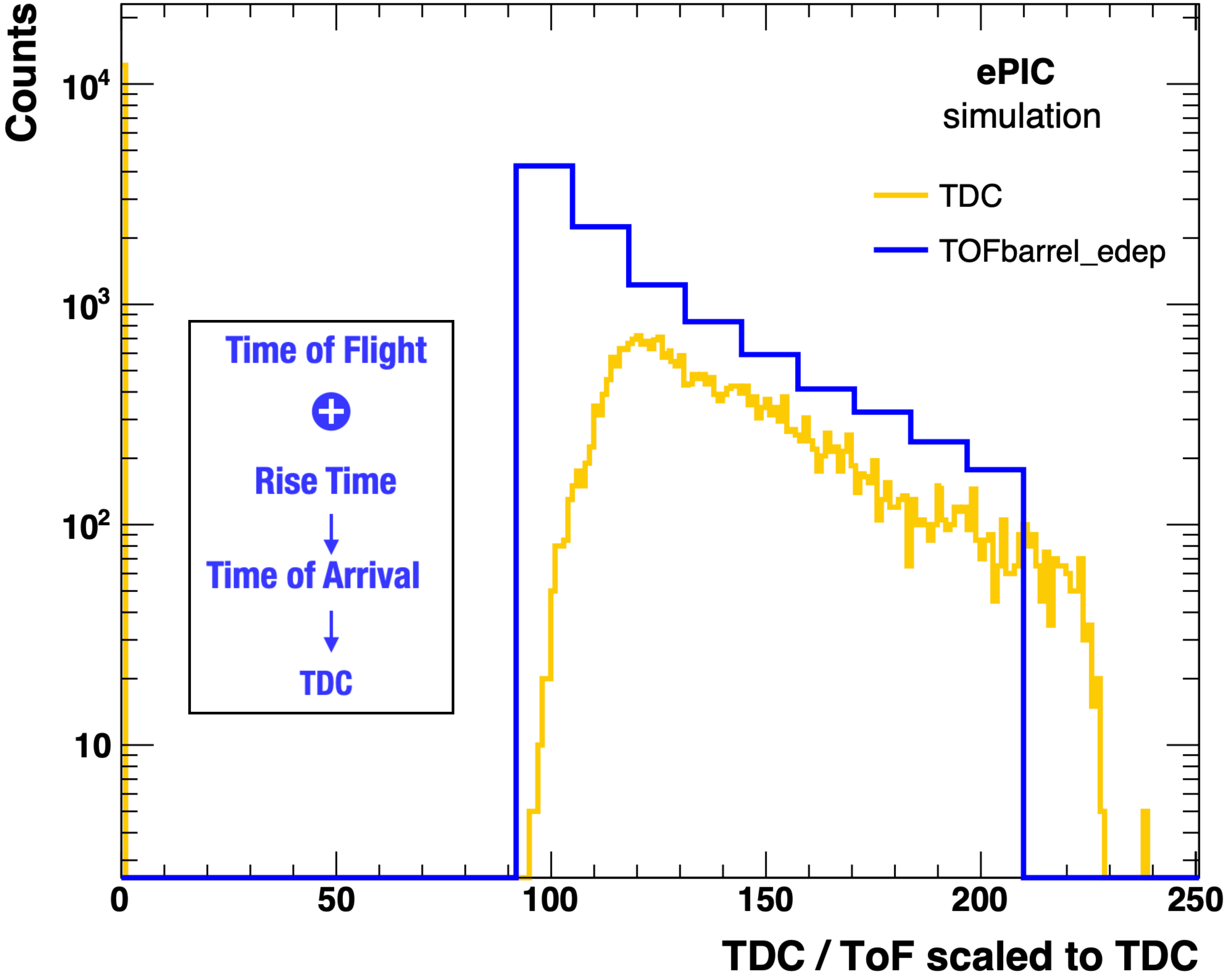
- A hit in Pixel H has a Gaussian-like distribution of charge vs distance (Charge shared inductively in sensor).
- The Gaussian peaks at the center of Pixel H, and has a standard deviation in X and Y, that can be tuned (Property of AC-LGAD).
- The maximum distance to which Pixel H can induce charge can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

Energy/ADC & time/TDC comparison

ADC and E_{dep} comparion

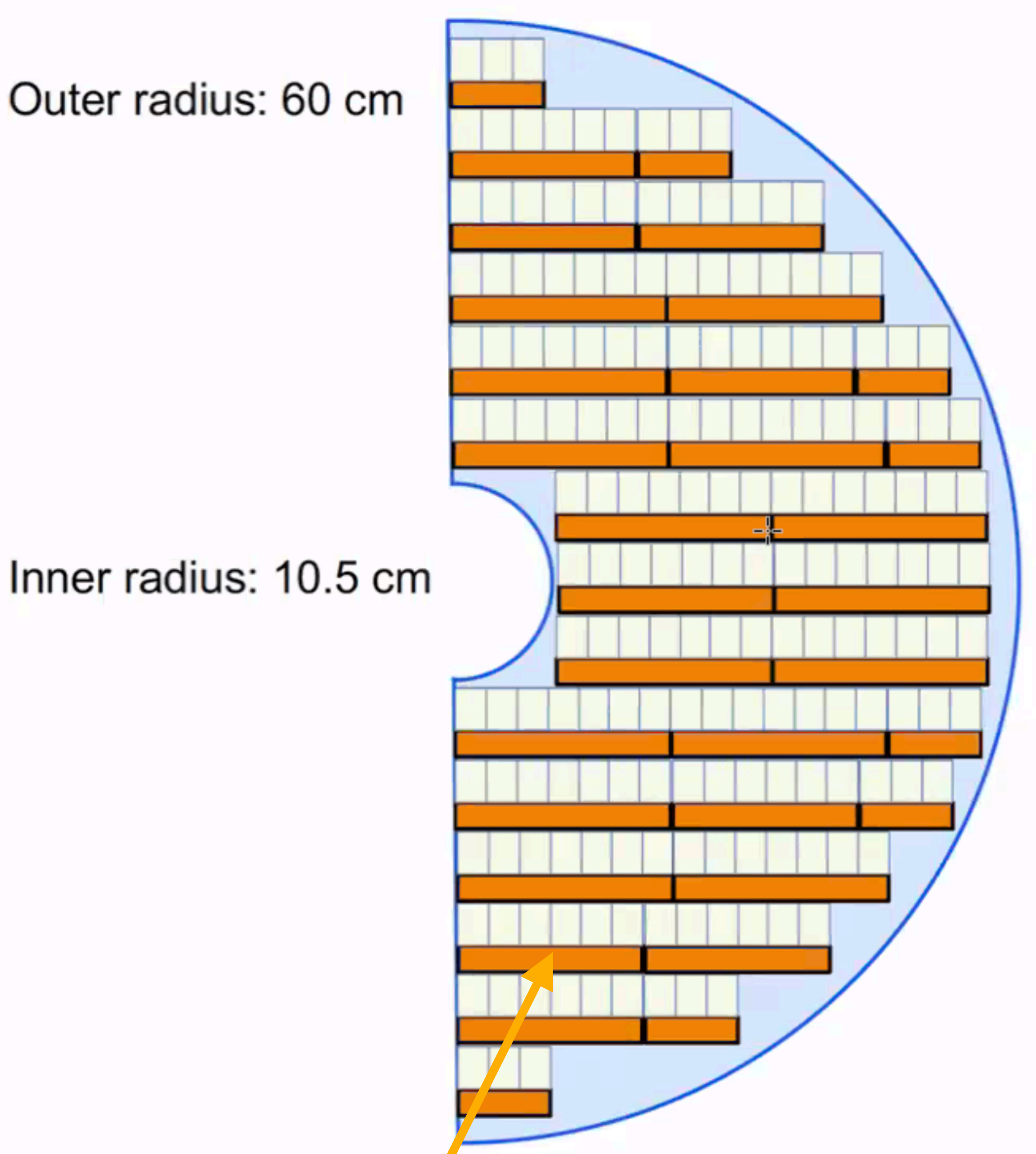


TDC and ToF



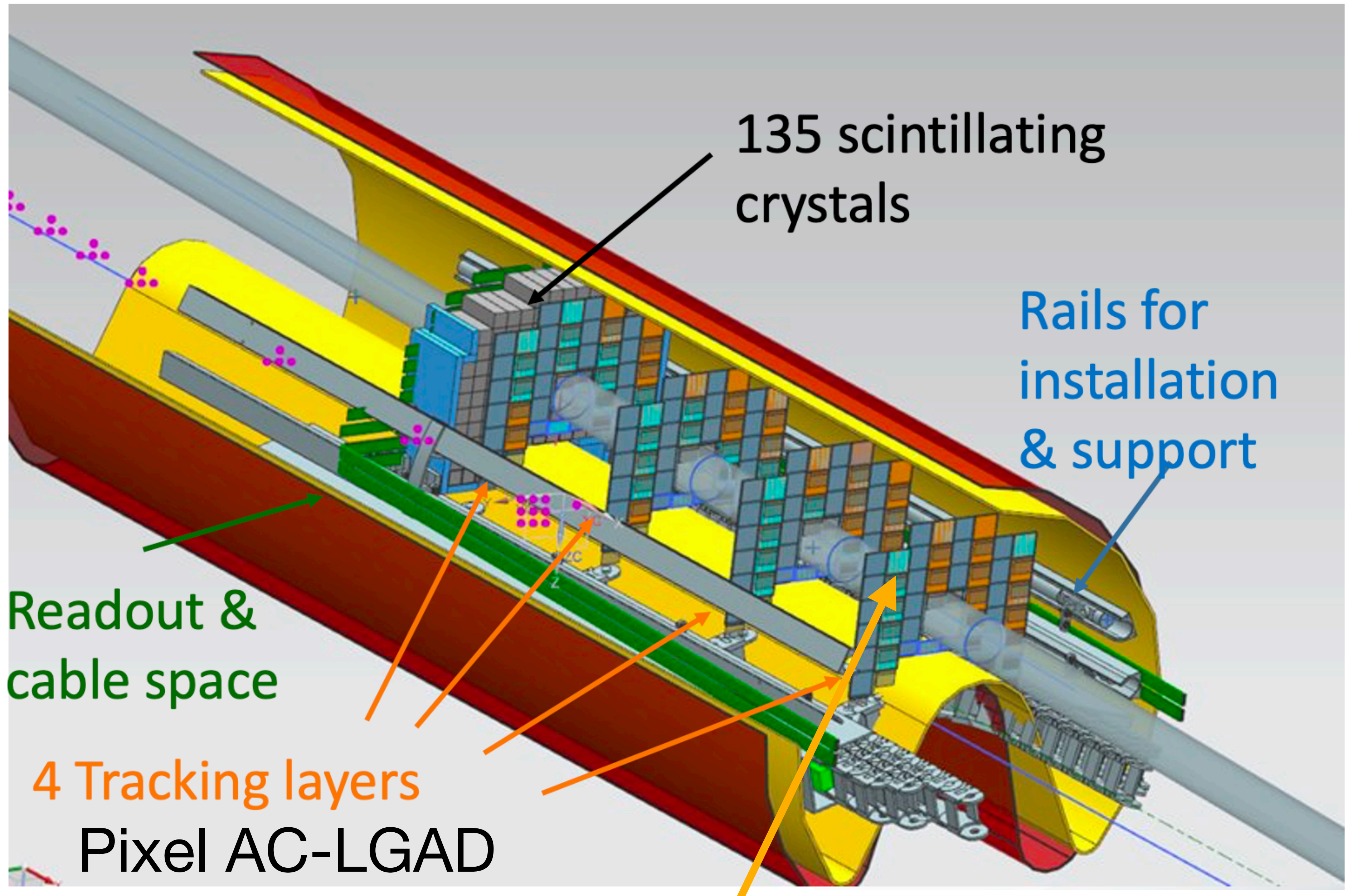
ADC and TDC distribution are final output consistent with GEANT input

Other AC-LGAD systems



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 one sensors

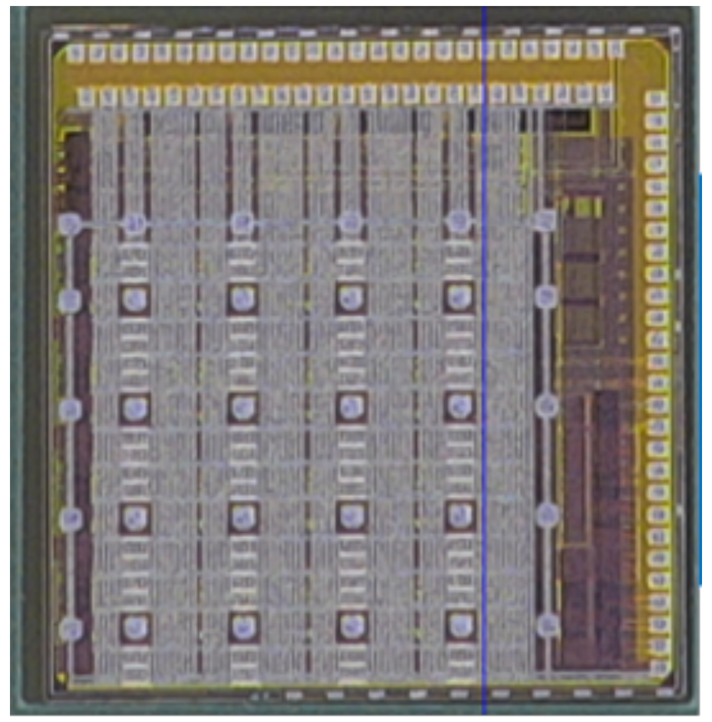
One square is four sensors

Pixel AC-LGAD

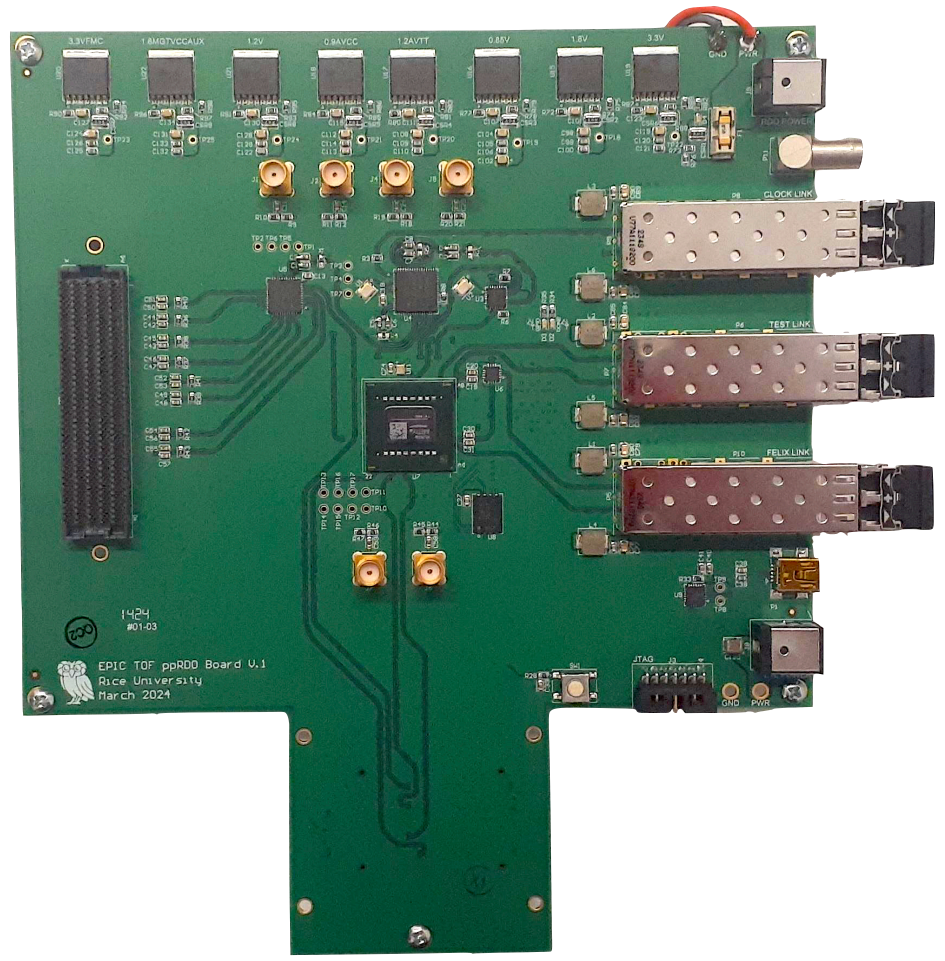
FTOF and B0 digitization in progress ….

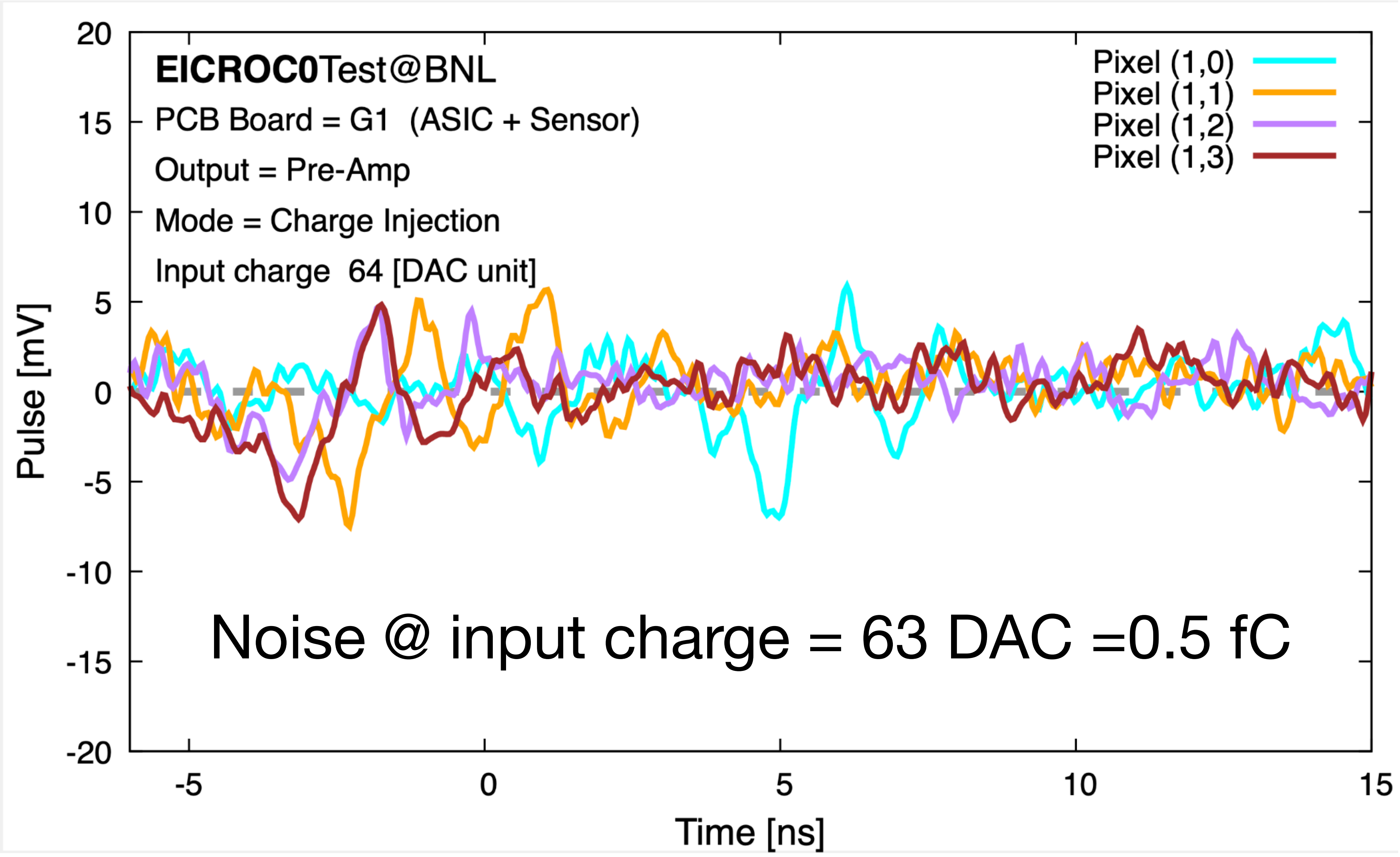
Noise implementation

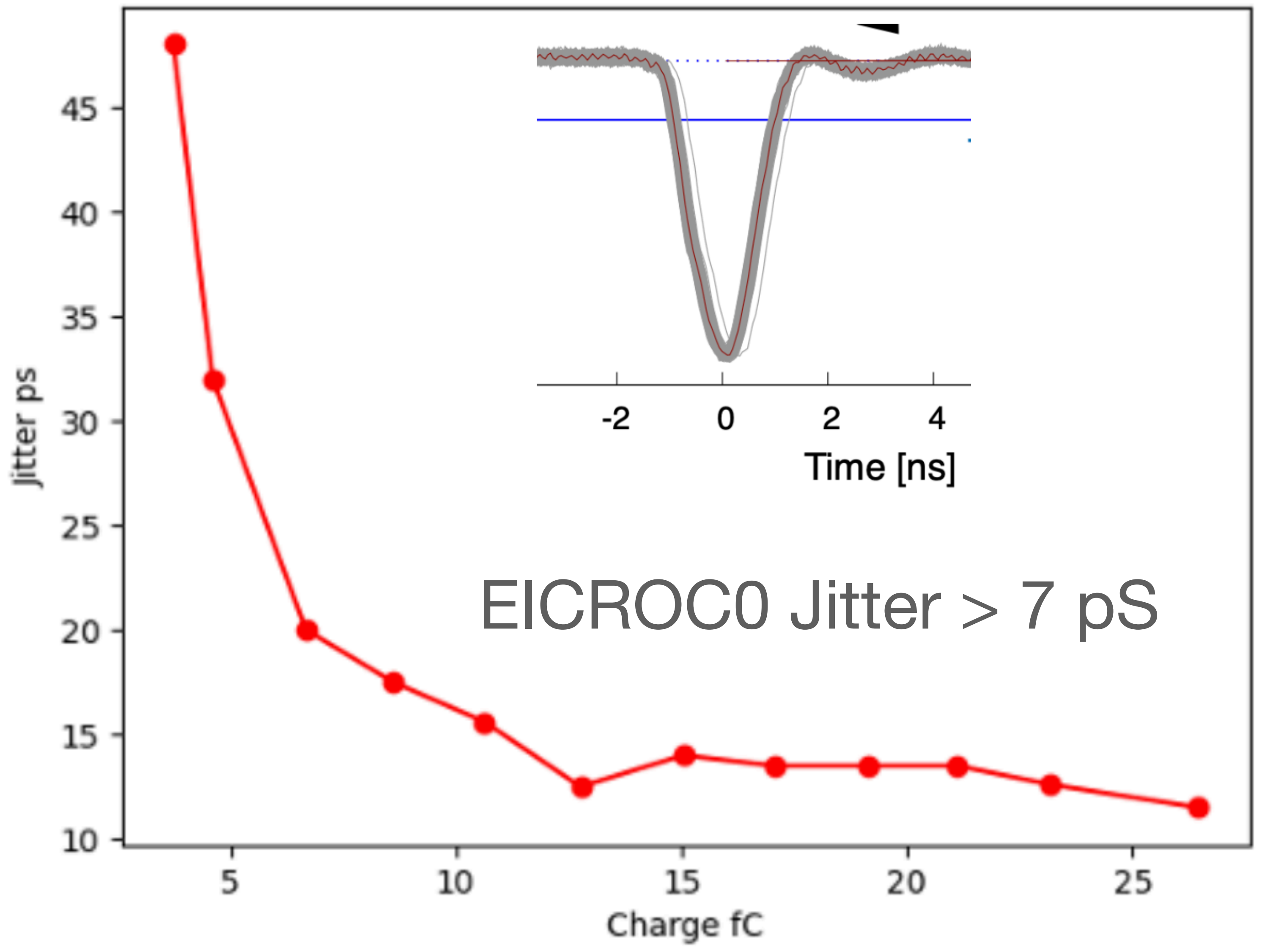
EICROC0 ASIC



AC-LGAD ppRDO

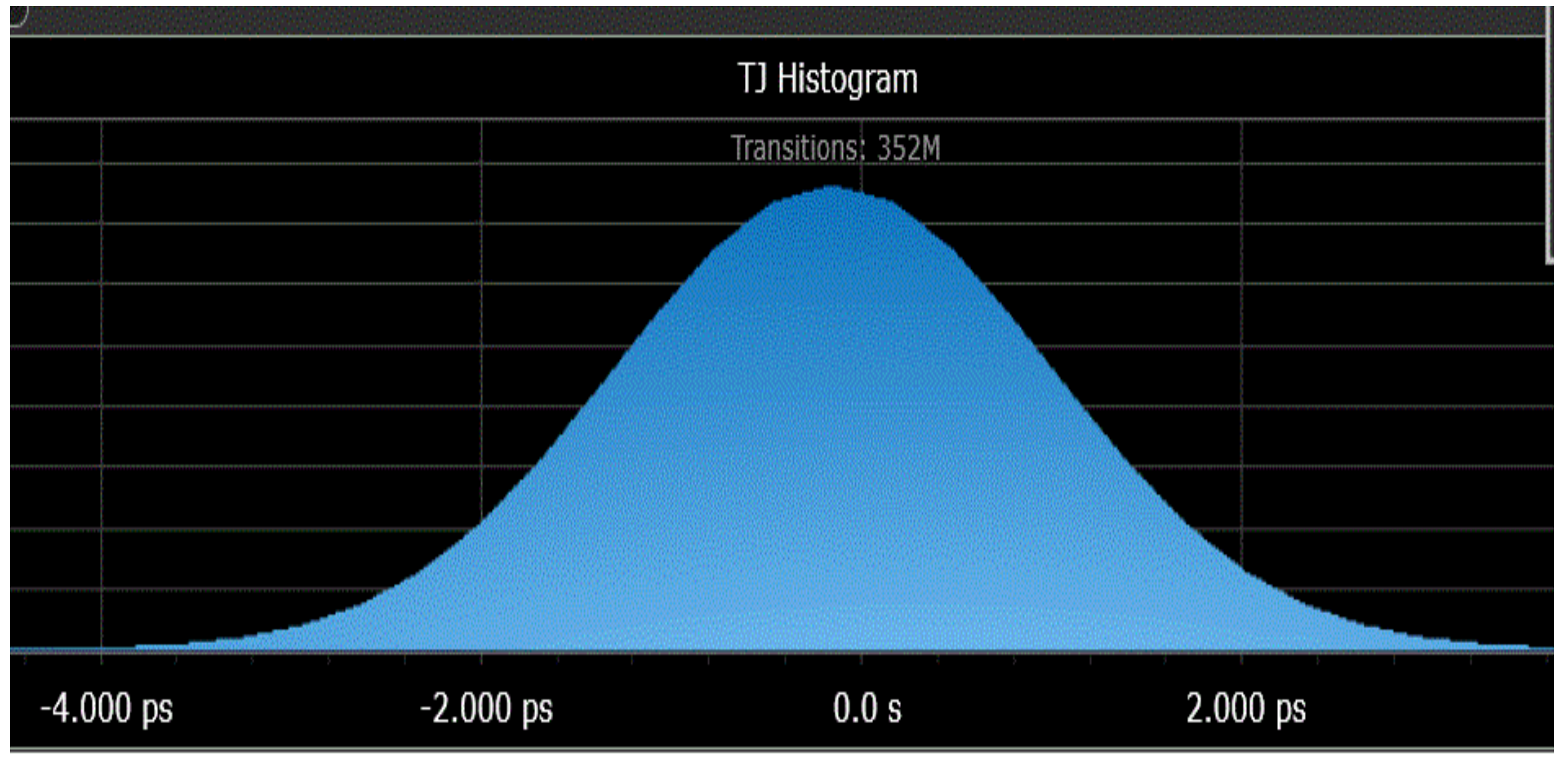






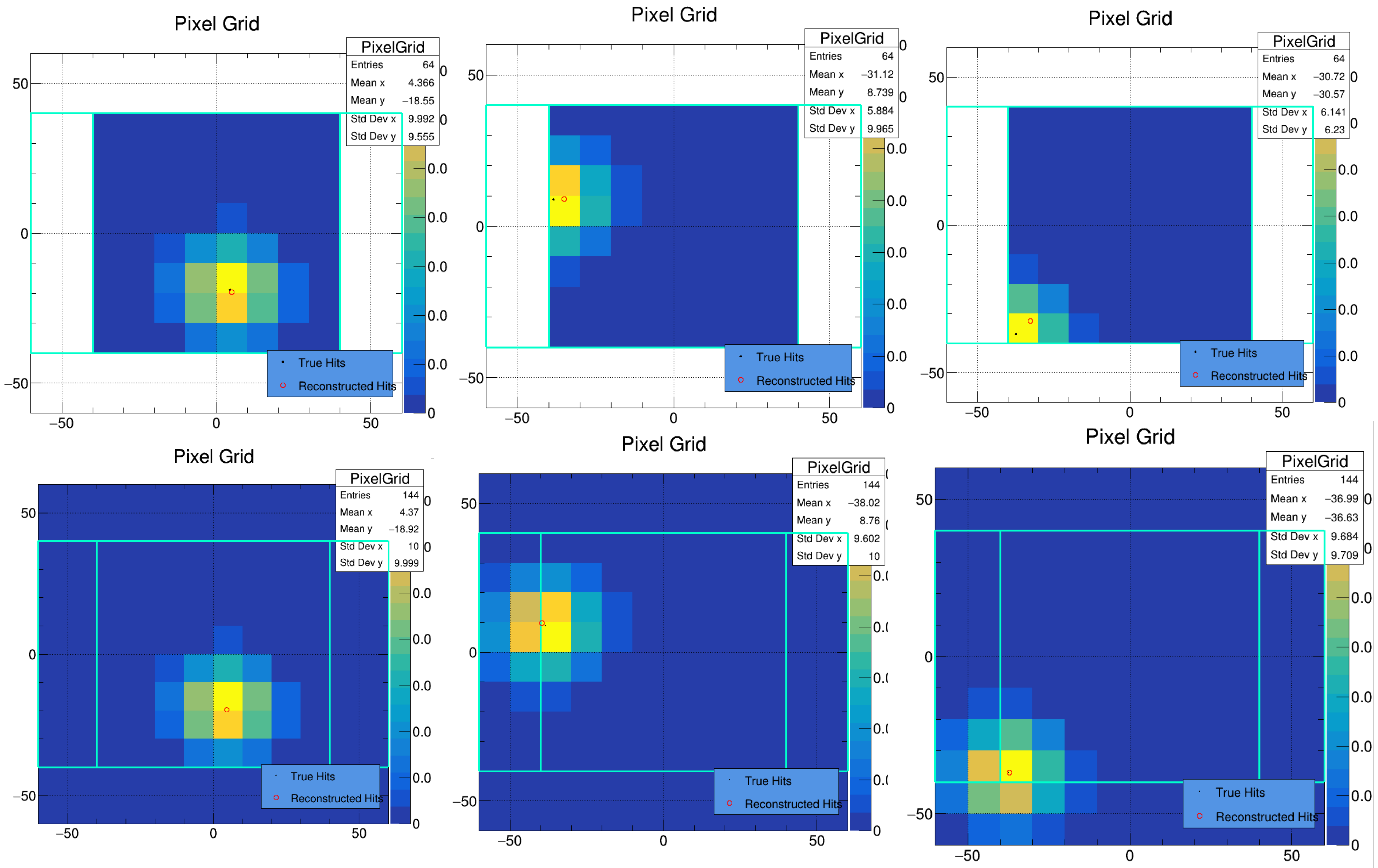
PLL output 98.5 MHz clock distribution

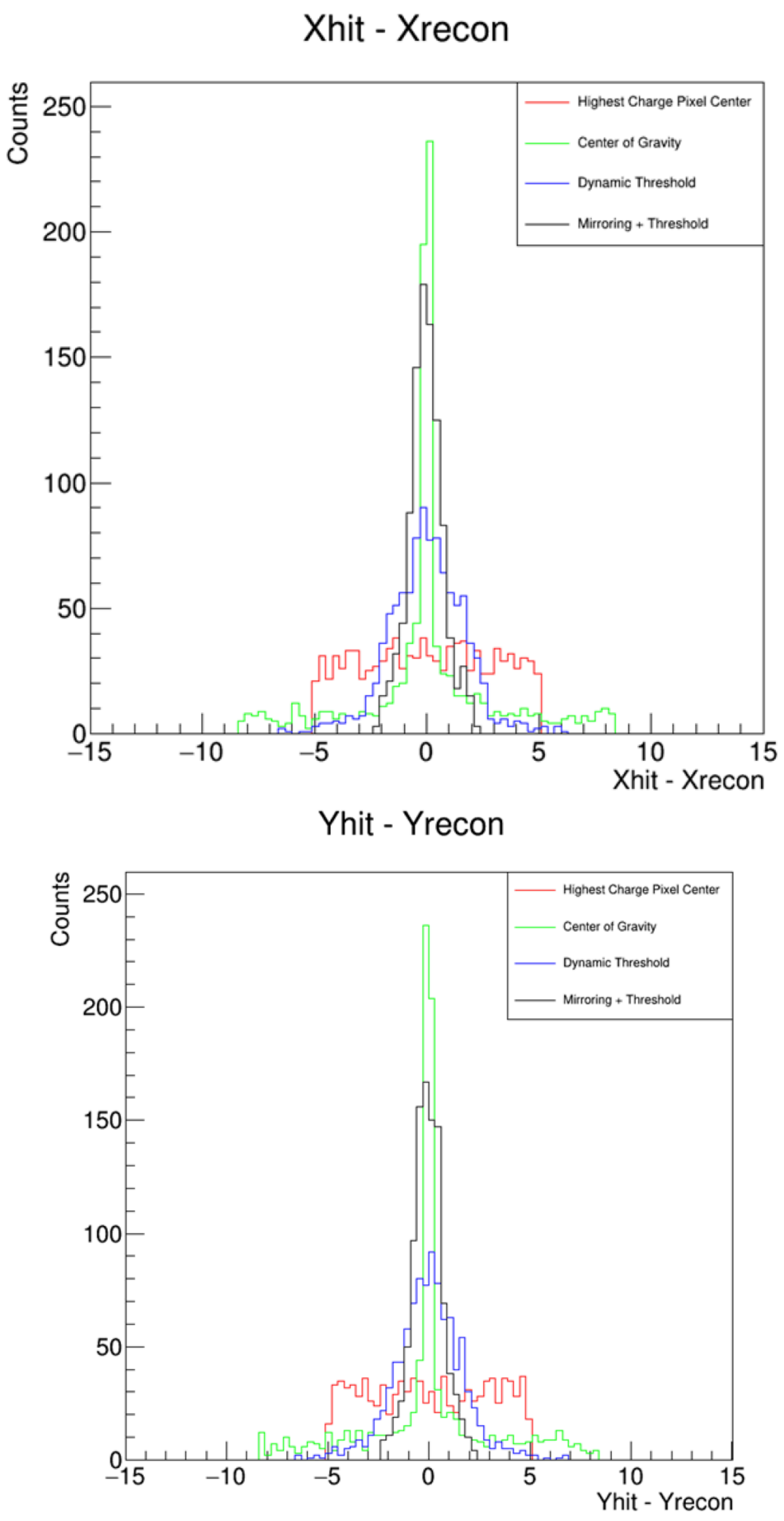
Clock jitter ~1.12 pS



Noise implementation in progress…

Reconstruction: charge sharing



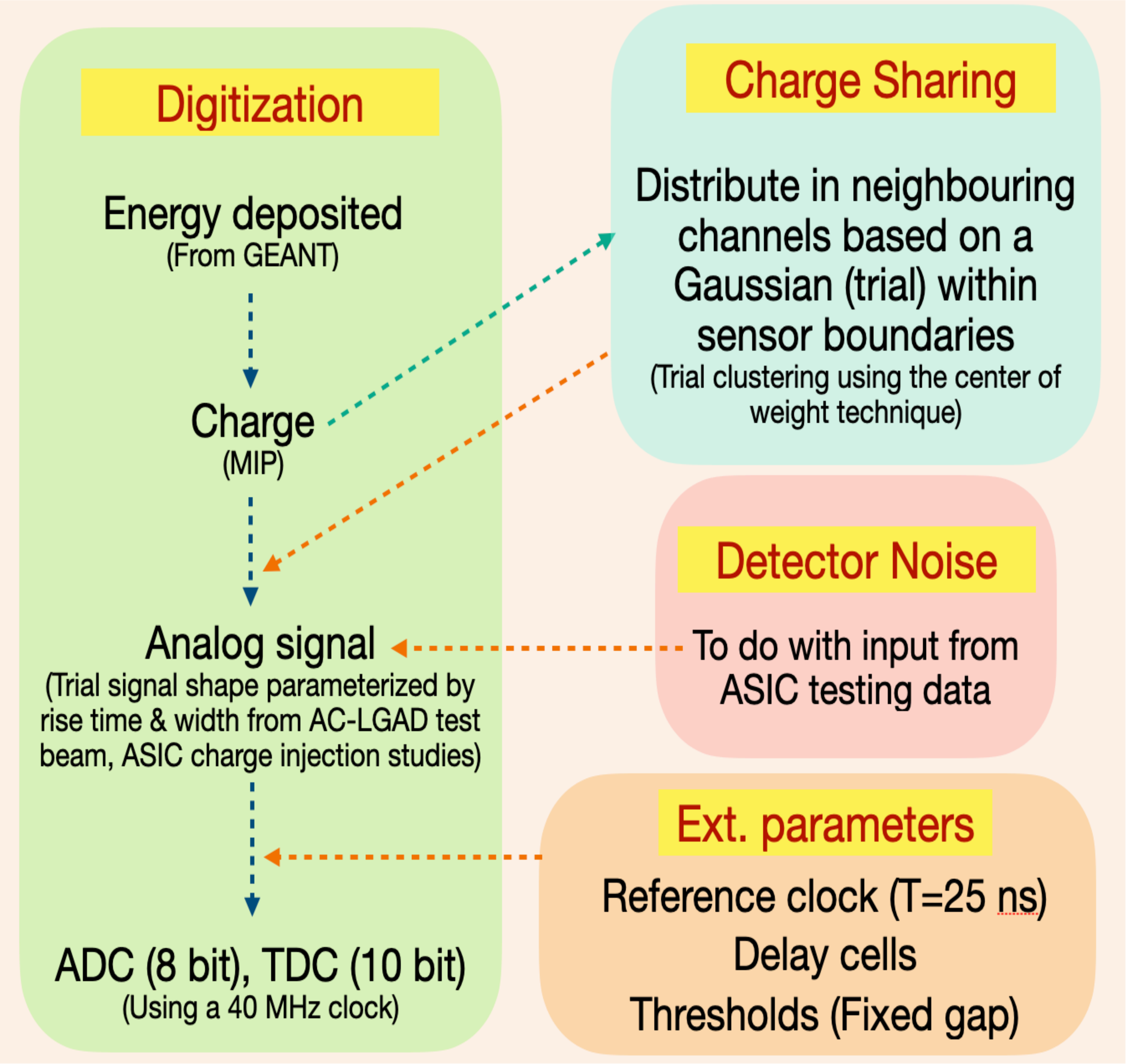


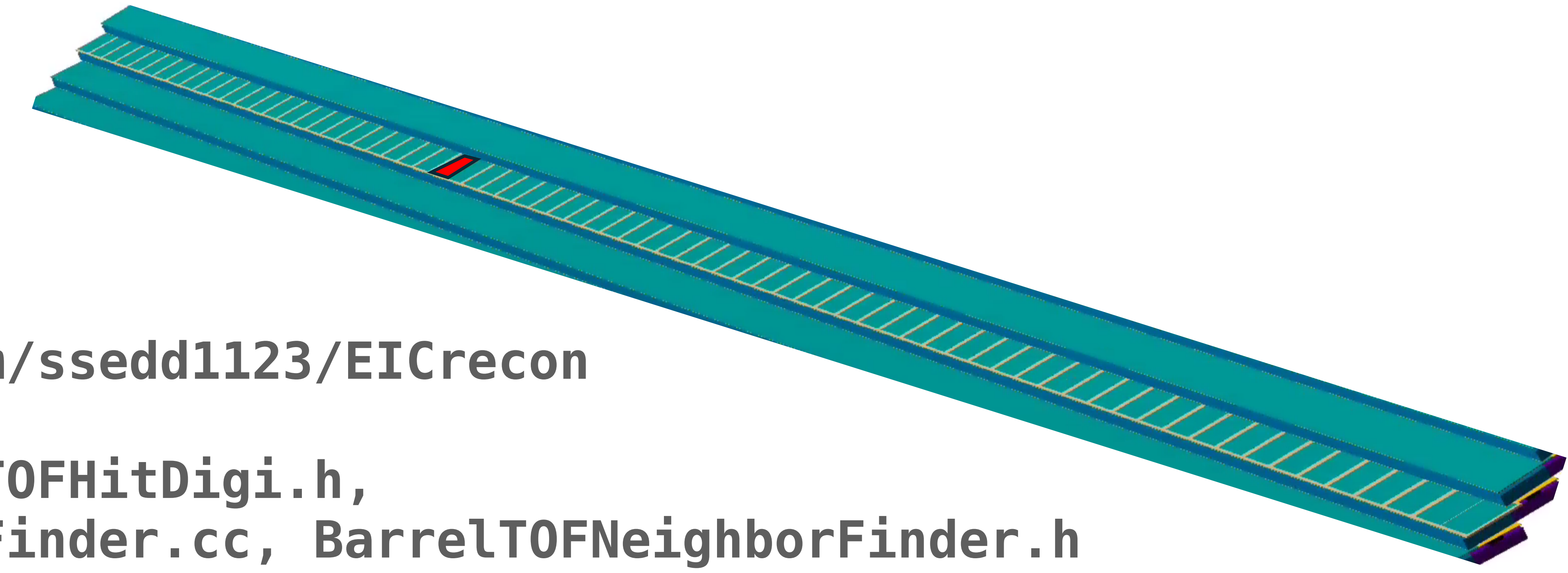
reconstruction in progress…

Brookhaven National Laboratory

Thank you

Summary of the package





```
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

Summary of Digitization in EICRecon

Importance:

- Crucial for realistic simulations driven by hardware parameters

Current Progress:

- Digitization efforts for BTOF (first AC-LGAD), FTOF, and B0 are underway
- Package divided into two modules:
  1. **Segmentation**
  2. **Digitization**

Segmentation Module:

- Implementation of boundaries and gaps in sensors
- Ongoing understanding of geometry, gaps, and segmentation for FTOF and B0

Digitization Module:

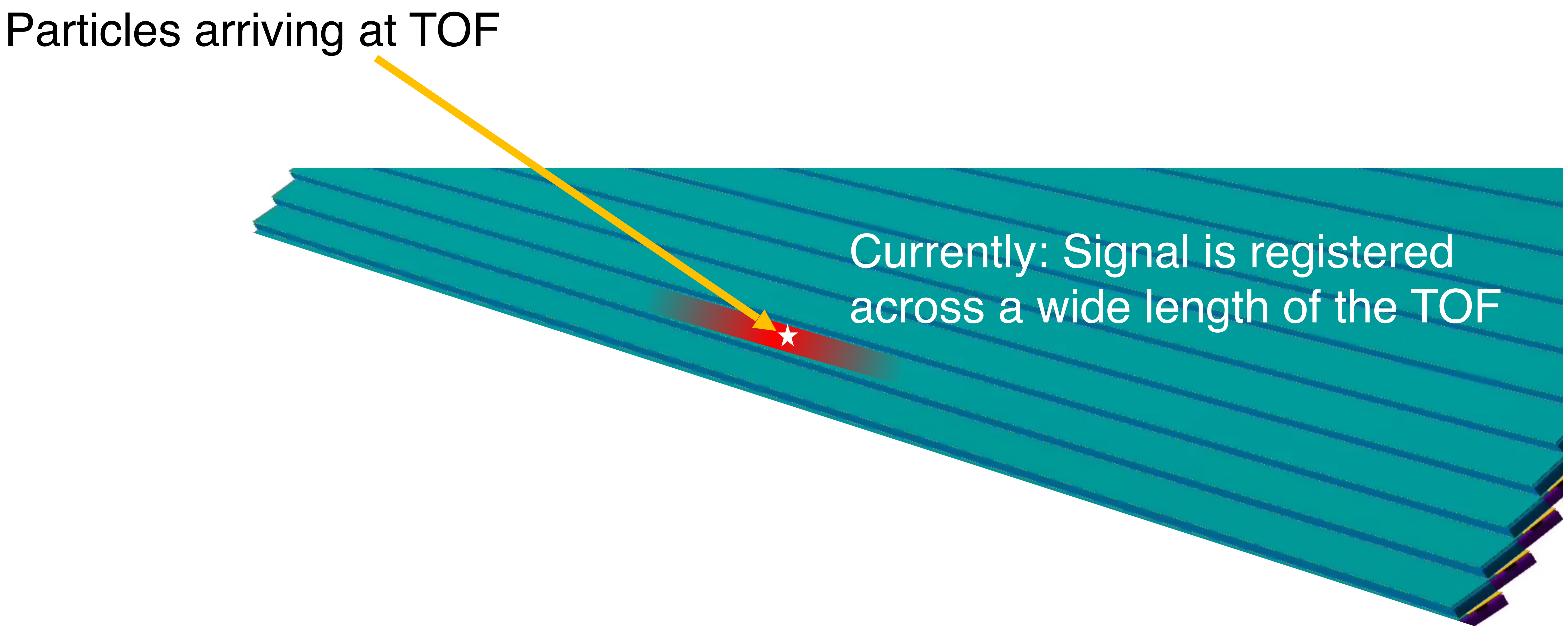
- Charge sharing model based on published sensor data is implemented (with room for adjustments)
- Noise implementation strategy developed, awaiting execution

Next Steps:

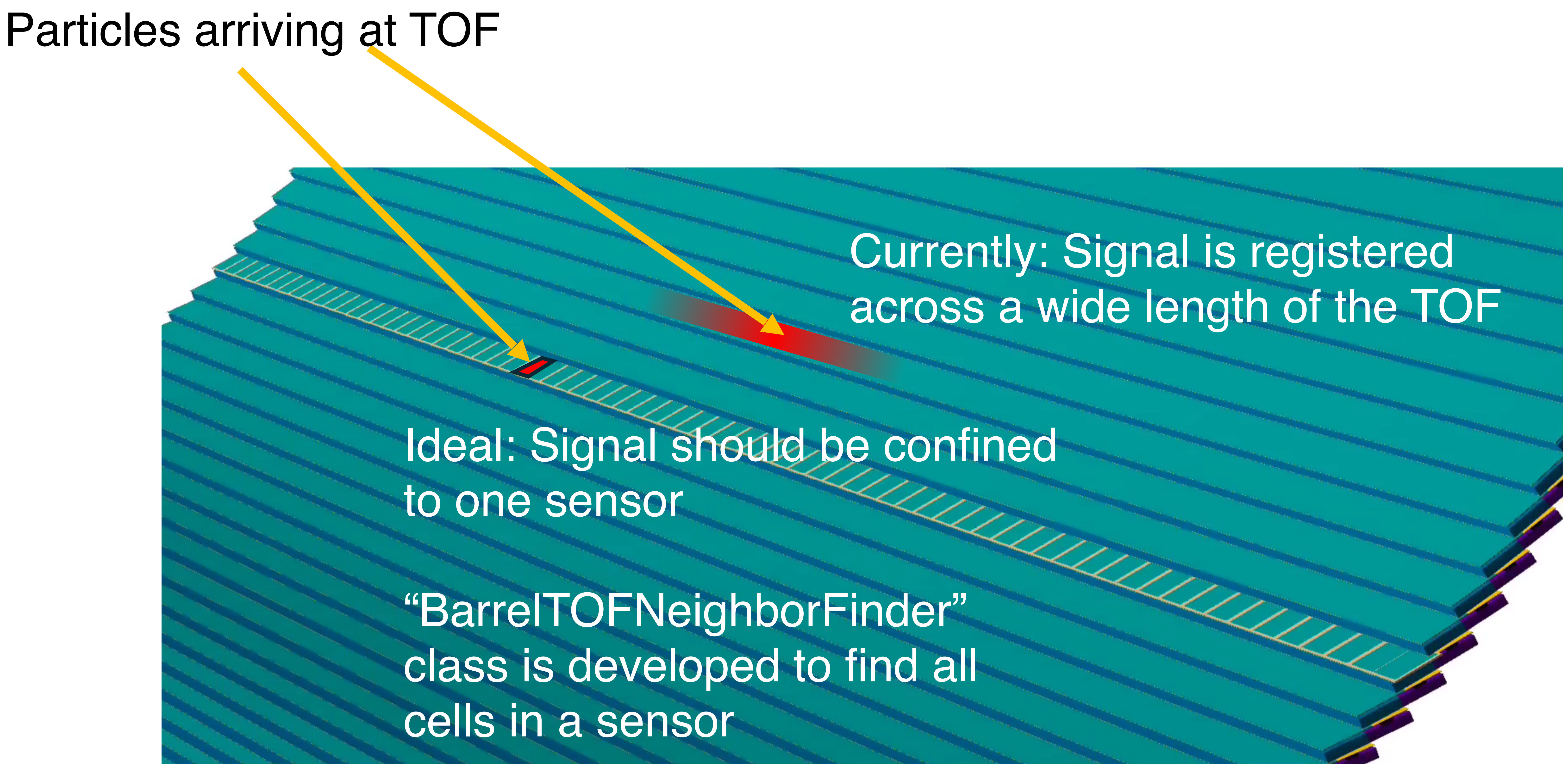
- Assemble a team for reconstruction with digitized info. (including charge sharing and TDC with clock)

Calculate energy for each pixel.

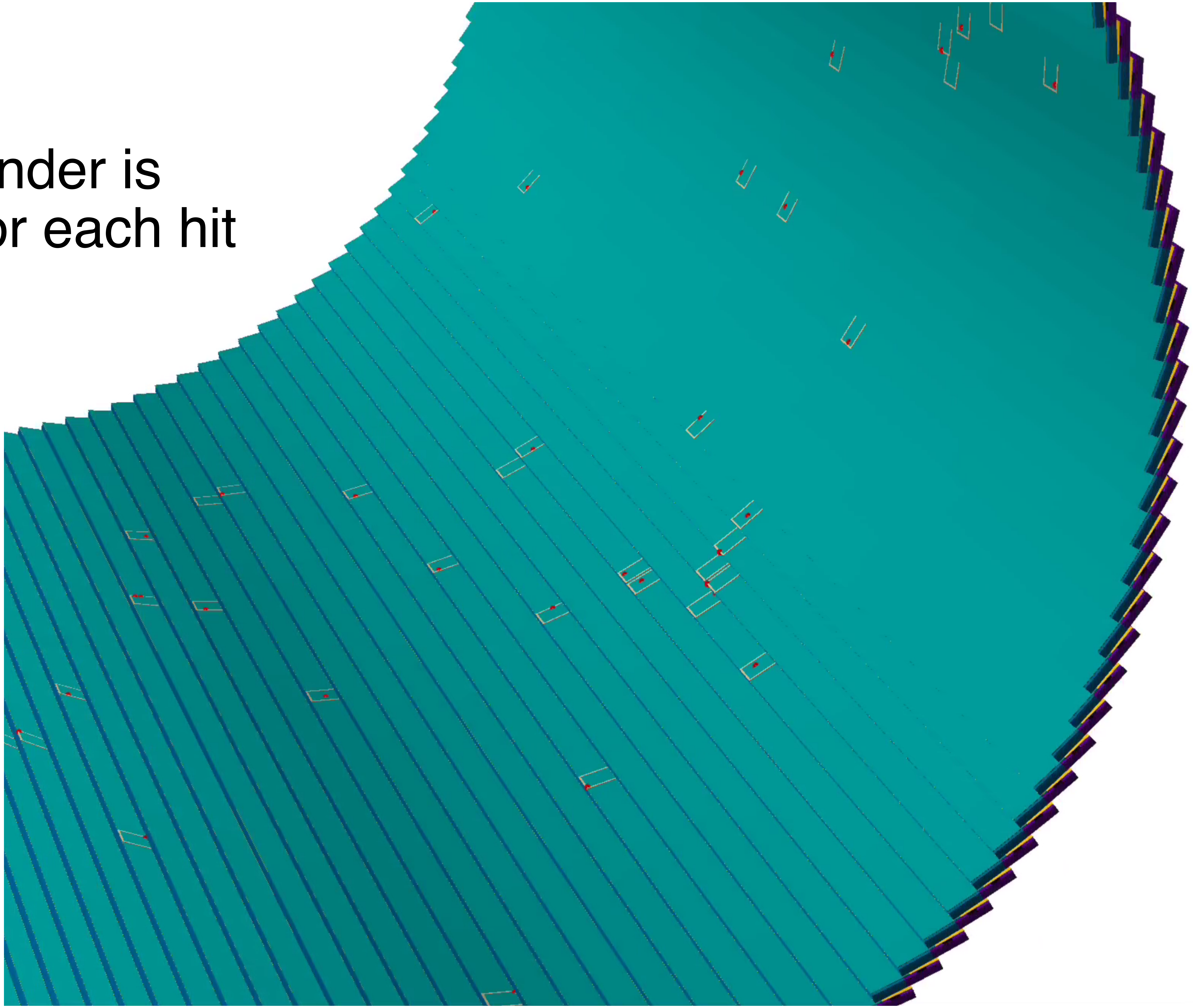
- Currently in GEANT, each stave of TOF is one entire unit.



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

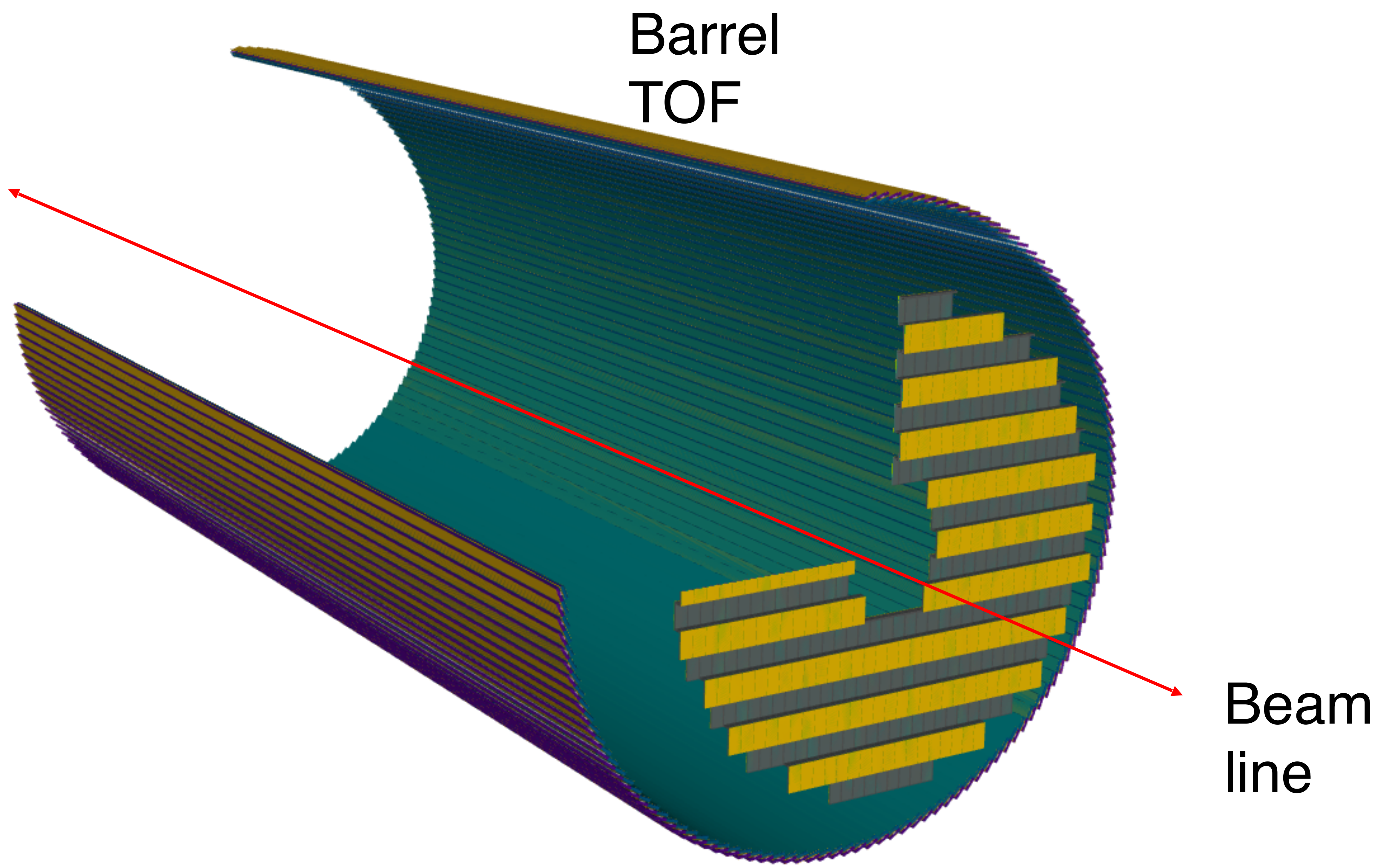


Simulation results: BarrelTOFNeighborFinder is able to find sensors for each hit



Current status

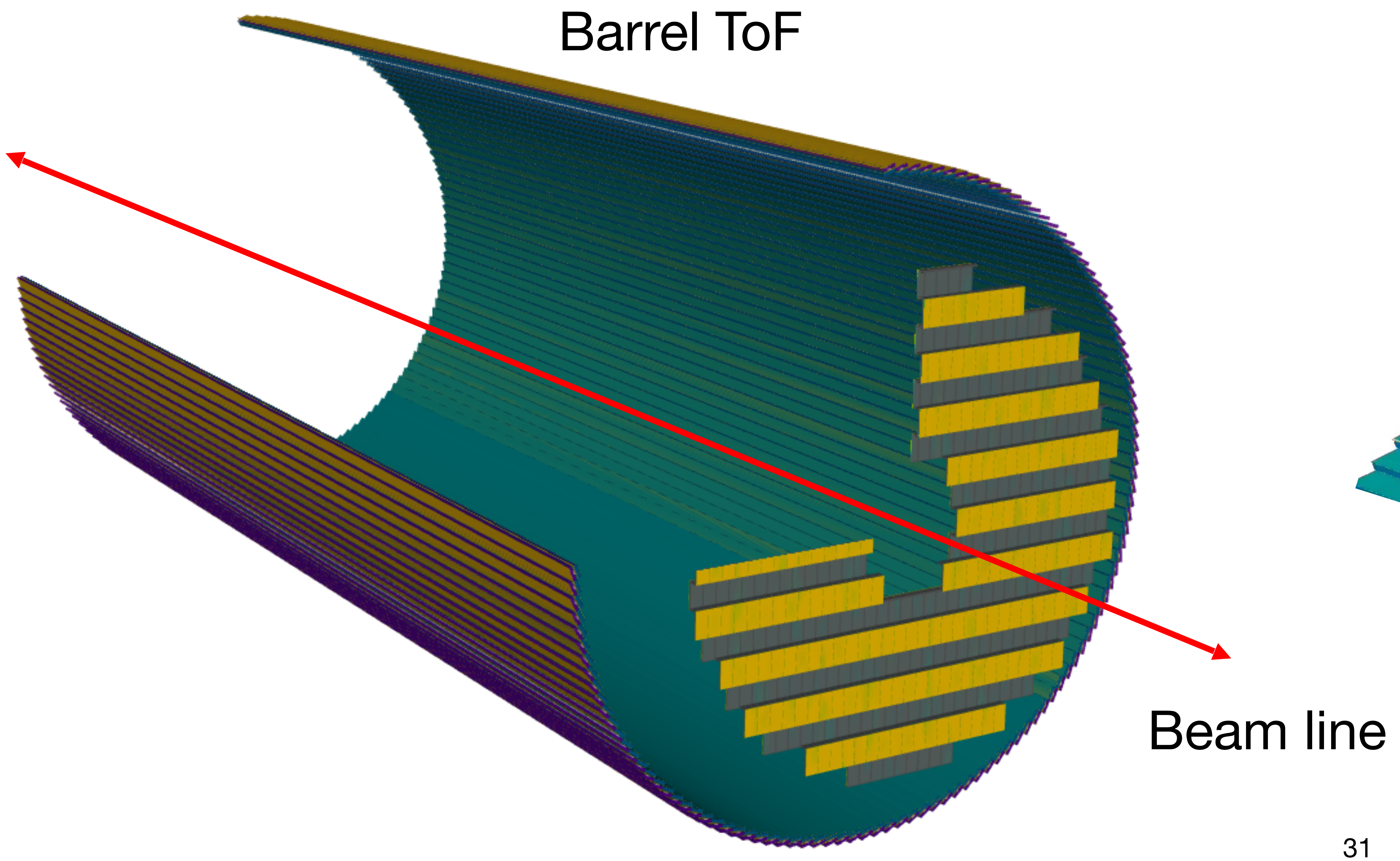
- Overarching goal: Develop simulation software for TOF.
- Things to do:
  1. Done: Put pixels in the right place.
  2. Done: Calculate energy for each pixel.
  3. Work in progress: Convert energy deposition into pulse. (Souvik is making good progress)

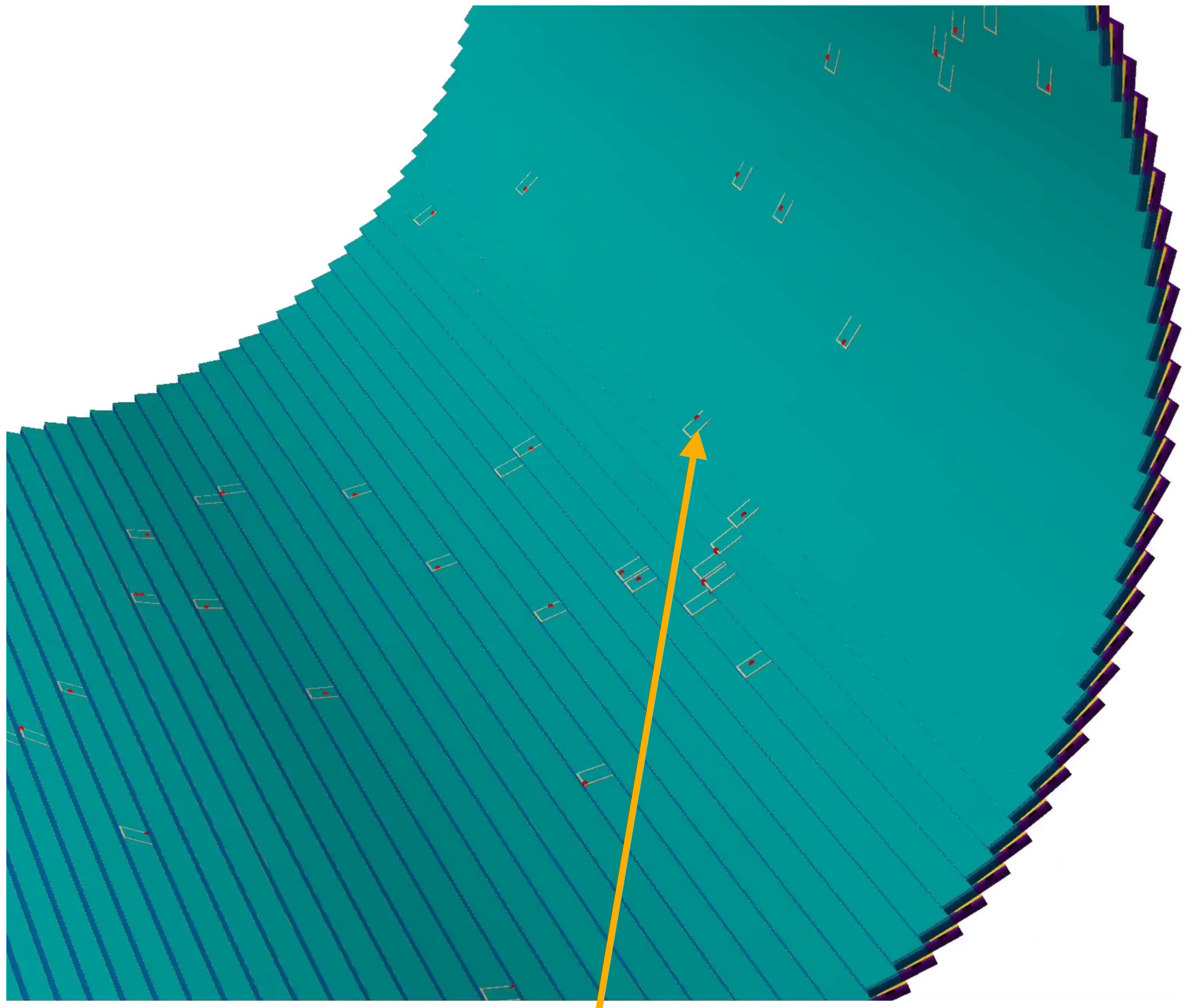


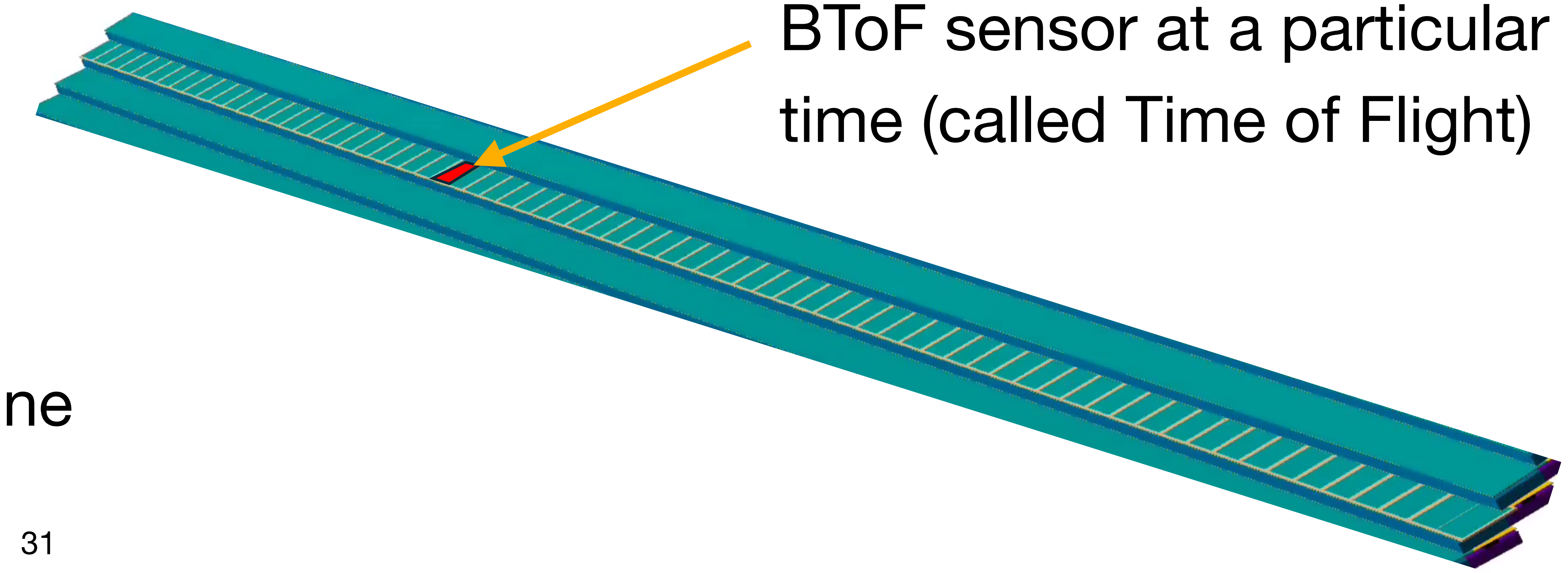
Event Generation & Transport

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°



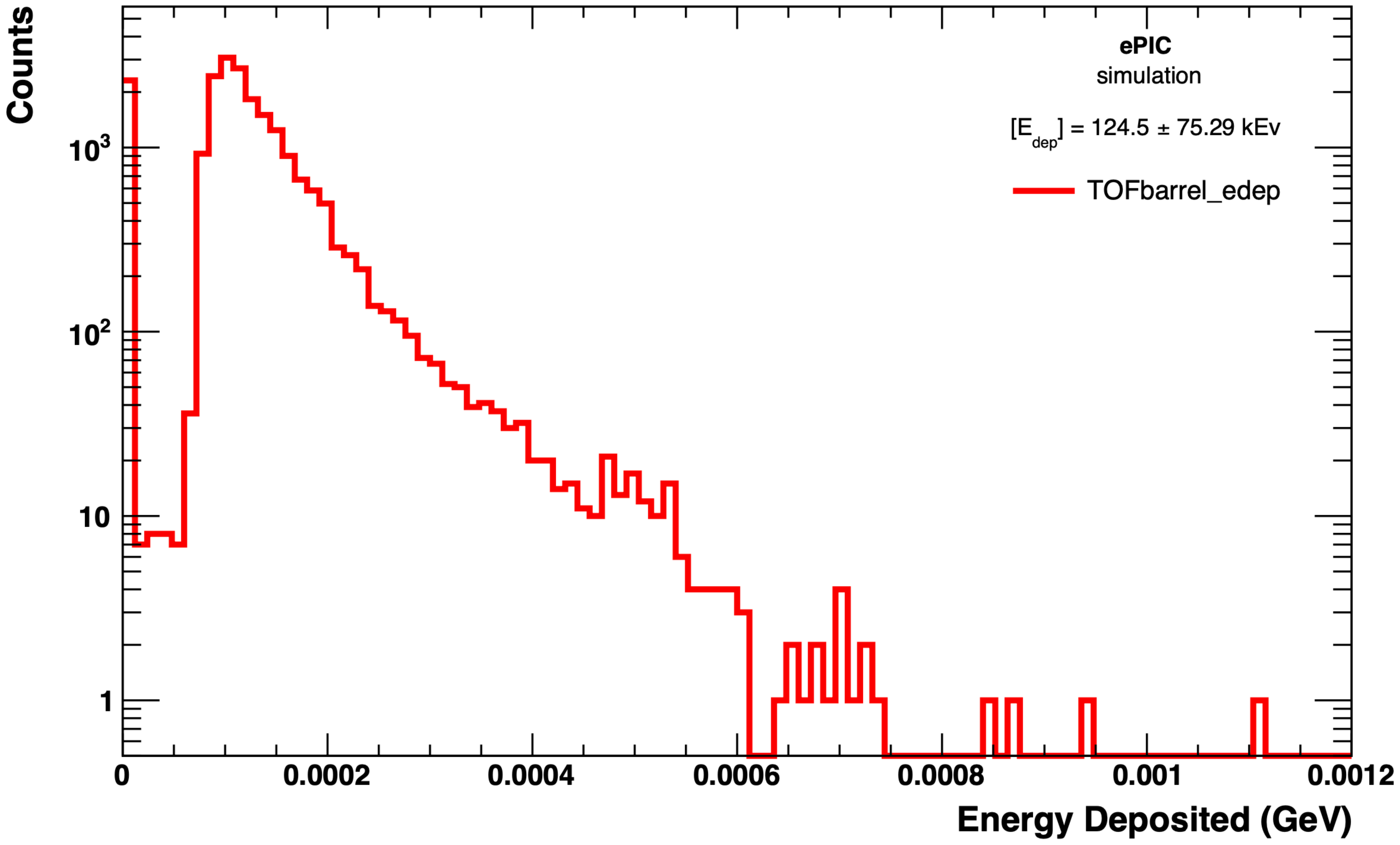




Each hit deposits energy in a BToF sensor at a particular time (called Time of Flight)

Energy deposition & Time of Flight

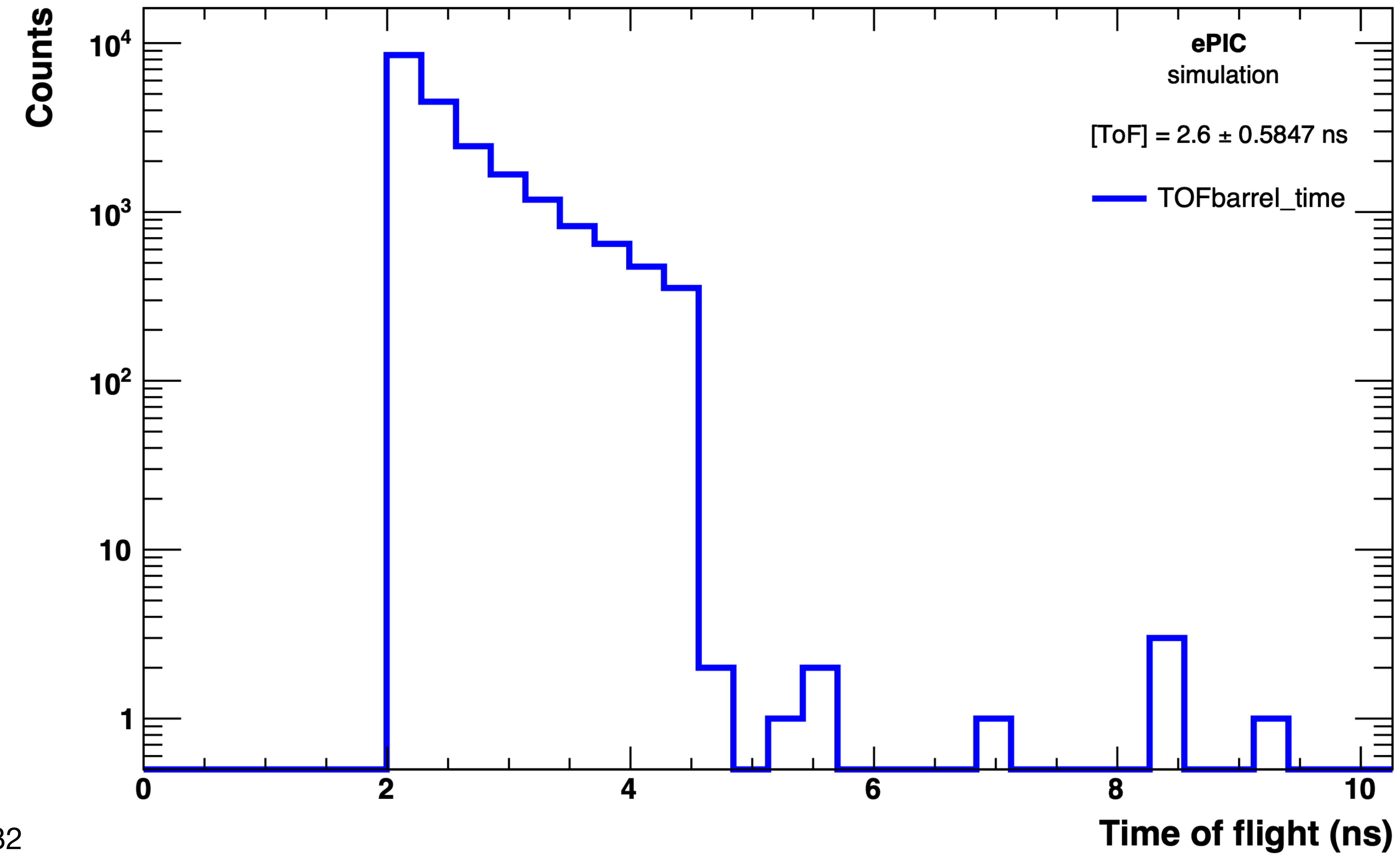
- Single particle generation (μ-) using npsim in DD4HEP
- # Events = 250k
- 0 GeV ≤ Particle Gun Momentum ≤ 30 GeV
- 0° ≤ Particle Gun Azimuthal Angle ≤ 180°



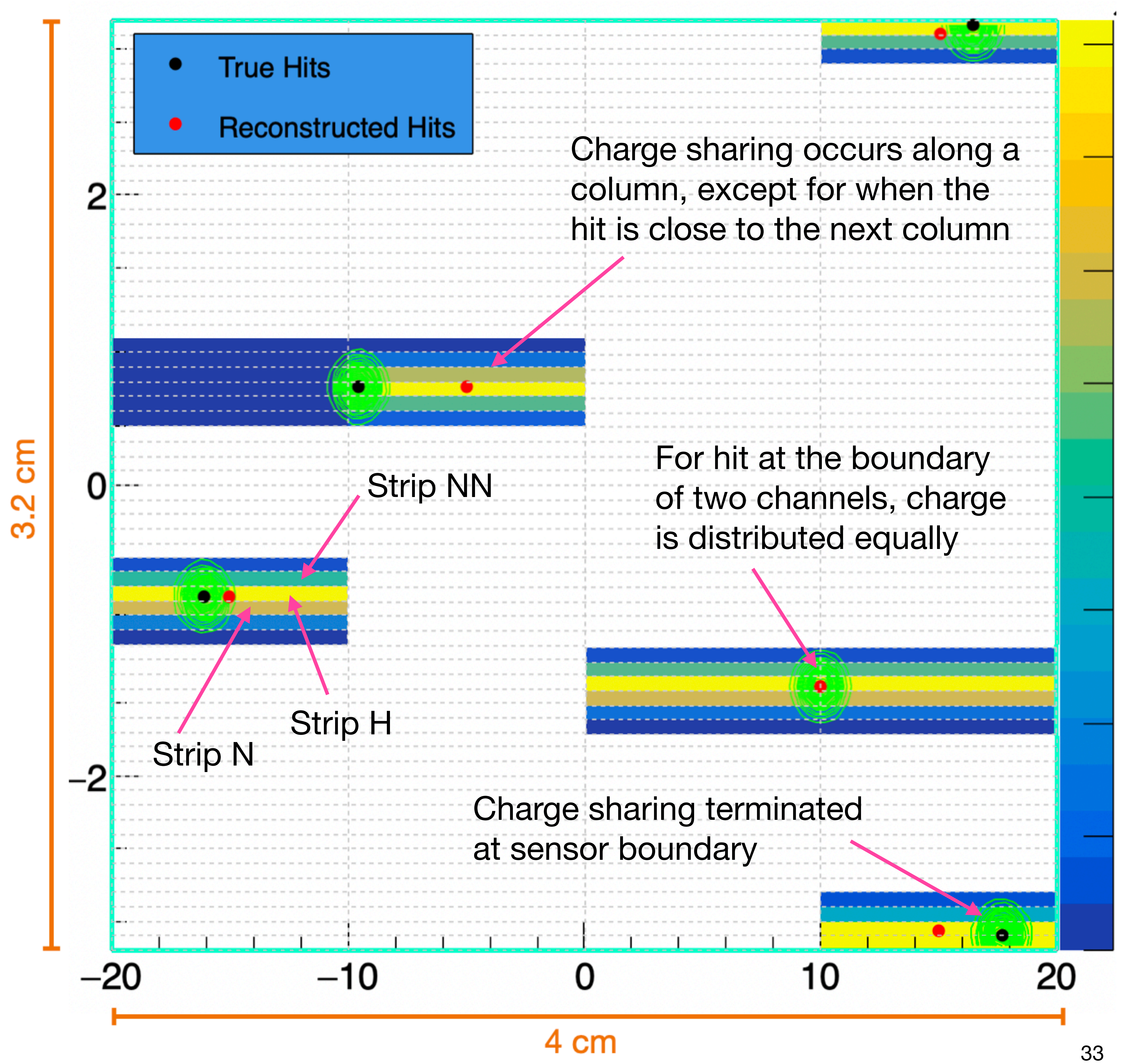
- For a hit, **Q_{dep}** and the corresponding **Time of Flight** are used to create an analog signal.

- Energy deposited (E_{dep}) is multiplied by a constant factor **q** (~19/0.0001 fC/GeV) to convert to charge deposited (Q_{dep}) in a sensor.

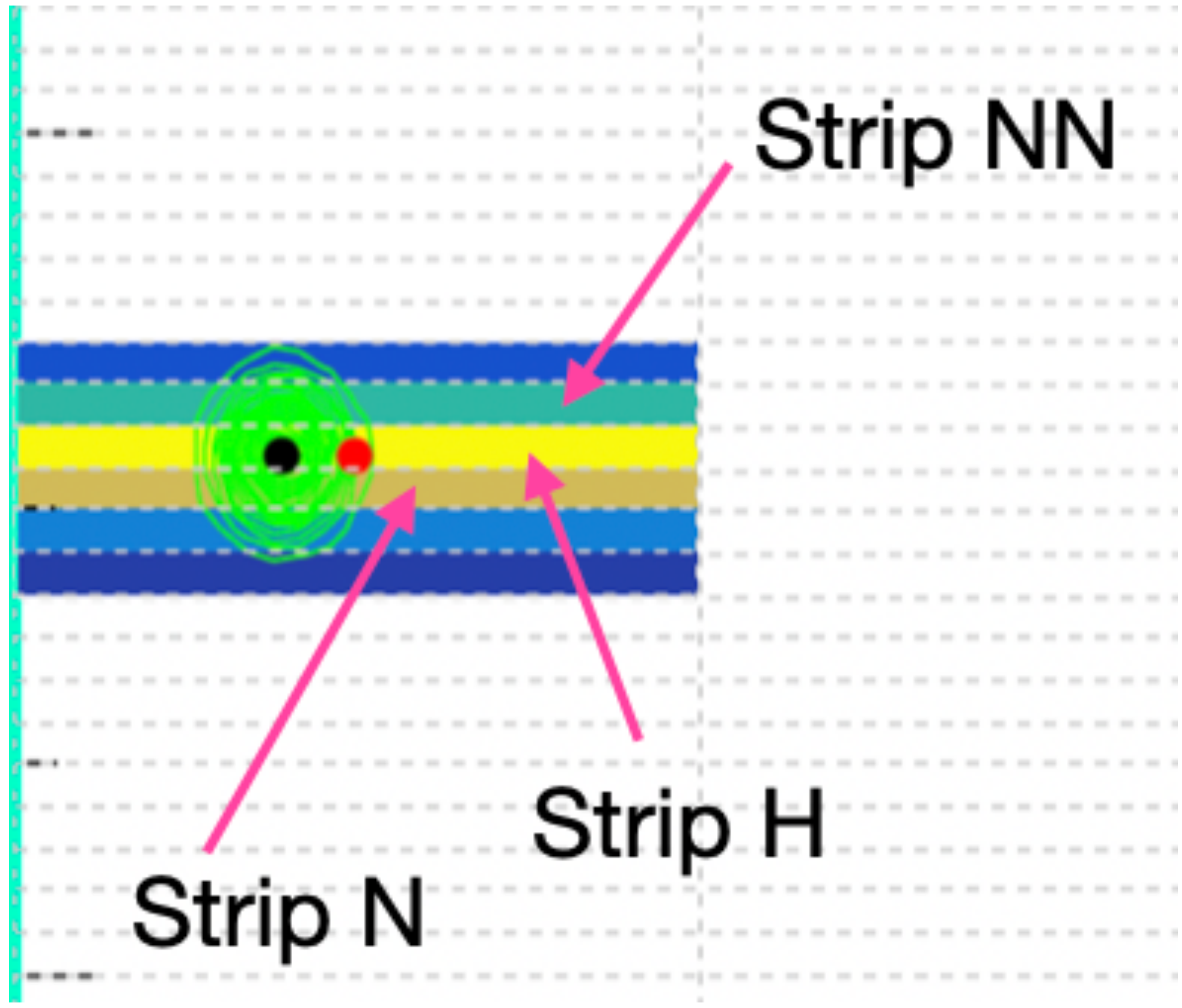
$$q = \frac{\text{Charge carried by a MIP (fC)}}{\text{Energy deposited by a MIP (GeV)}}$$

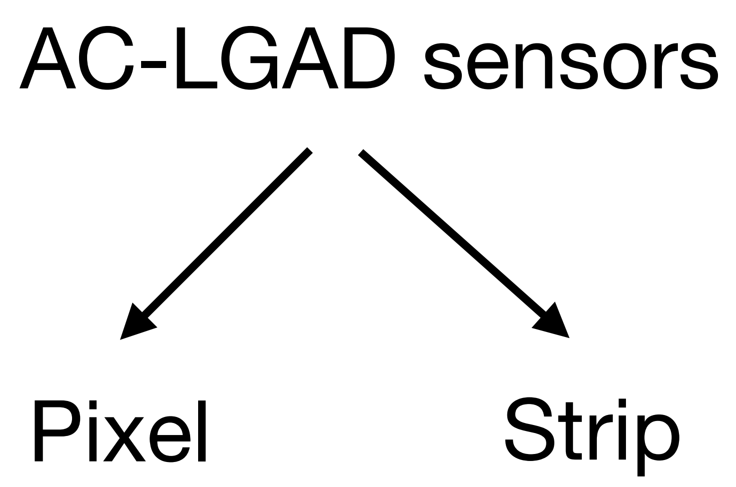


AC-LGAD & Charge Sharing



- Multiple ePIC detectors will employ novel AC-LGAD technology.
- Trial reconstruction using center of weight technique.





- 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.

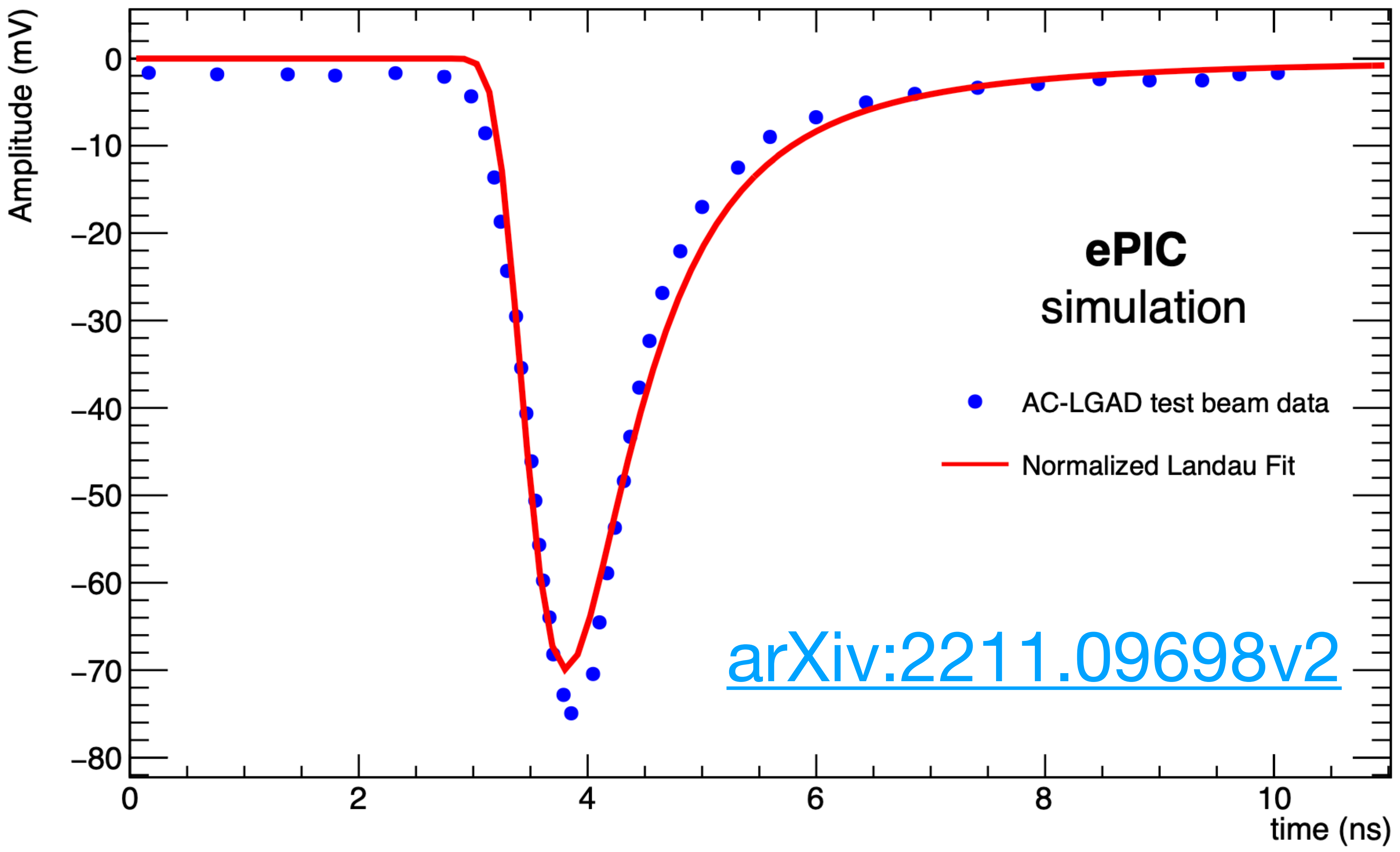
Creation of Analog Signal

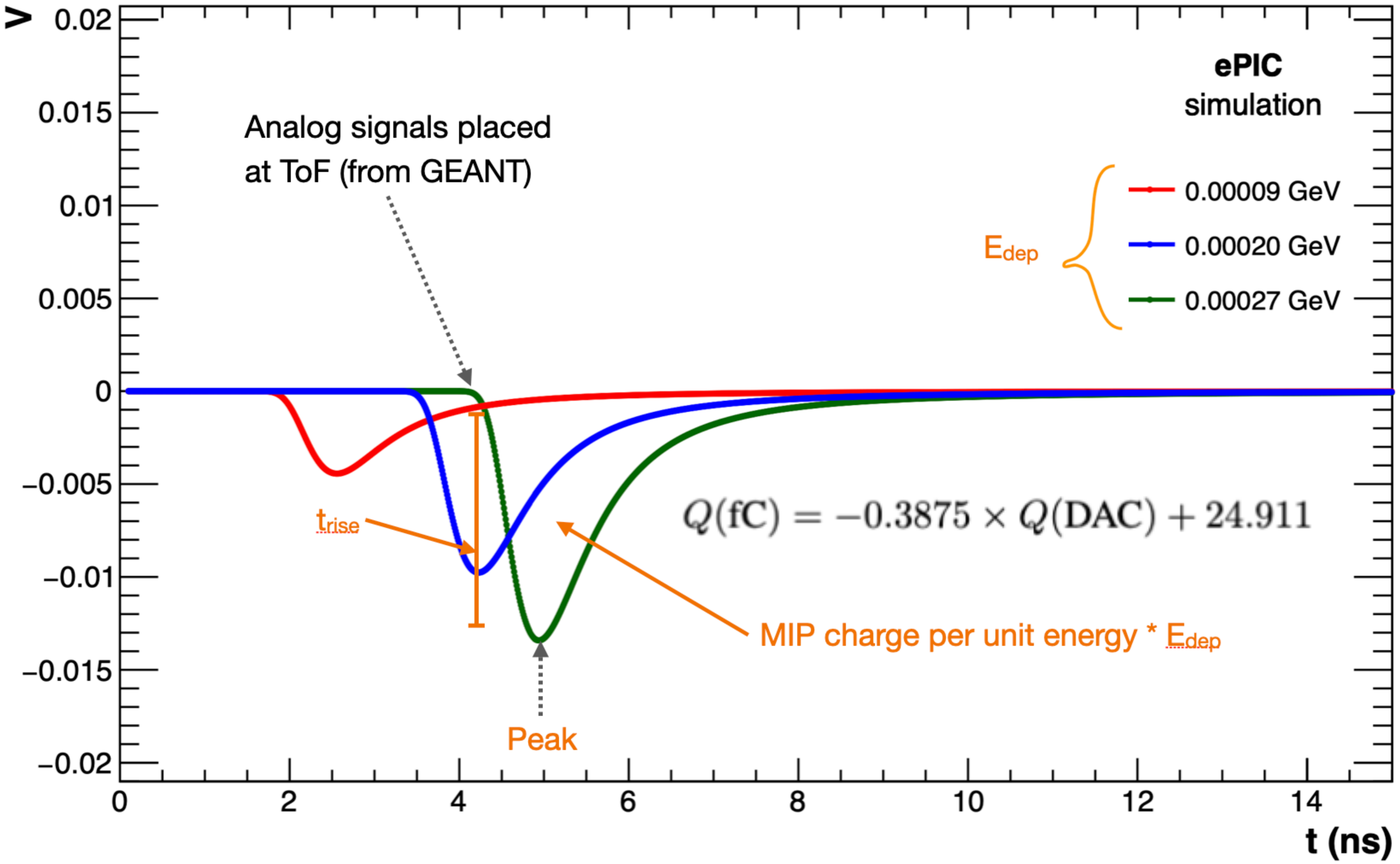
GEANT input:

- 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.





Analog Signal, Voltage Thresholds & ADC

Voltage Thresholds

- V_{th_1}: 0
- $V_{th\text{-}2}$: 0.005
- V_{th_n}: $V_{th\_2} + (n-1)*(V_{th\_max}-V_{th\_2})/(2^8-1)$

Should be set at the mean of noise

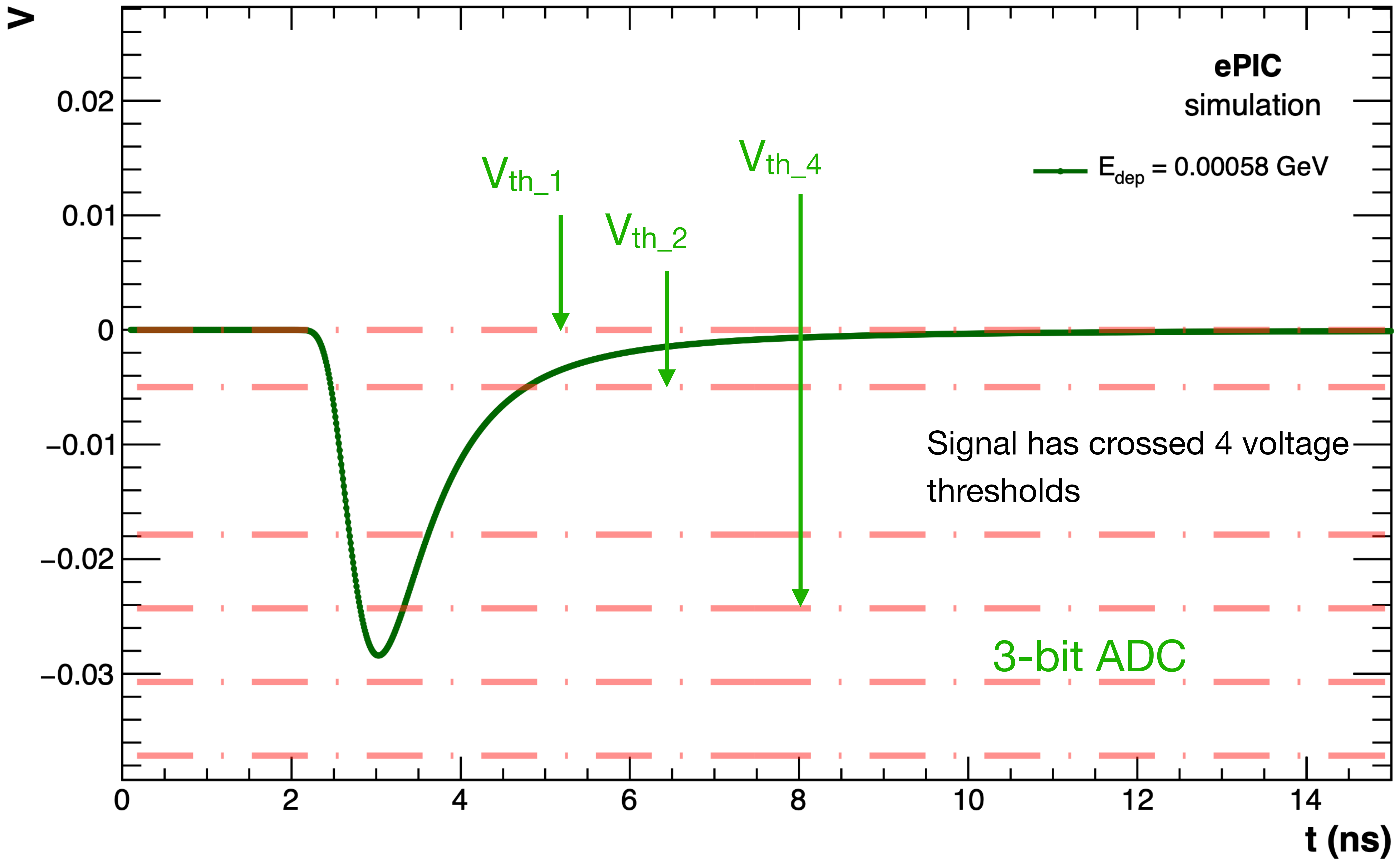
$V_{th\_max}/10$

$3 \leq n \leq 256$

n_{max} (for 8-bit ADC)

Voltage thresholds crossed by analog signal

8-bit ADC

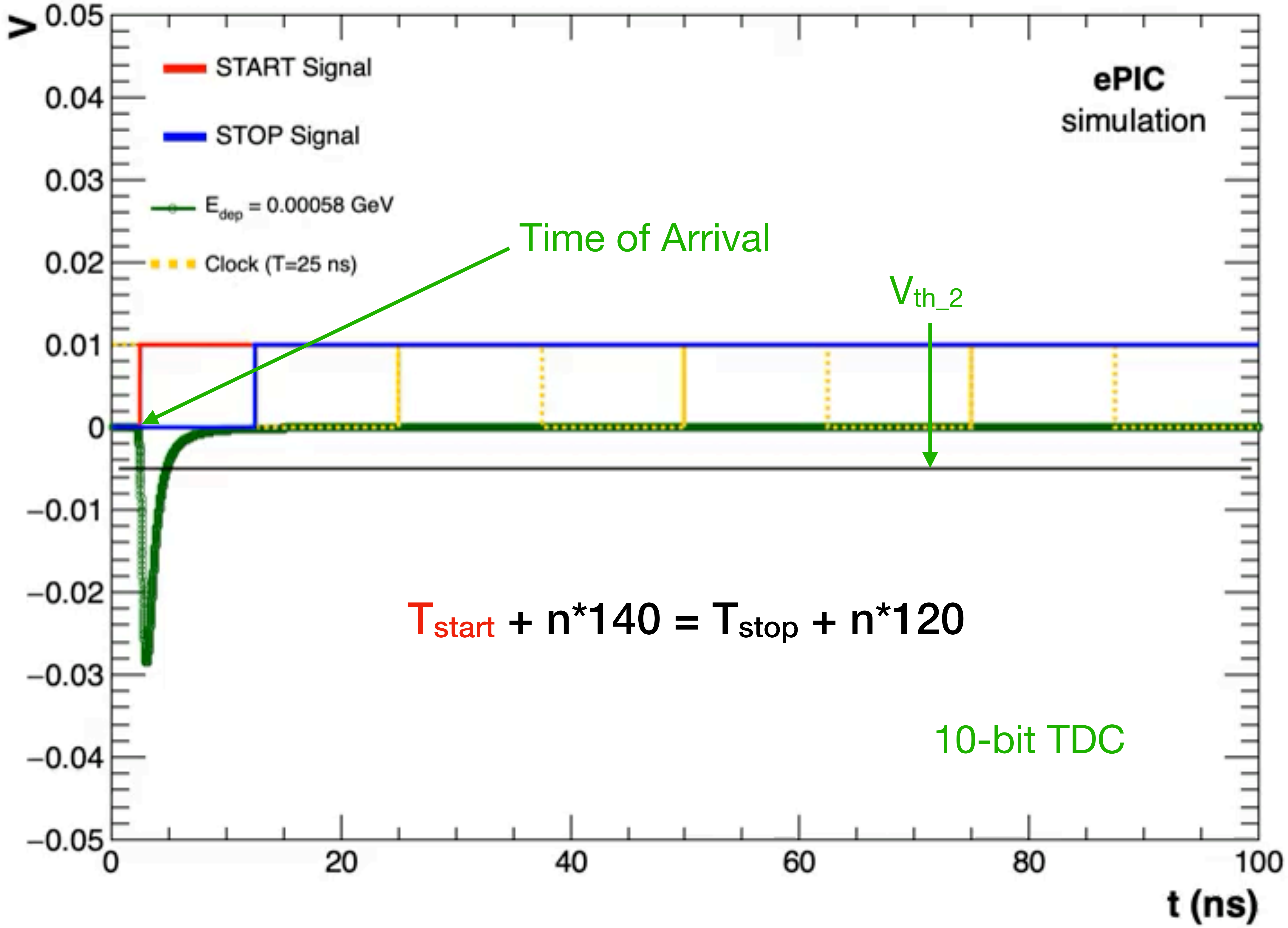


Analog Signal, Clock & TDC

- 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** switch flips from 0 to 1. When the clock flips from the 1st to the 2nd half-cycle, the **STOP** switch flips from 0 to 1.

- Consecutive delay cells propagate the START signal (140 ps delay) and the STOP switch (120 ps delay) in parallel until the START switch crosses the STOP signal (Mathematically, **|START-STOP| < 20 ps**).

Quantization time of ePIC ToF detector



Times START/STOP switch moves ⟶ **10-bit TDC**

Summary: Digitization Model for AC-LGAD sensors

Energy deposited

↓

Charge deposited

↓

Peak of Analog Signal

↓

ADC

Time of Flight

+

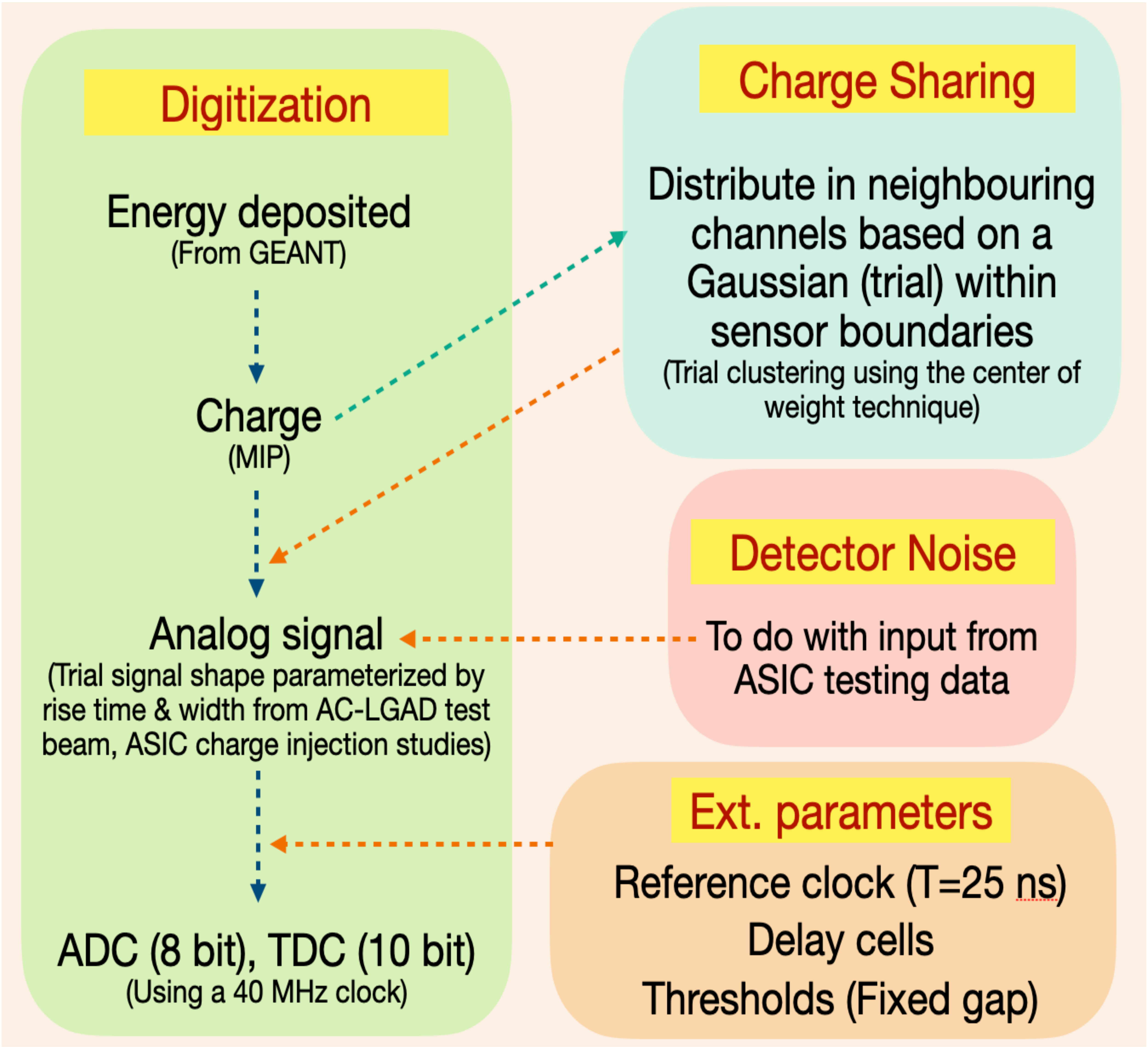
Rise Time

↓

Time of Arrival

↓

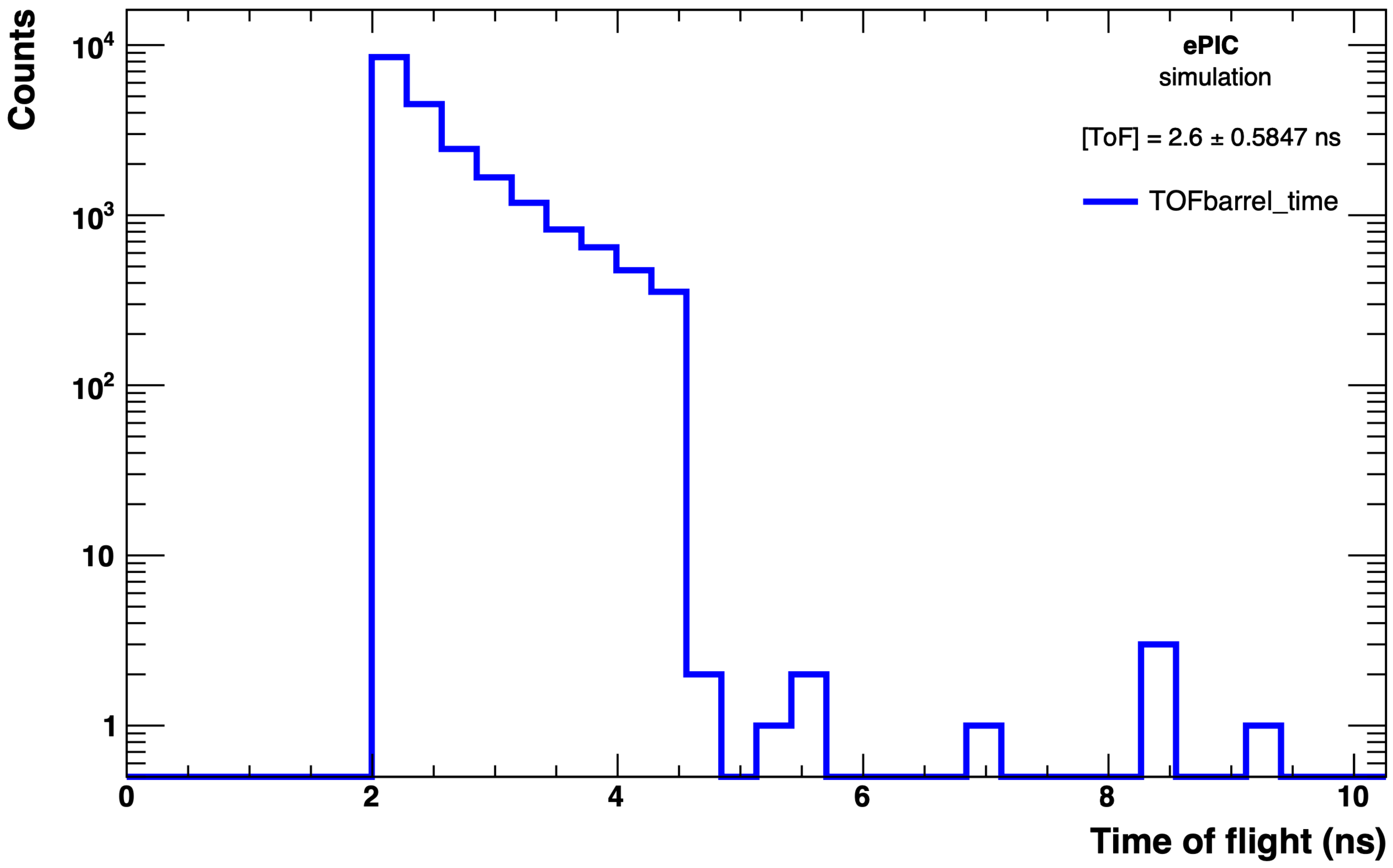
TDC

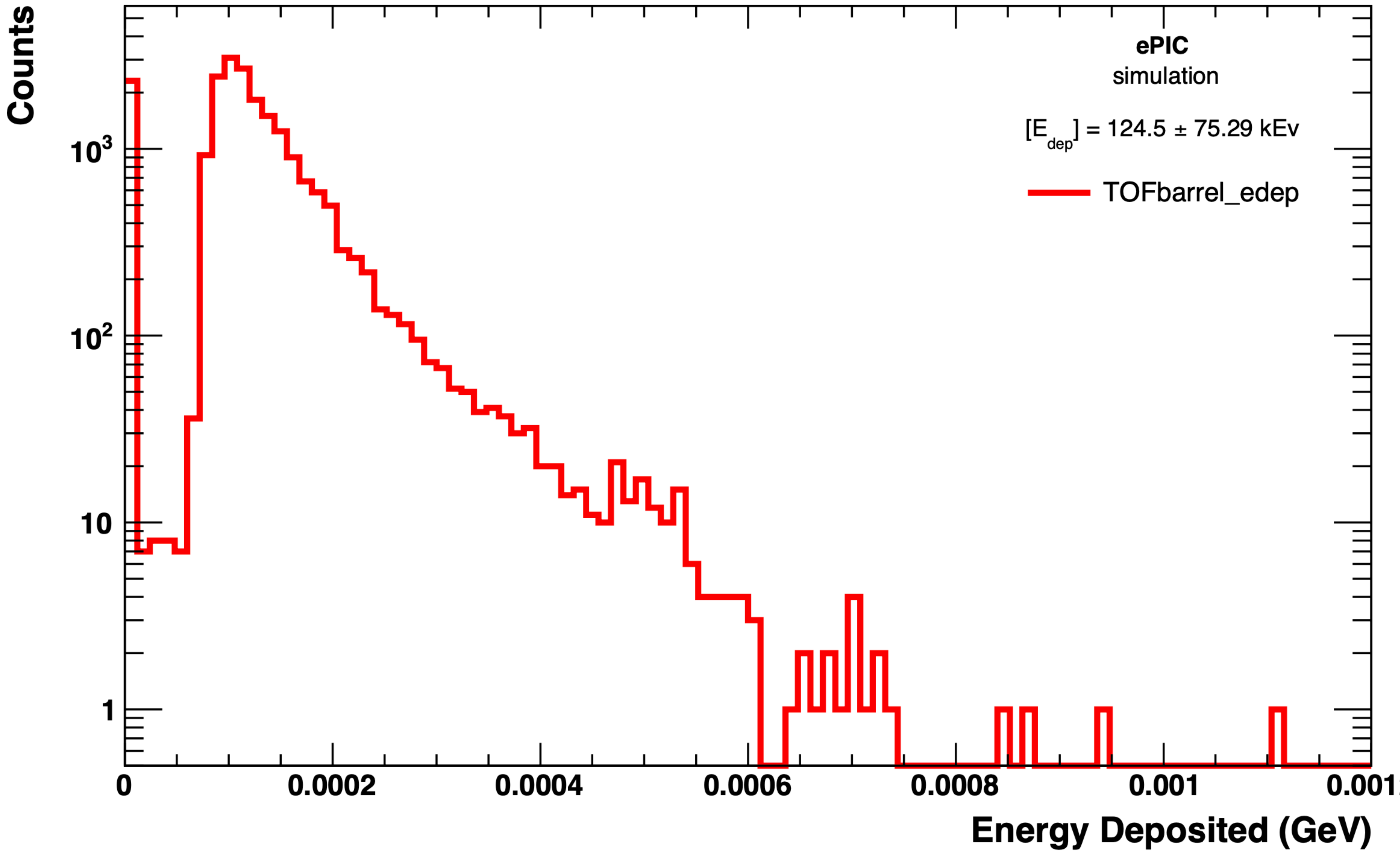


Energy Deposition & Time of Flight

GEANT run specifications:

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

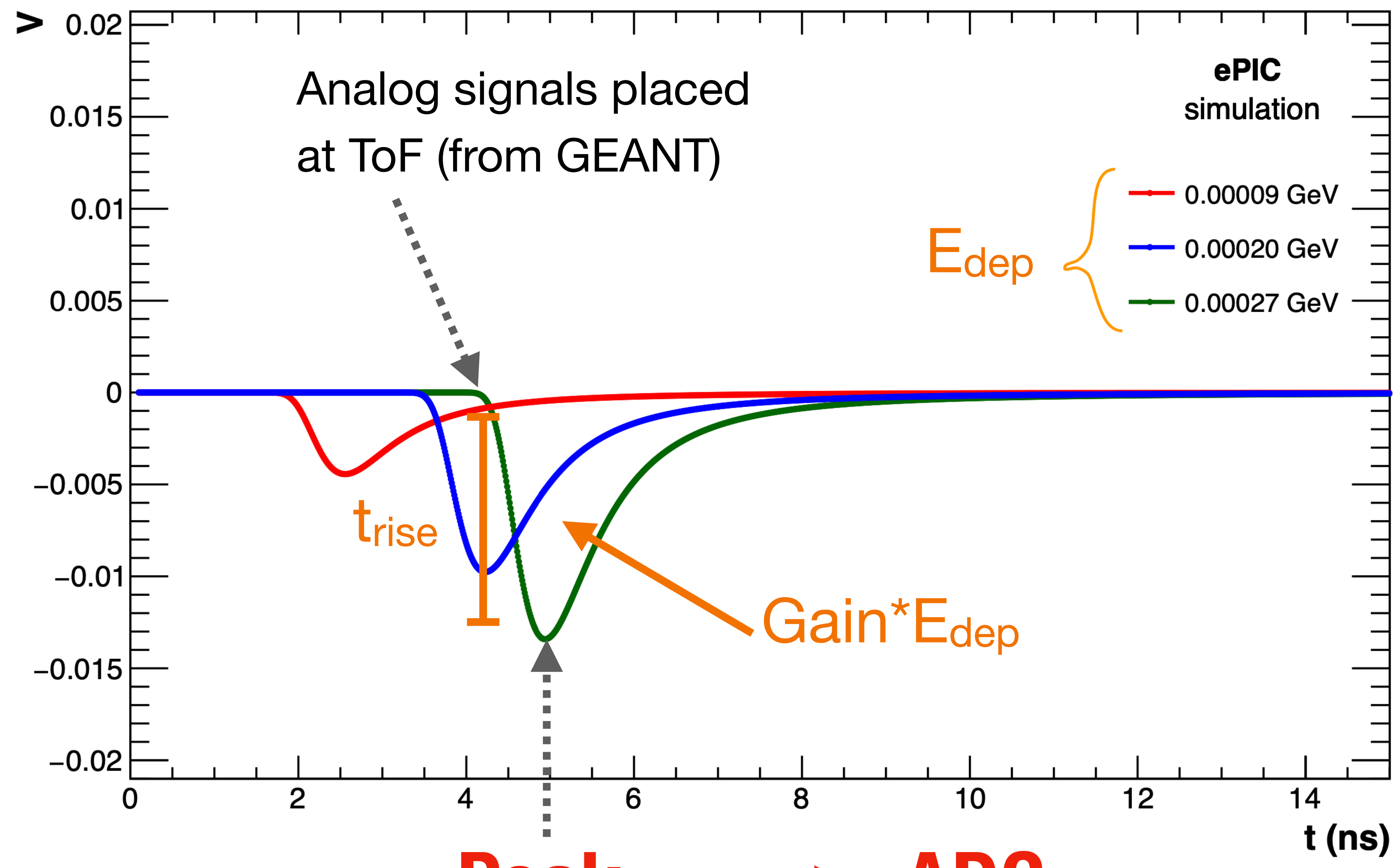




- Every sample of energy deposited is converted to charge for digitization.
- Corresponding time sample (Time of Flight) is used as input for TDC calculation.

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.



Peak → ADC

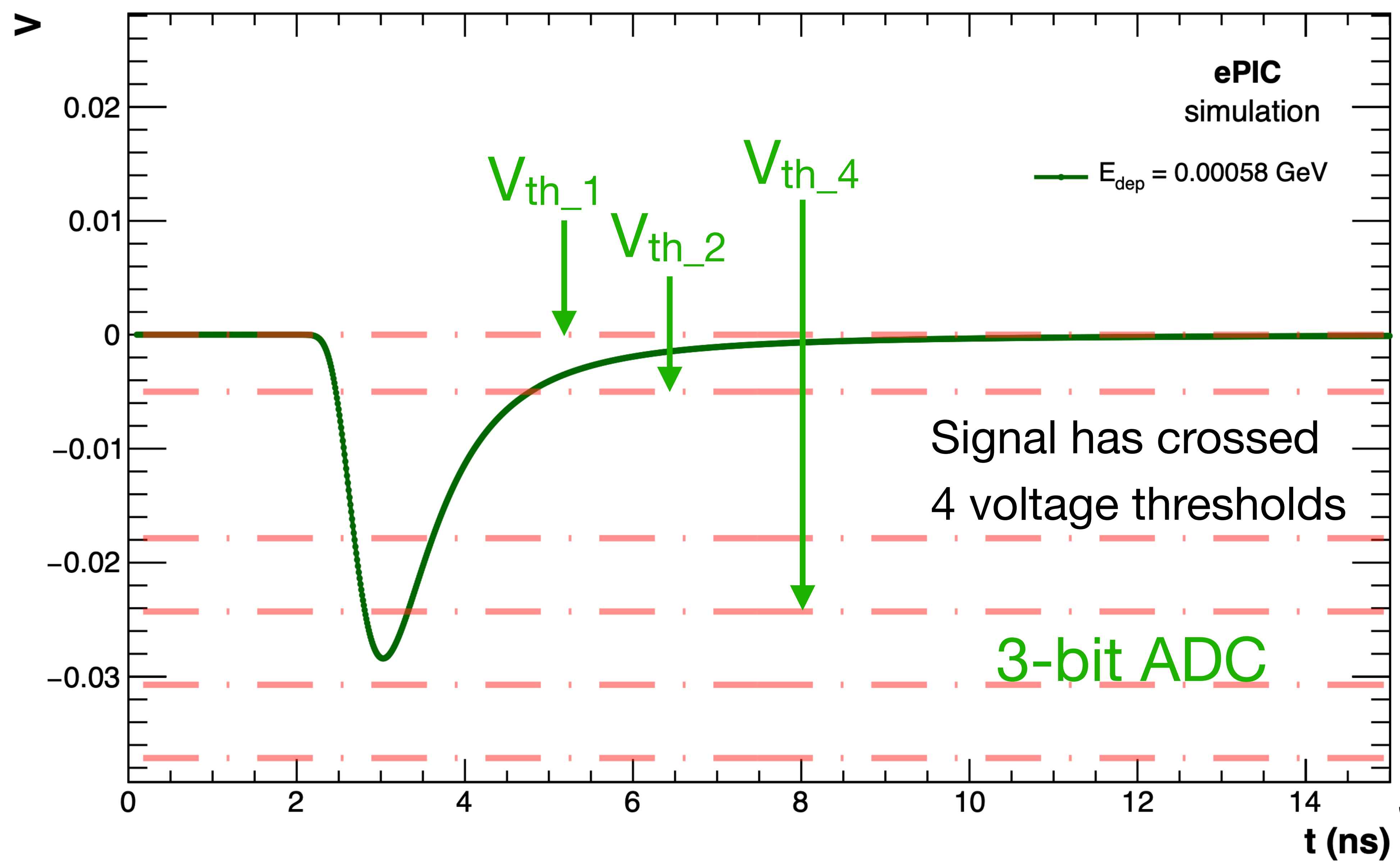
Voltage Thresholds

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

V_{th-2}: 0.005 — $Th_{max}/10$

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

$3 \leq n \leq 256$ — n_{max} (for 8-bit ADC)



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

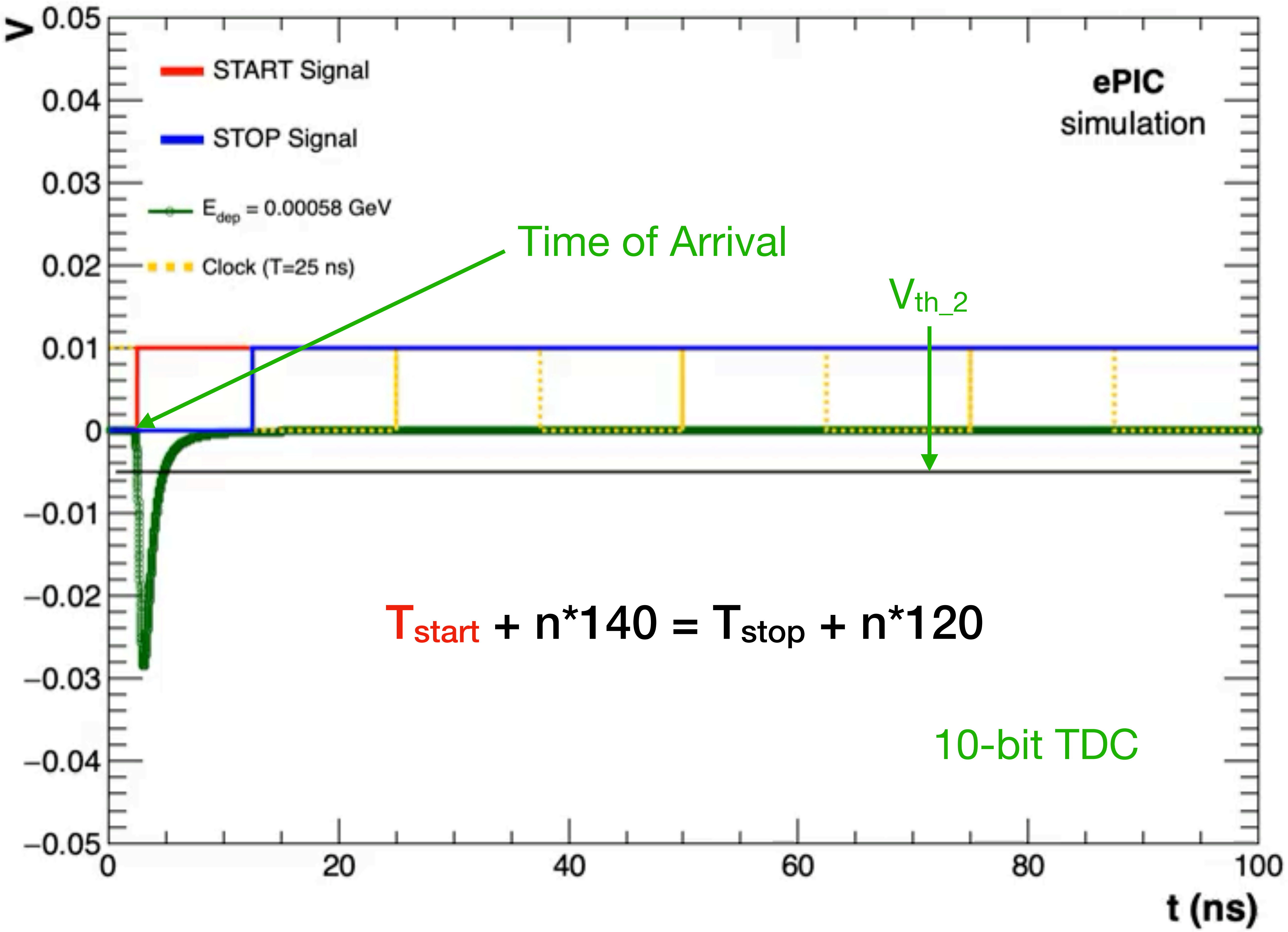
Analog Signal & TDC

- 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**).

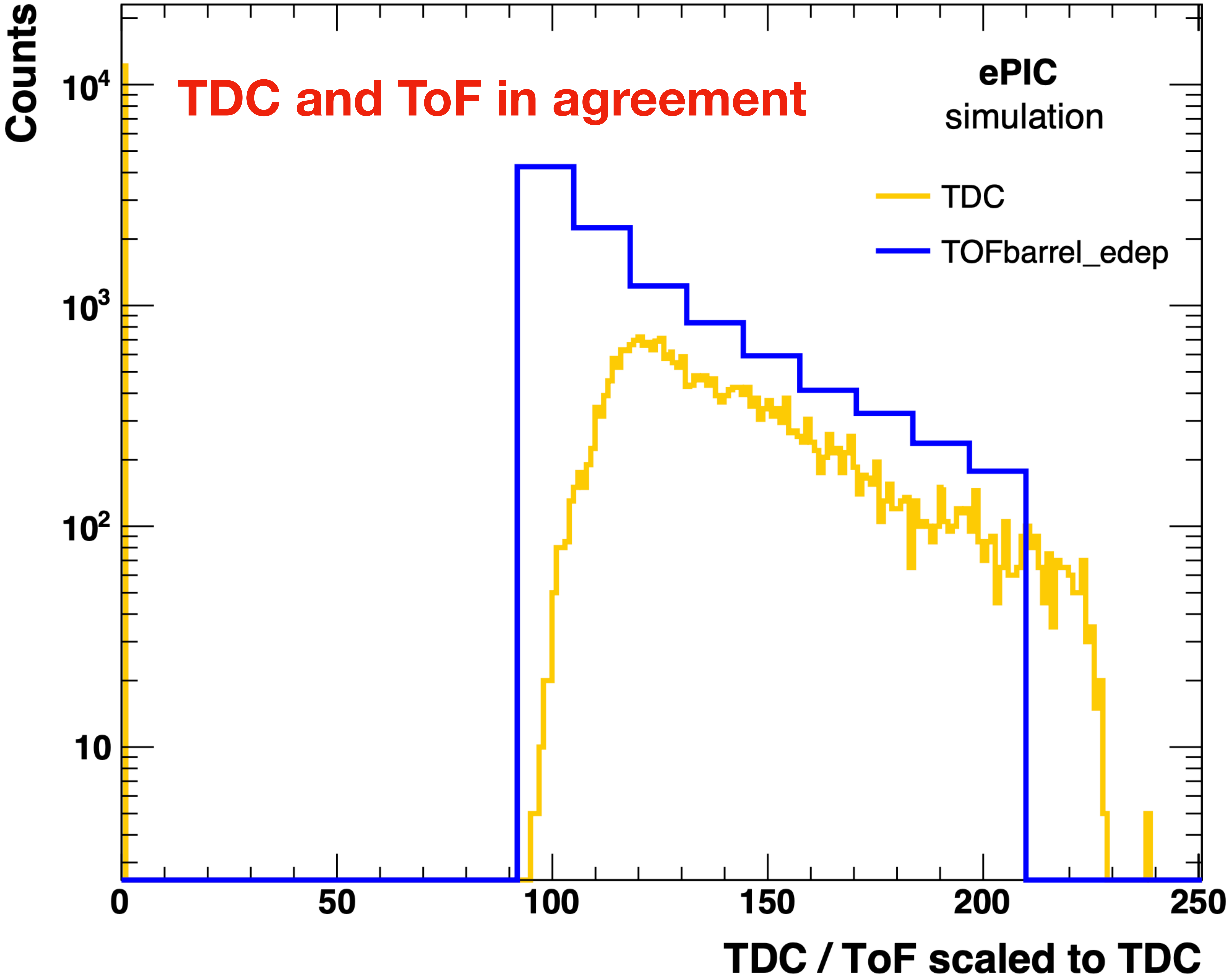
Quantization time of ePIC ToF detector

Time of Arrival → TDC

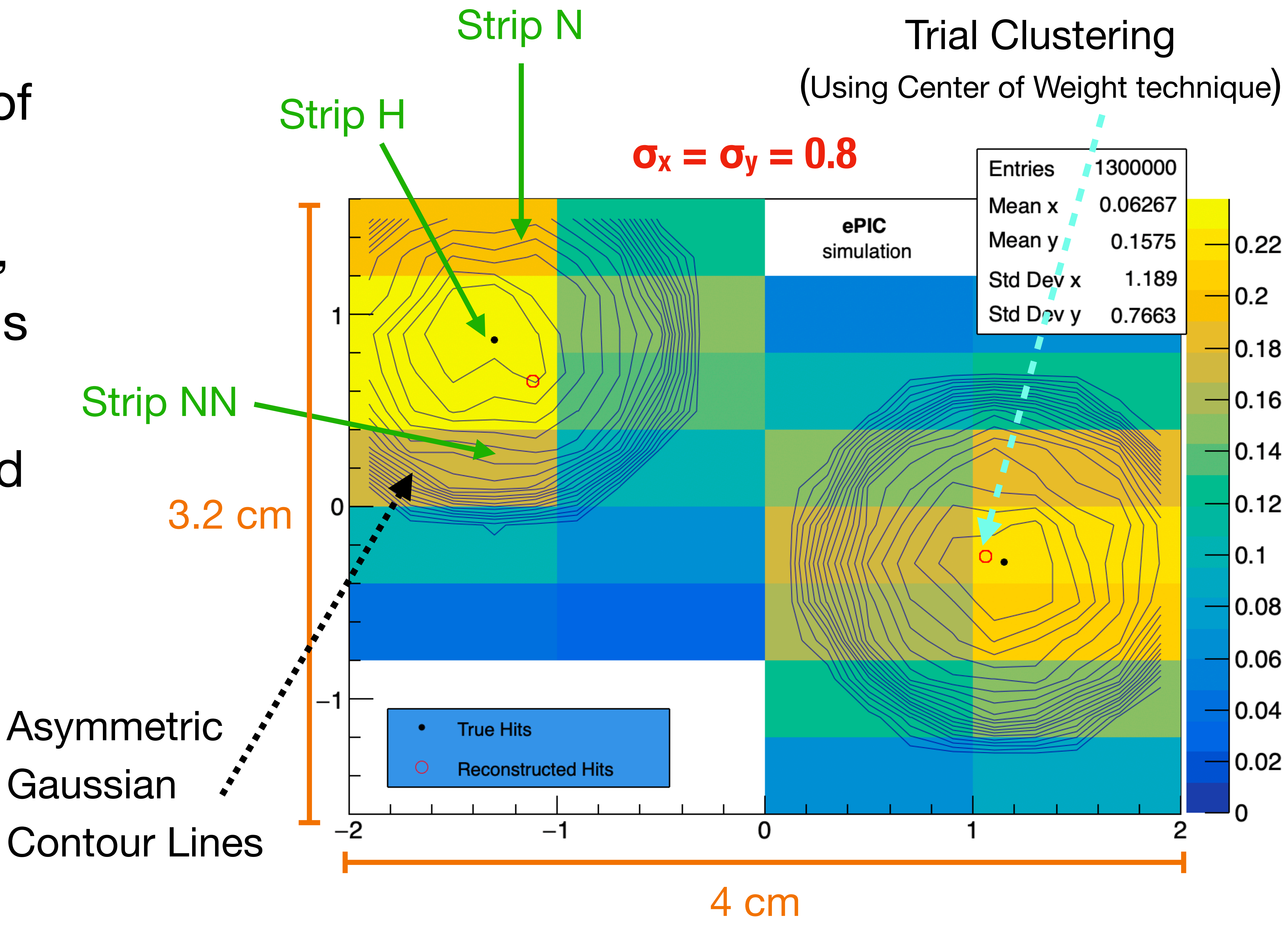


- The number of times the signals move ($1 \leq n \leq 1024$) is converted to a 10-bit TDC code.

Time of Flight & TDC Comparison



- 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.



- 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.

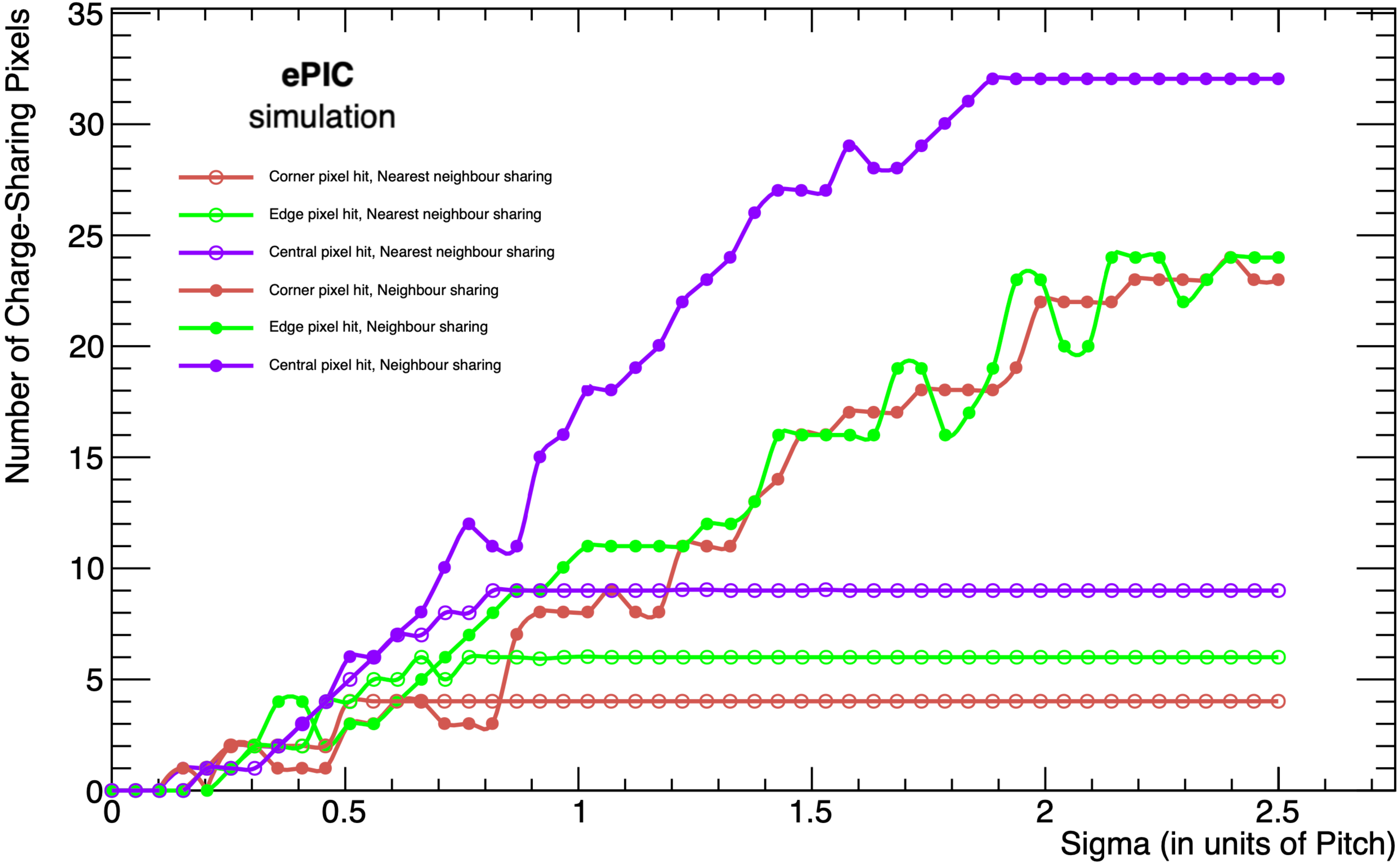
Each AC-LGAD strip sensor has 8X4 = 32 channels

Barrel ToF →	Strip Sensor
Endcap ToF →	Pixel Sensor

Charge Sharing (Geometric effects)

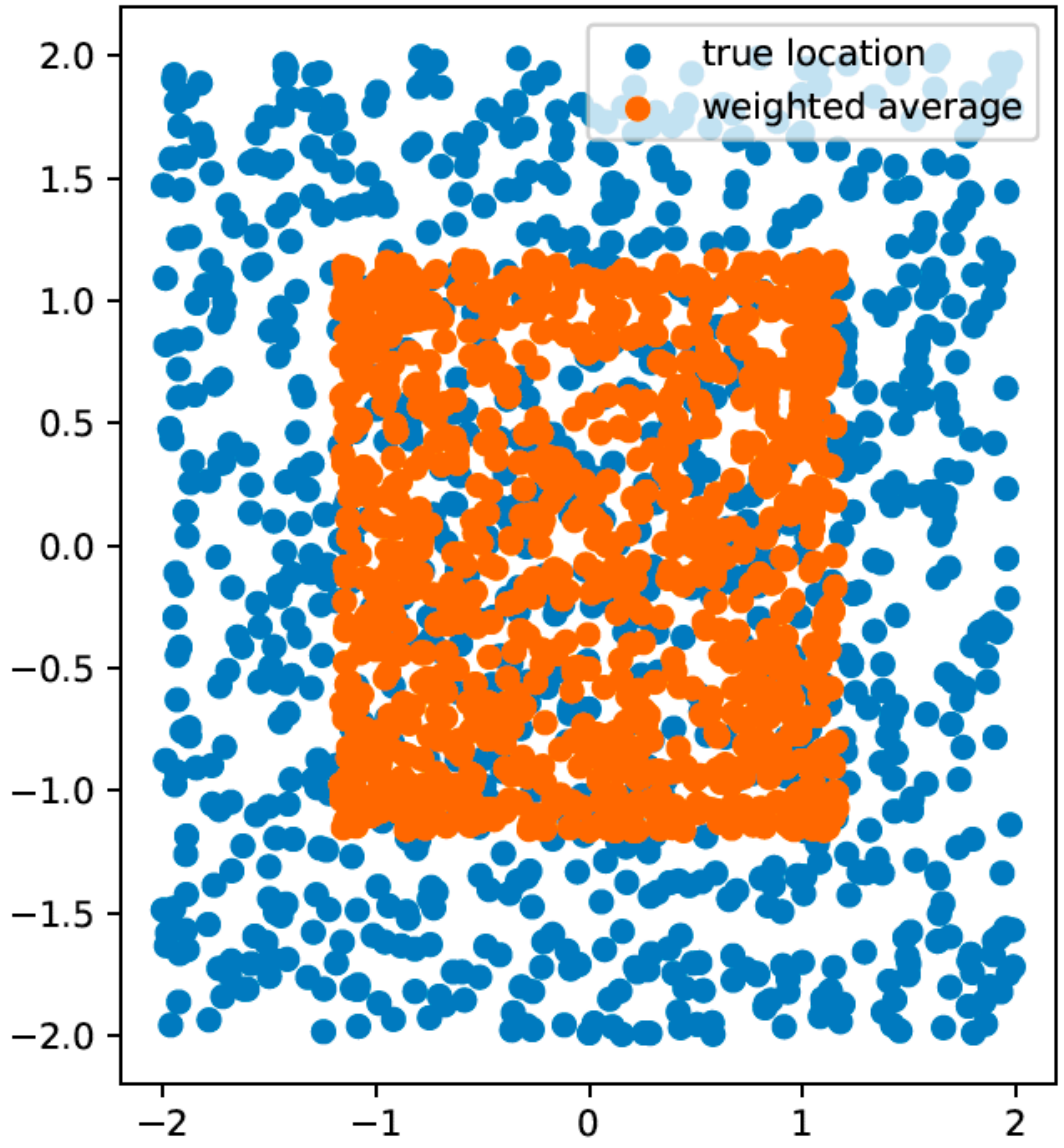
- The position of the hit pixel and the number of charge-sharing neighbours has an effect on the reconstruction accuracy of the hits.
- Reconstruction accuracy decreases as the pixel hit position changes from central to corner.
- Central pixel has 8 nearest neighbours, edge pixel has 5 nearest neighbours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

Charge Sharing (More geometric effects)



Charge Sharing (Reconstruction Technique Comparison)

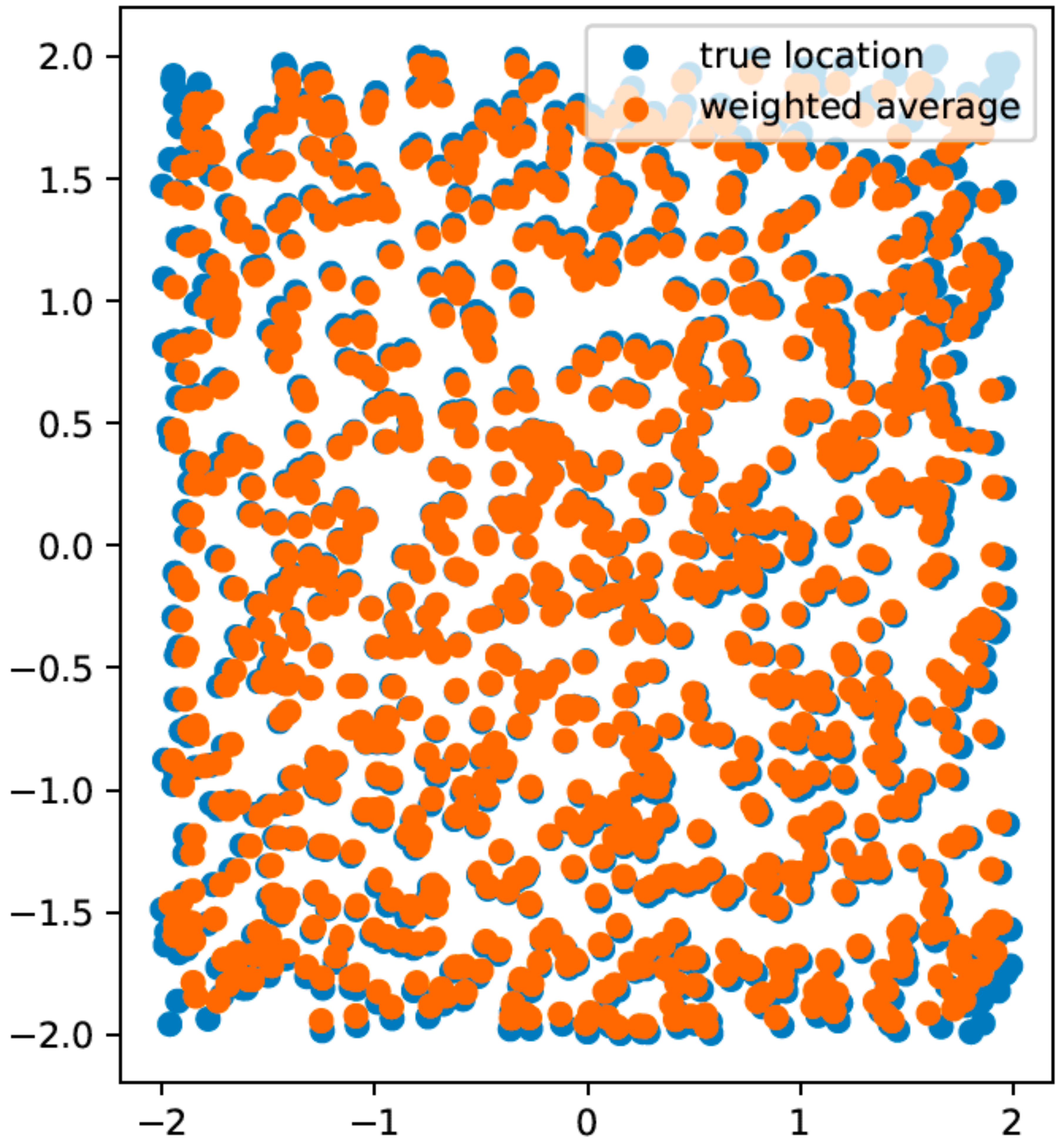
Courtesy of *Tommy Tsang*



Center of Weight technique

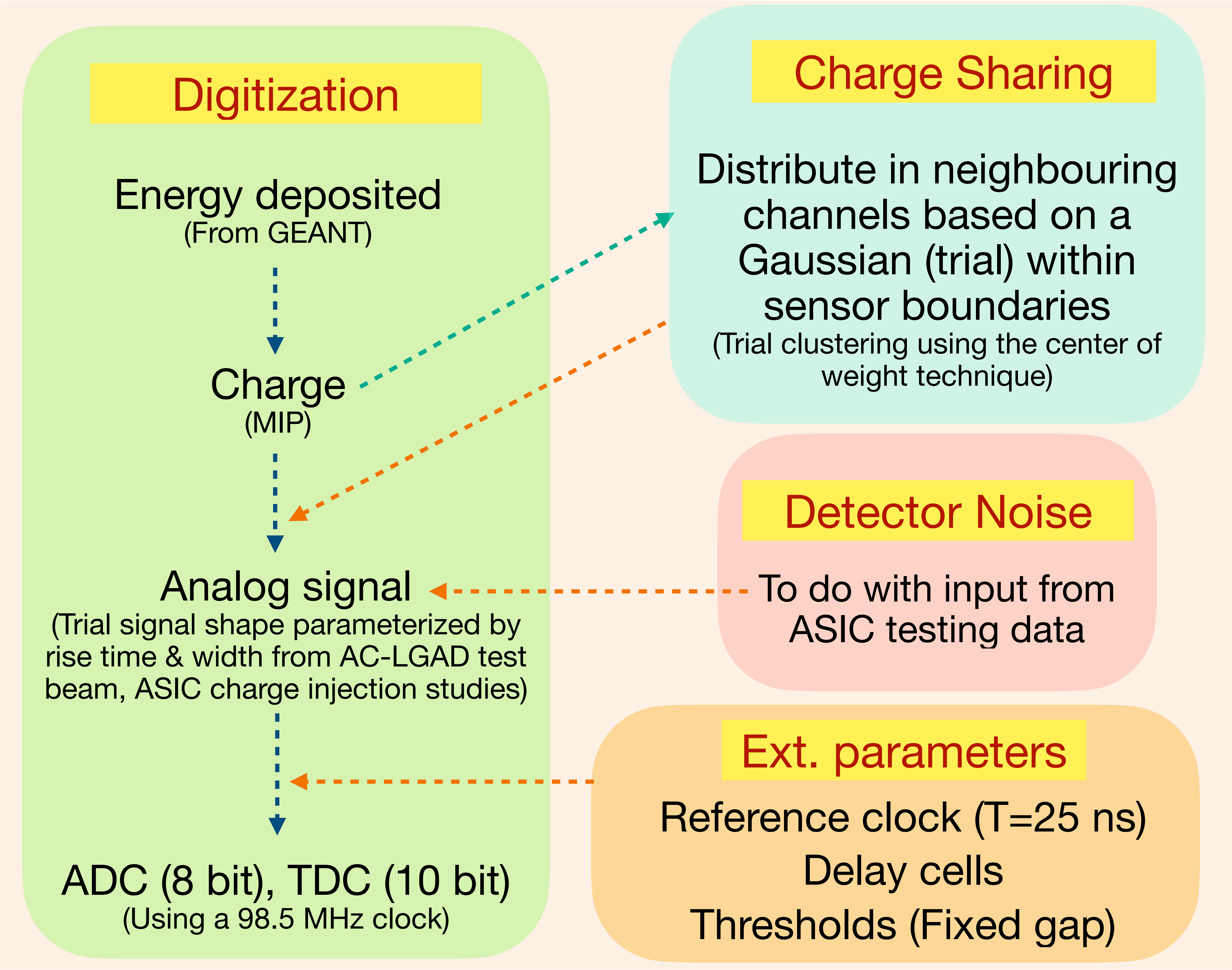
Reconstruction accuracy remains constant with σ.

ML reconstruction technique



Reconstruction accuracy worsens with increasing σ.

Summary & Future Work



To do:

1. Delay correction.
2. Resolution studies with reconstructed o/p and digitized o/p.
3. Effect of different charges on charge-sharing.
4. Incorporating realistic noise.
5. Implementation of local work on digitization in ePIC simulation framework.