

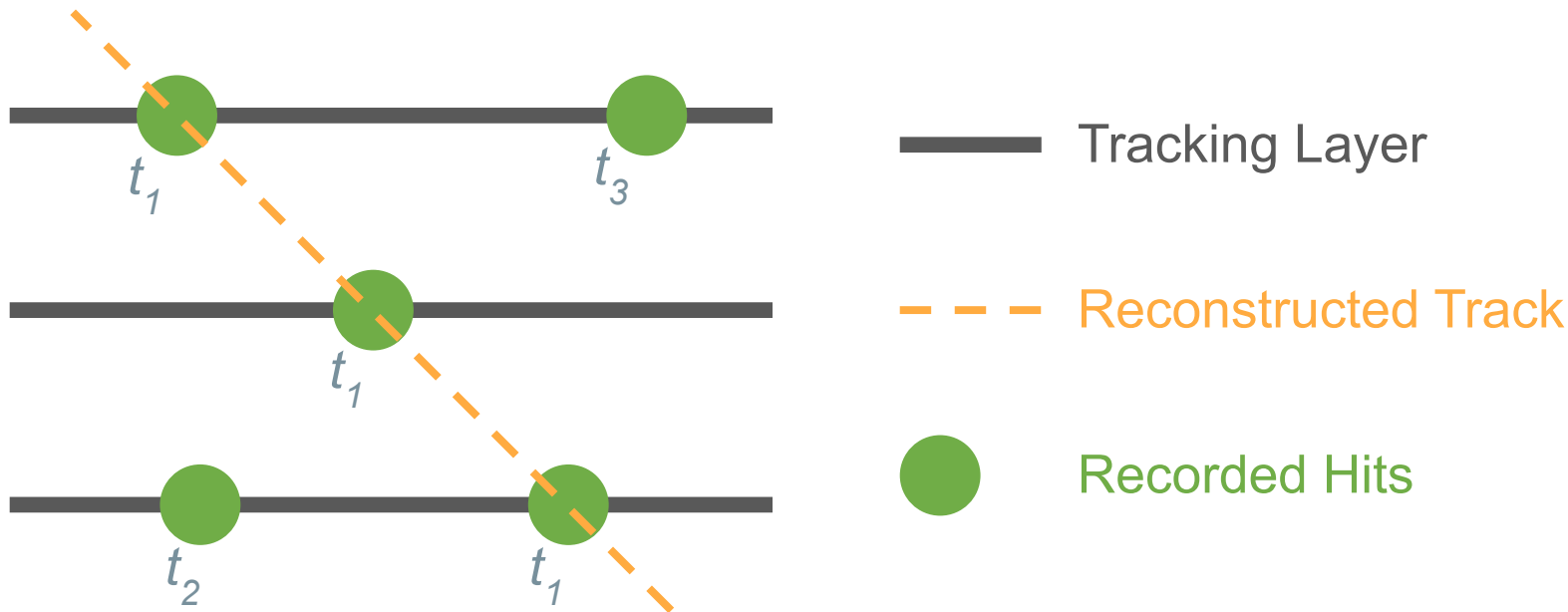
Using fast-timing to determine track position, time, and angles

[arXiv:2605.24736](https://arxiv.org/abs/2605.24736) - under review at JINST

V. Turbinder^{a,b}, E. Villhauer^c, S. Jain^a, A. Gupta^a, M. Cardiff^d, J. Segal^b, C. J. Kenney^b, M. Horowitz^a, S. Mazza^e, A. Schwartzman^b, A. Dragone^b

^aStanford ^bSLAC ^cUChicago ^dBrandeis ^eSCIPP

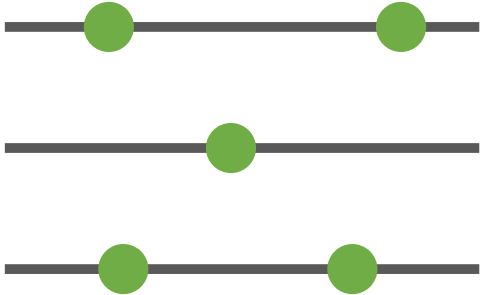
Fast-timing is coming



6D Tracking

3

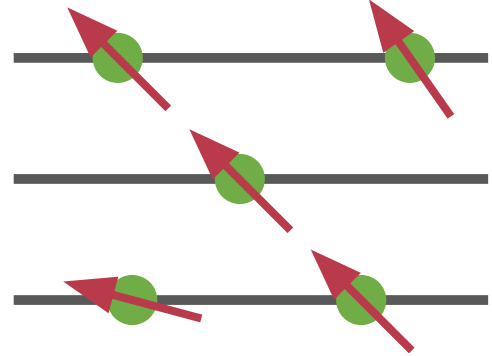
POSITION
 $X Y Z$



TIME
 T



ANGLES
 $\theta \phi$

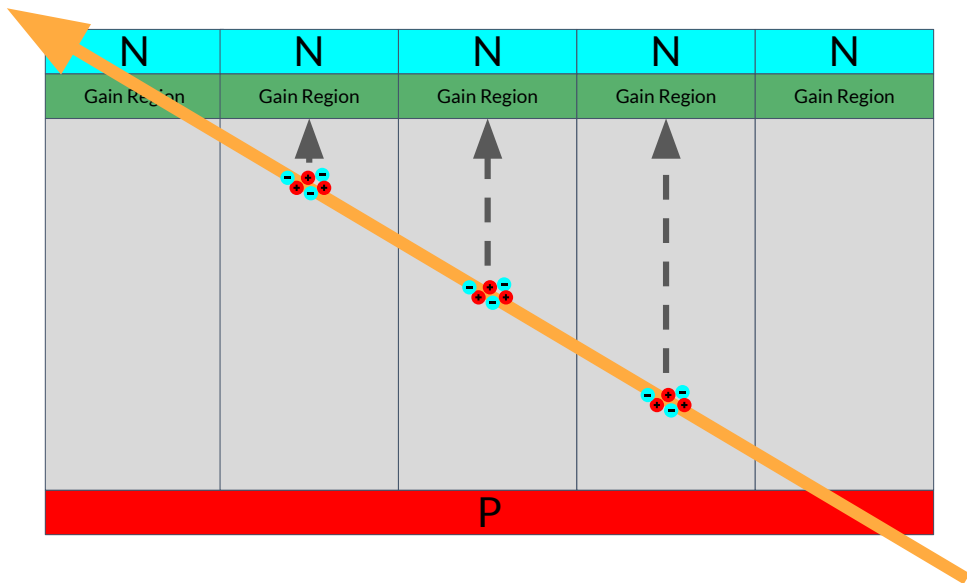
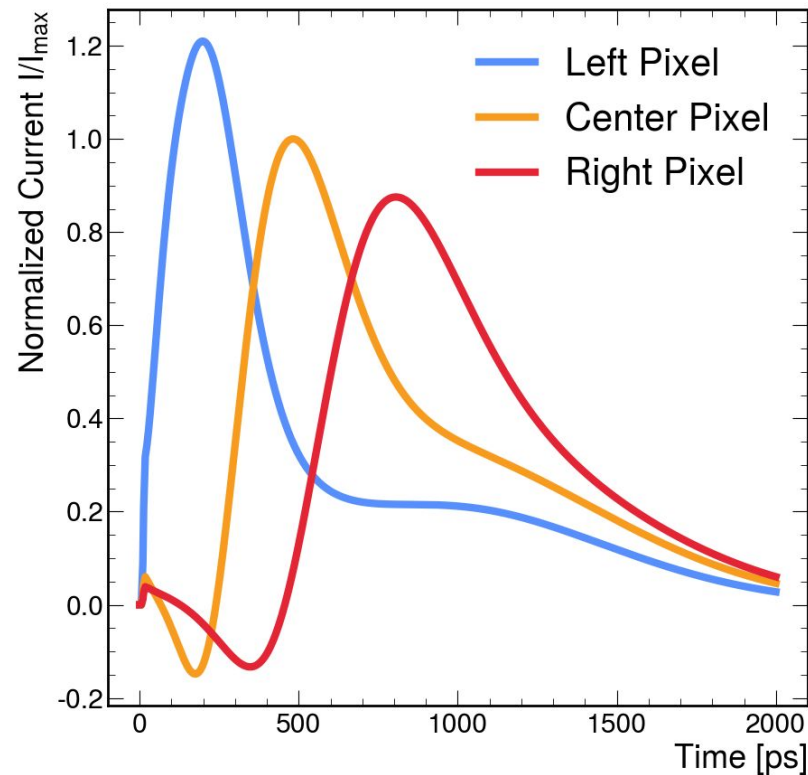


3D

4D

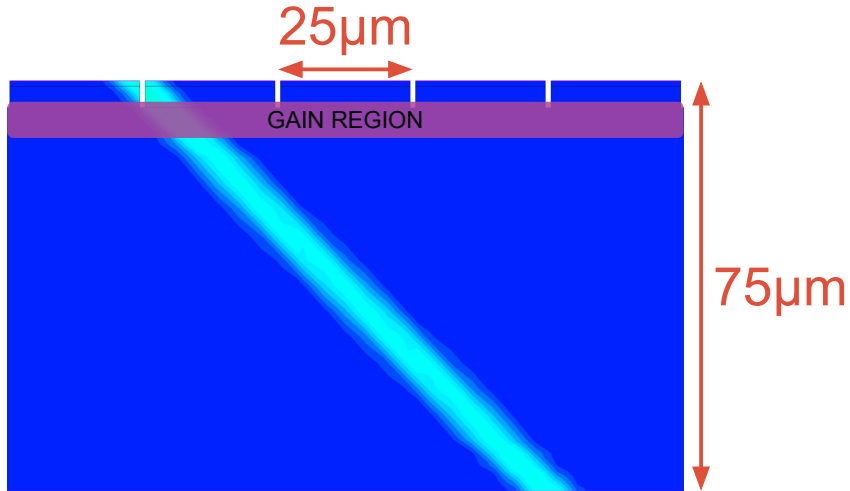
6D

Multi-pixel LGAD hits

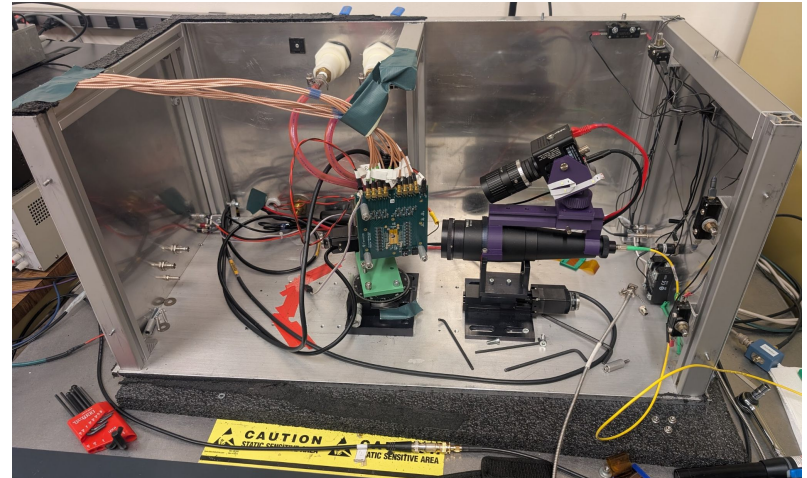


Tools

2D TCAD Simulations

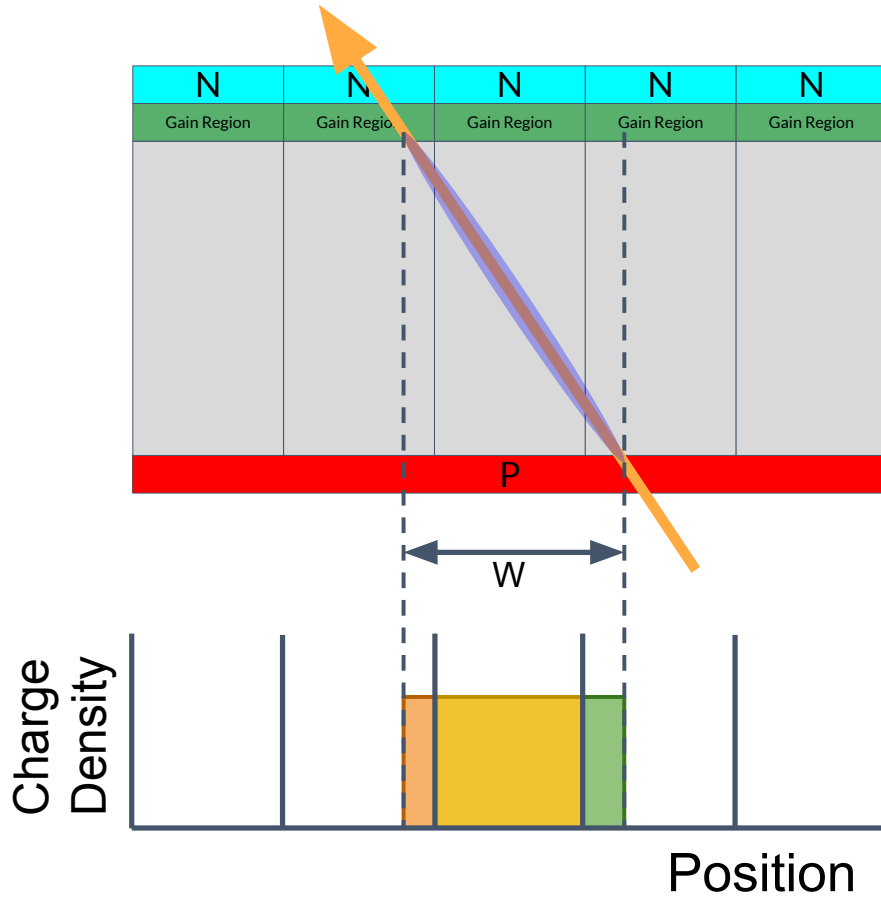
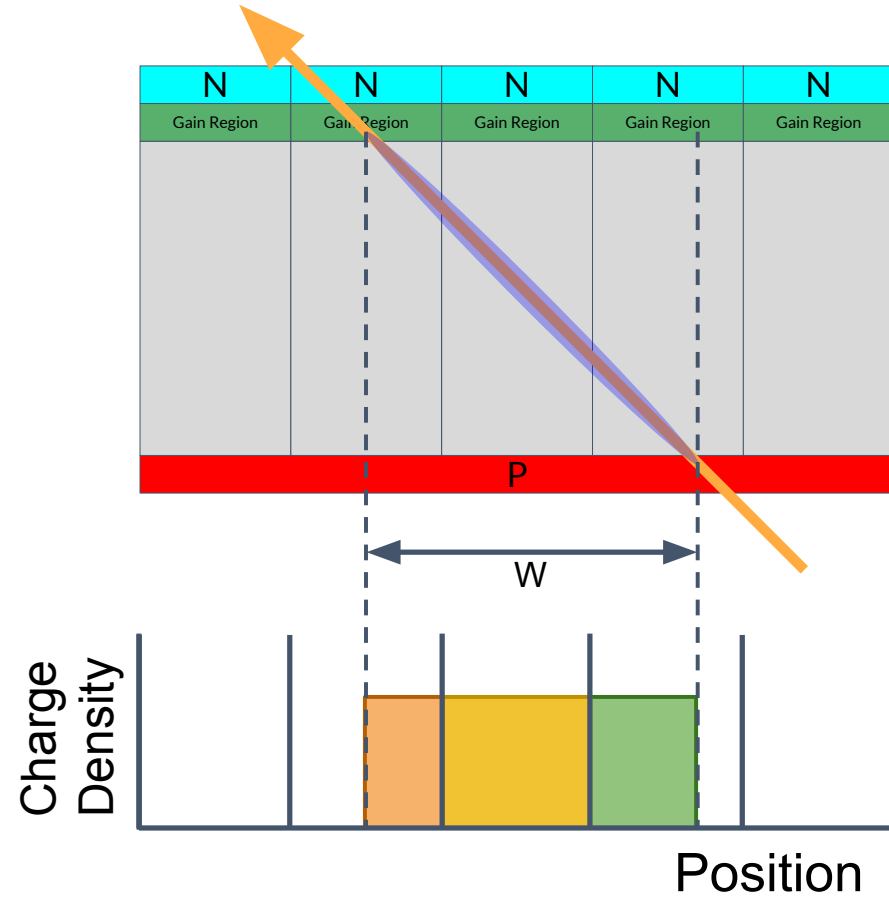


IR Laser Experiment

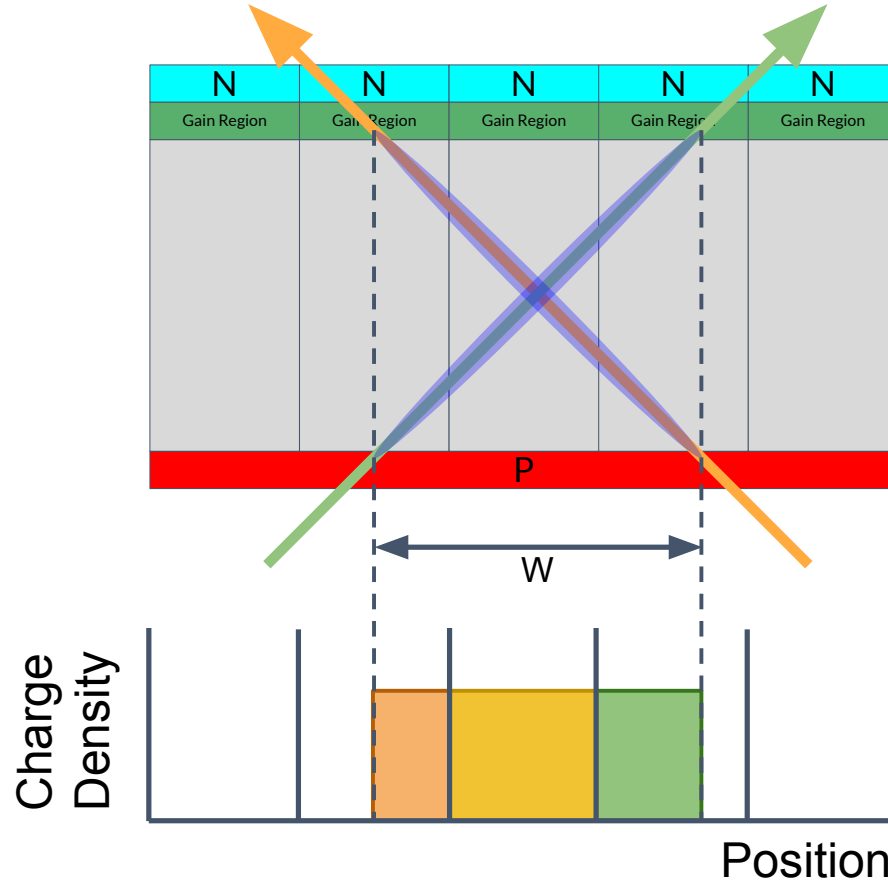


Angles from cluster charge

6

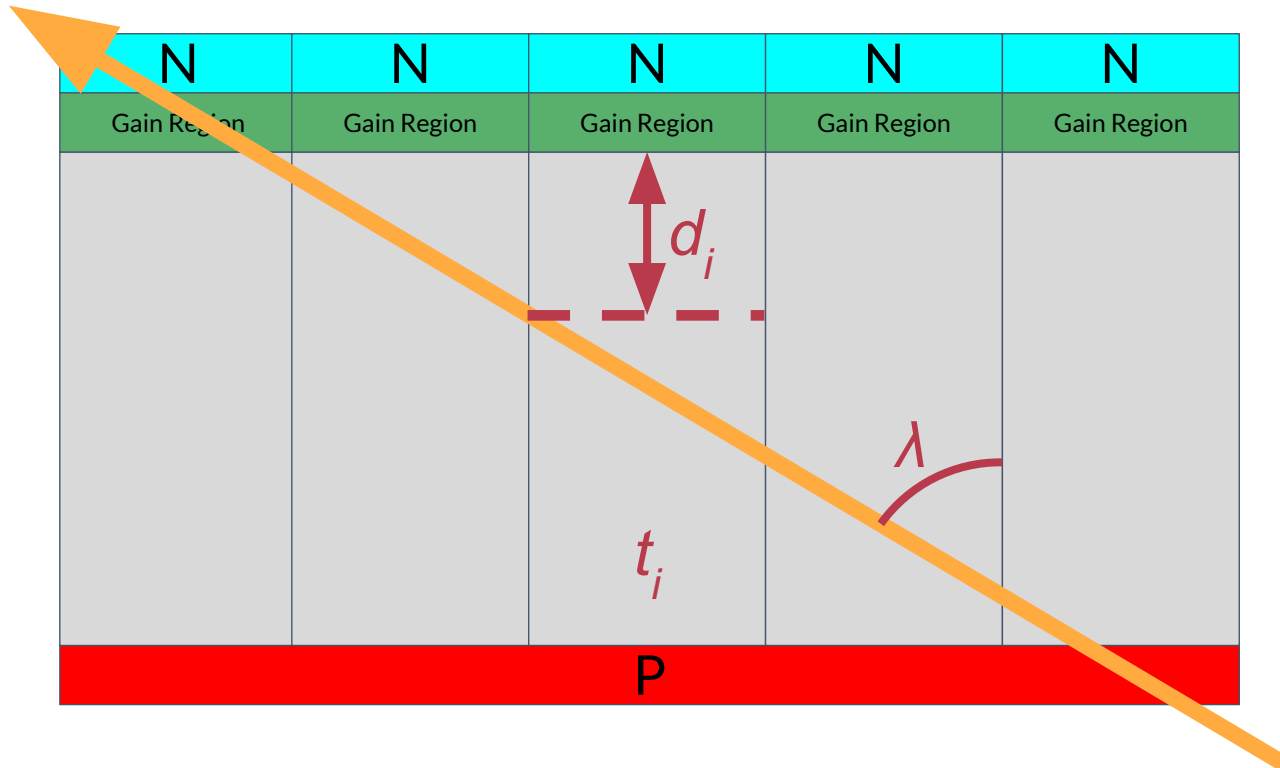


Ambiguous track direction

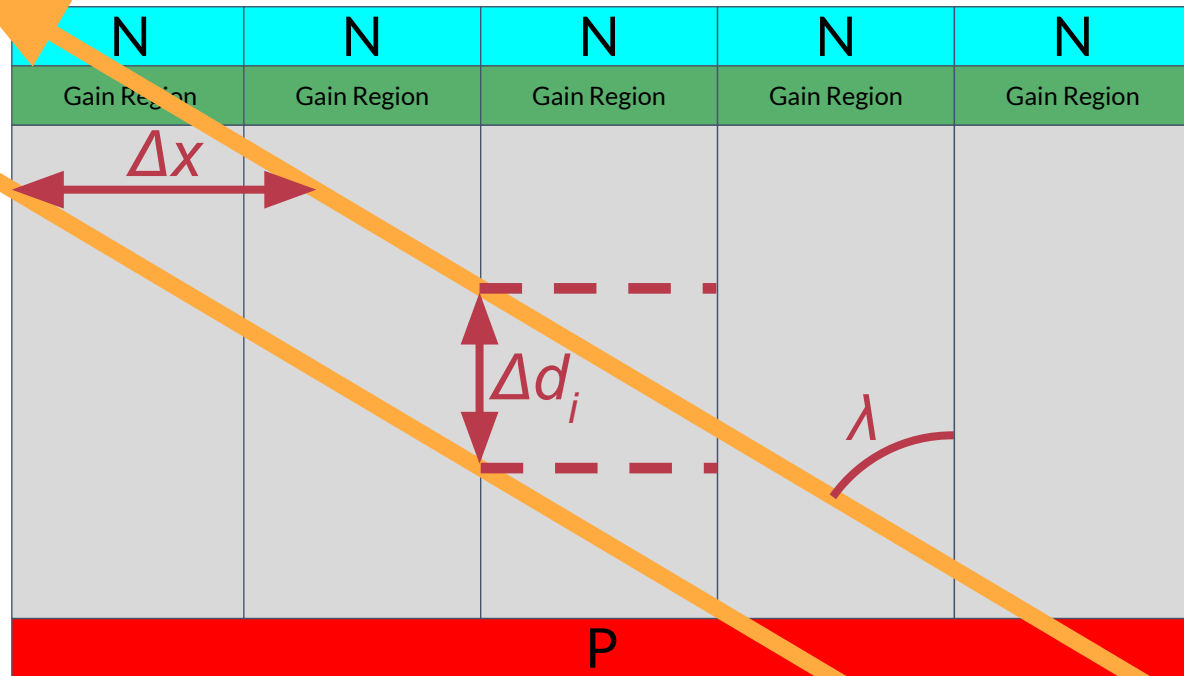


The relationship between timing and angles

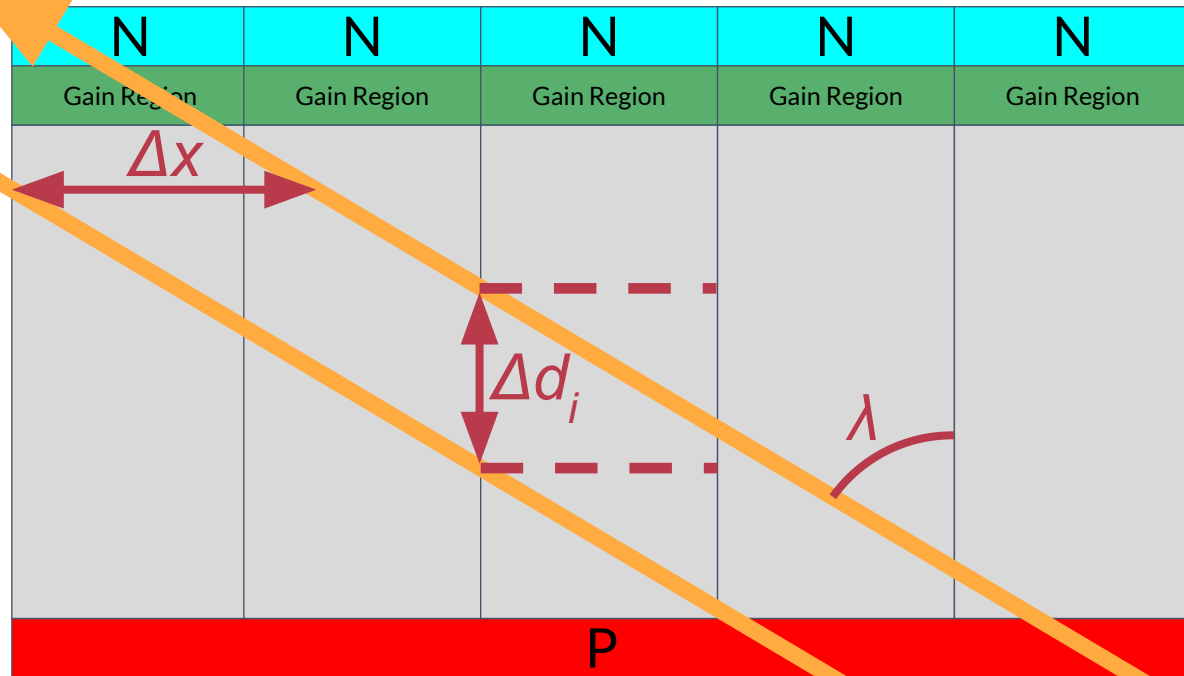
$$t_i = t_{\text{hit}} + d_i / v_{\text{drift}}$$



$$\Delta d_i = \Delta x \cot \lambda$$

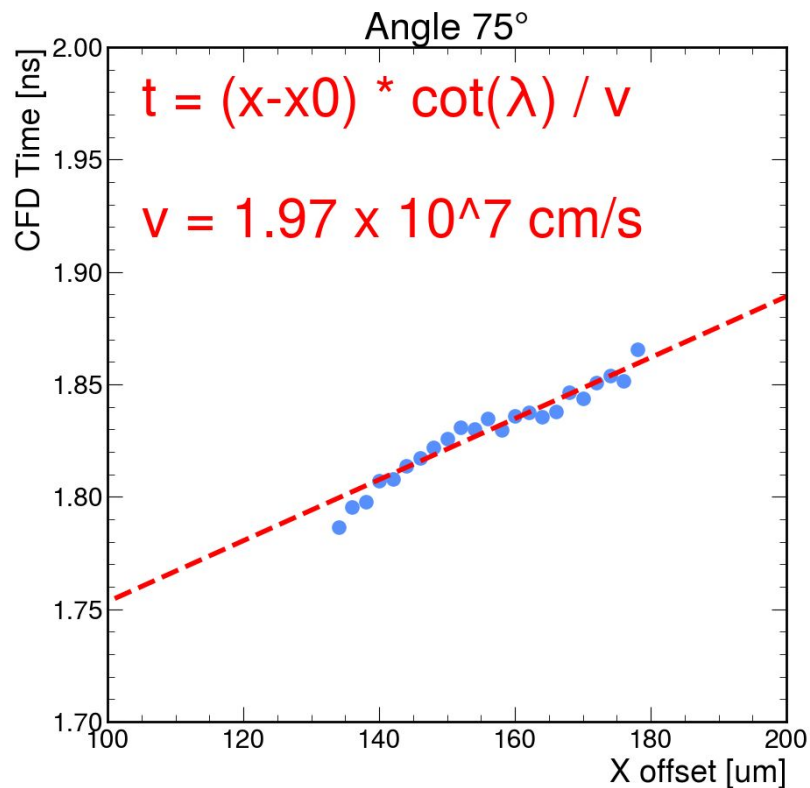
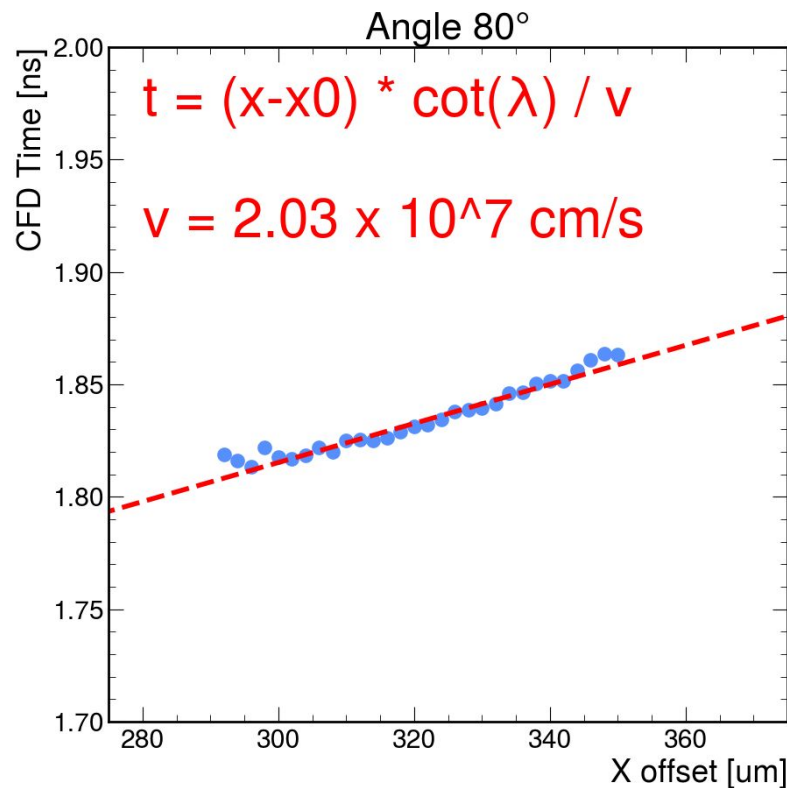


$$\Delta t_i = \frac{\cot \lambda}{v_{\text{drift}}} \Delta x$$

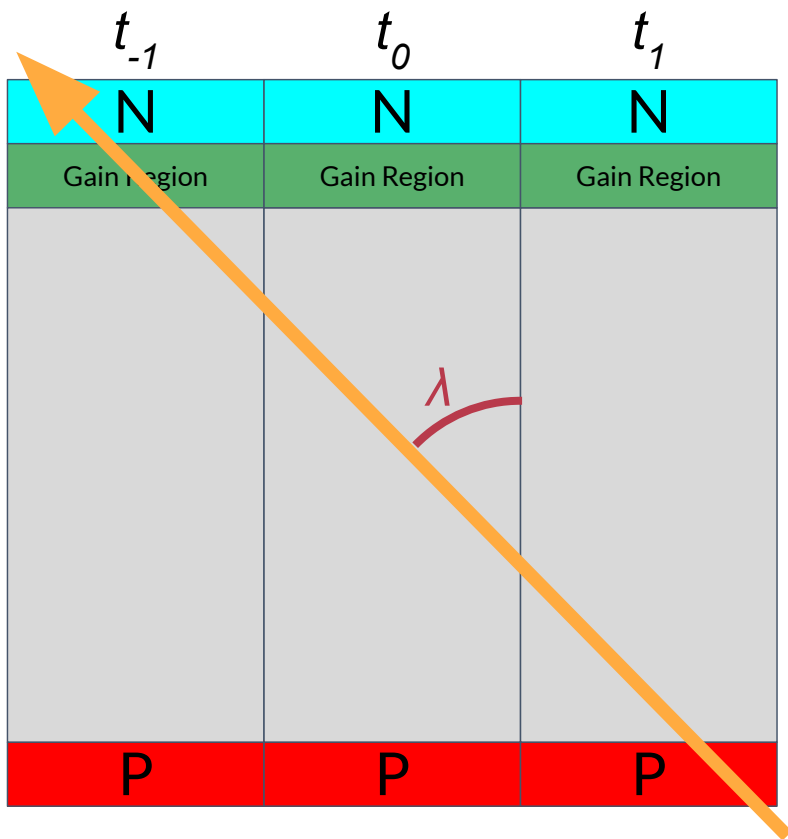


IR laser measurements (preliminary)

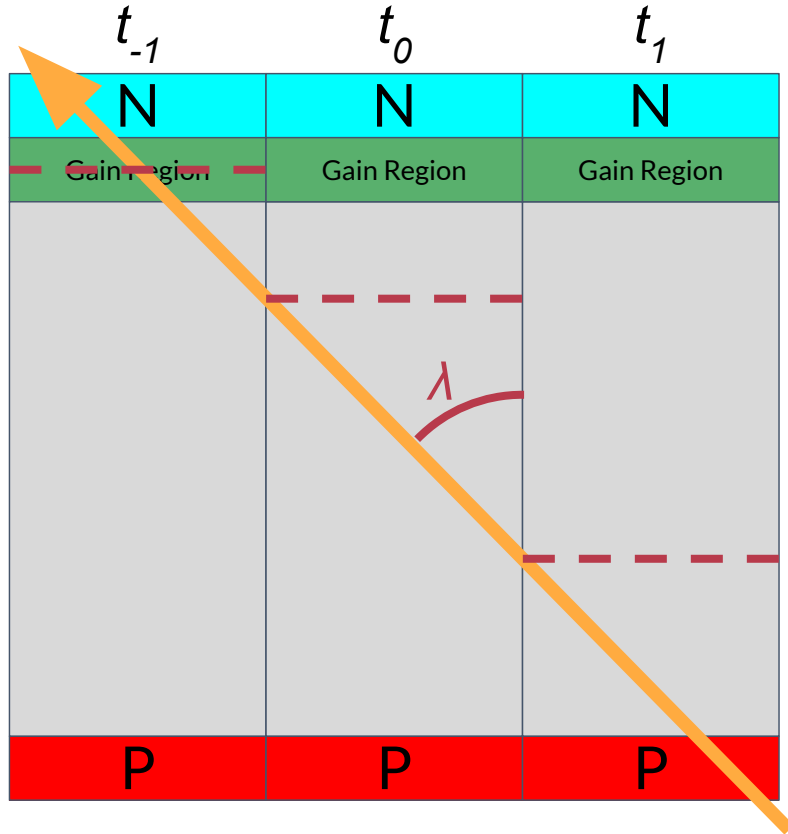
12



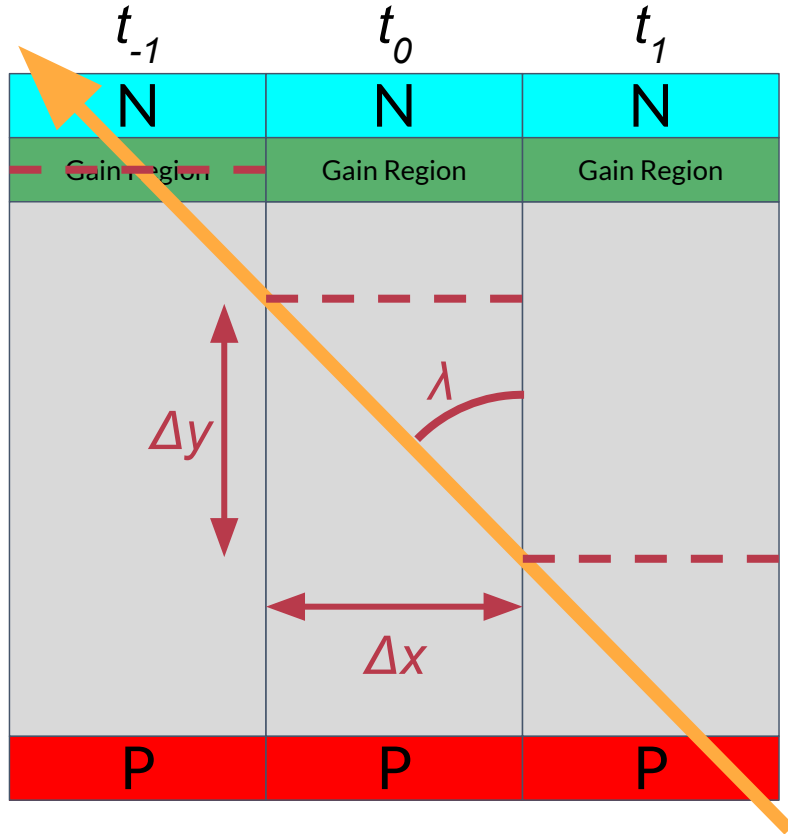
Angle reconstruction



Angle reconstruction

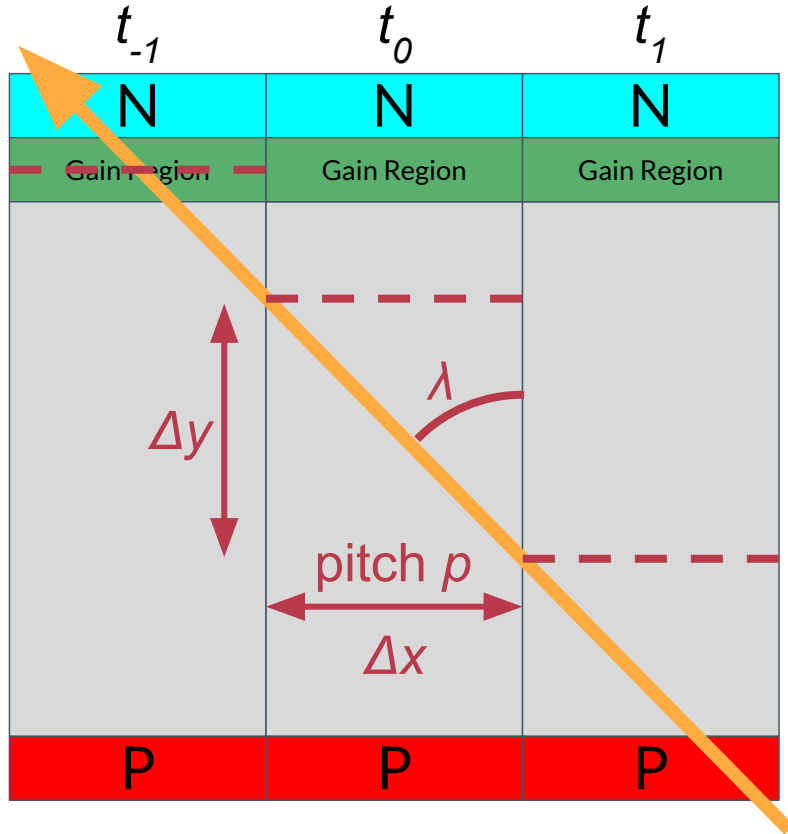


Angle reconstruction



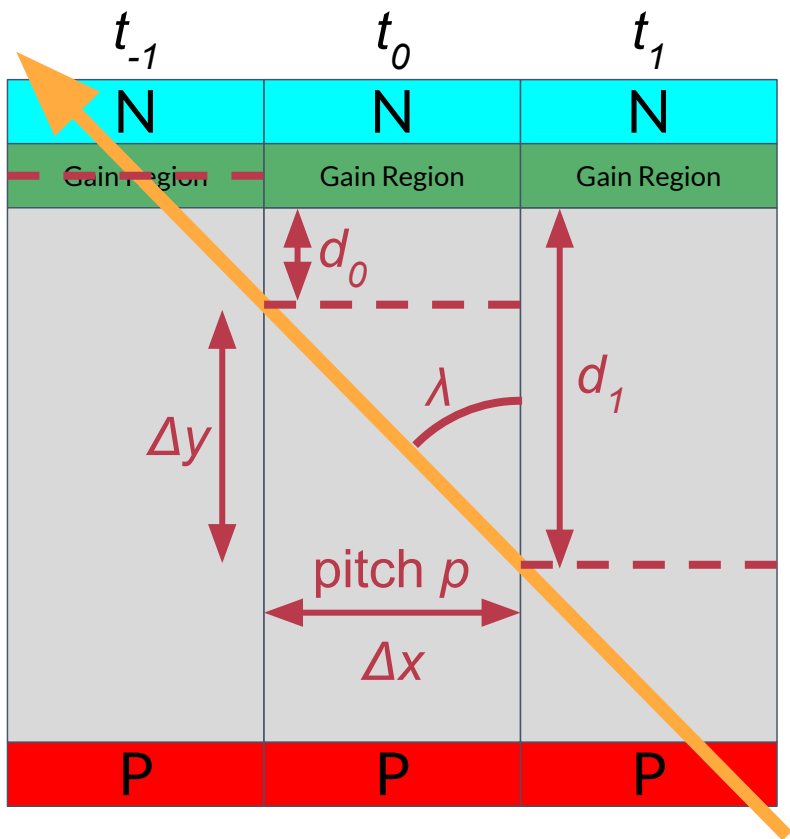
$$\cot \lambda = \frac{\Delta y}{\Delta x}$$

Angle reconstruction



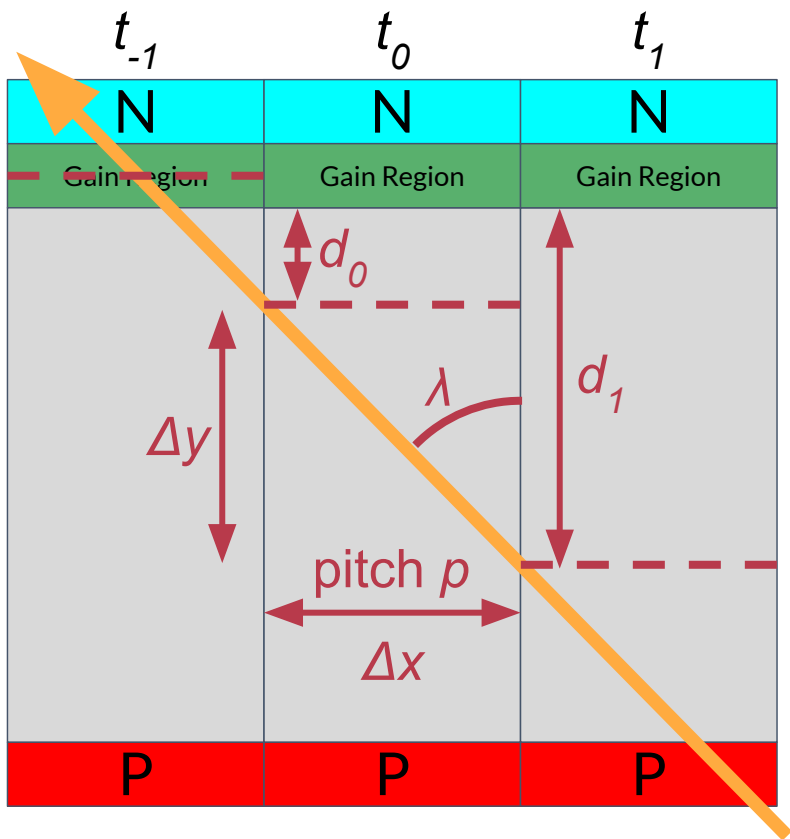
$$\cot \lambda = \frac{\Delta y}{\Delta x}$$

Angle reconstruction



$$\cot \lambda = \frac{\Delta y}{\Delta x} = \frac{d_1 - d_0}{p}$$

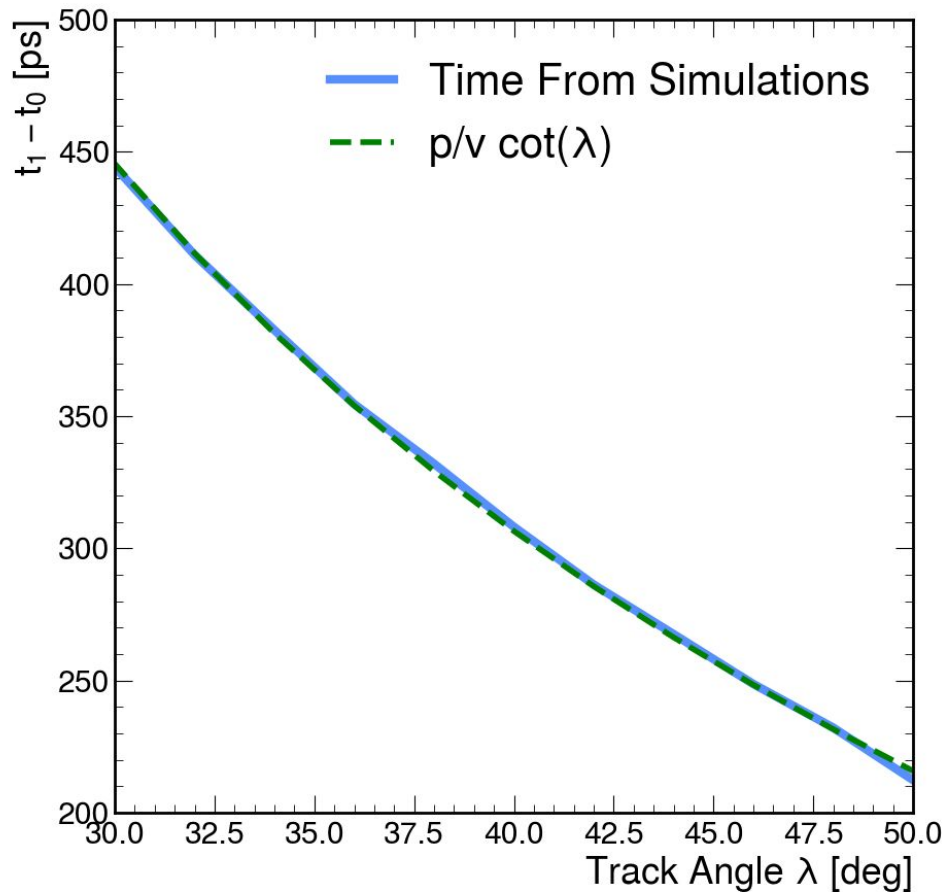
Angle reconstruction



$$\cot \lambda = \frac{\Delta y}{\Delta x} = \frac{d_1 - d_0}{p}$$

$$\cot \lambda = \frac{v_{\text{drift}}}{p} (t_1 - t_0)$$

The model fits the data (simulation)



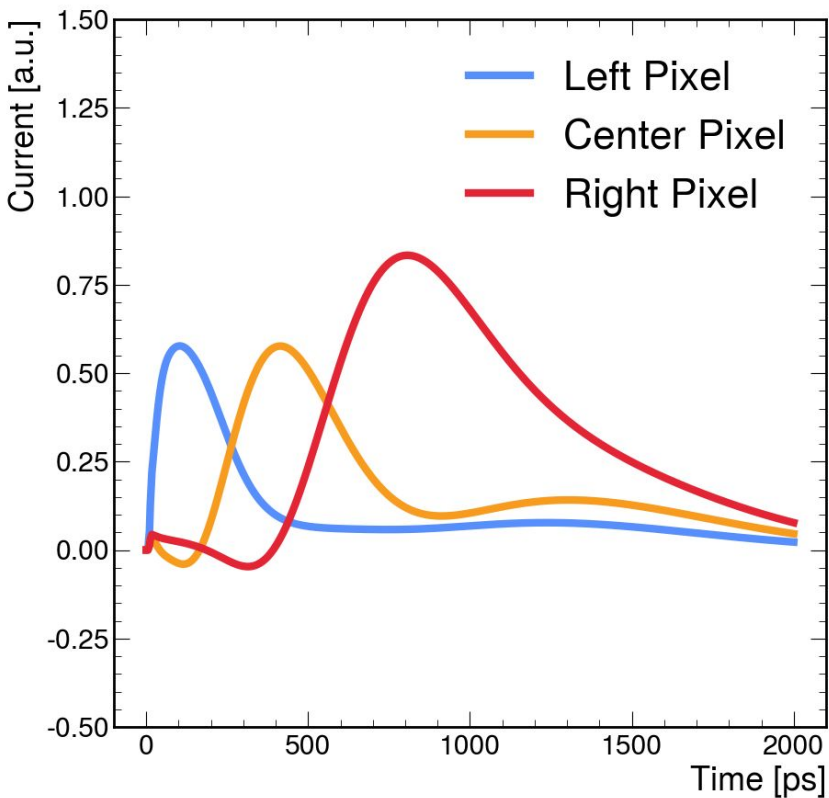
$$\cot \lambda = \frac{v_{\text{drift}}}{p} (t_1 - t_0)$$

Challenges

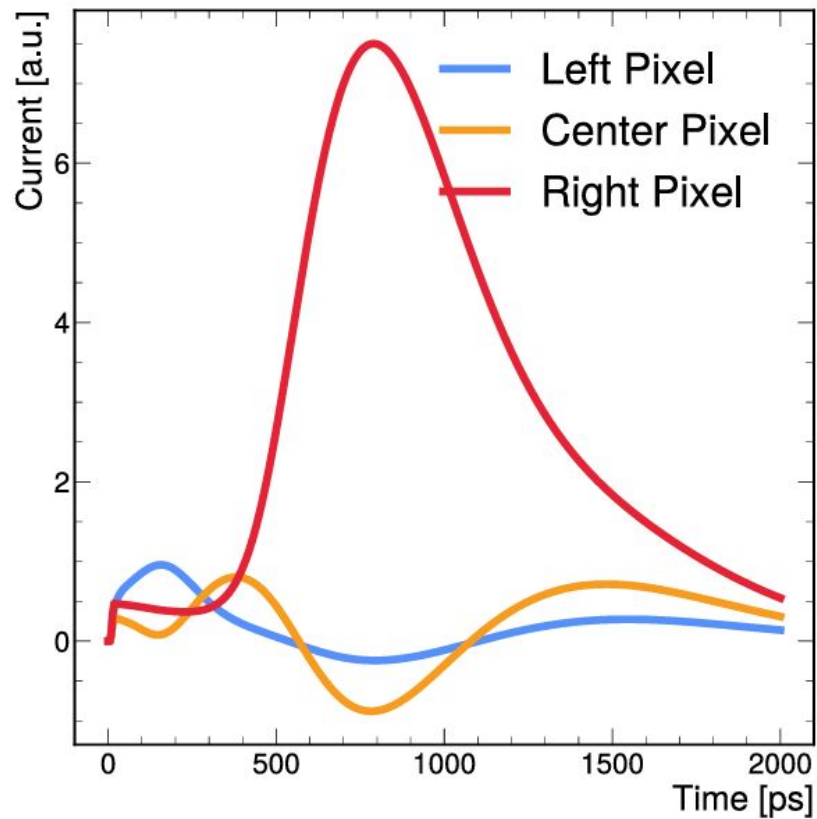
Current waveforms (simulation)

21

~90% of tracks

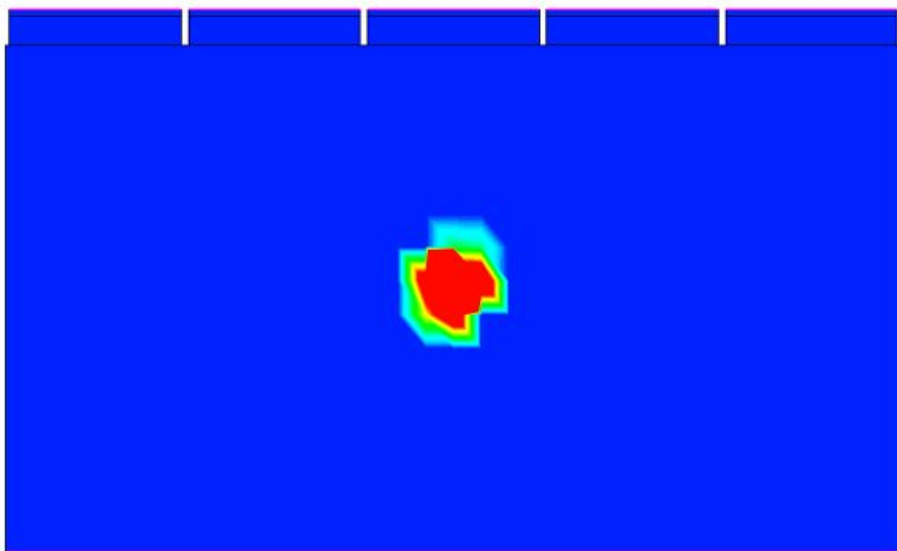
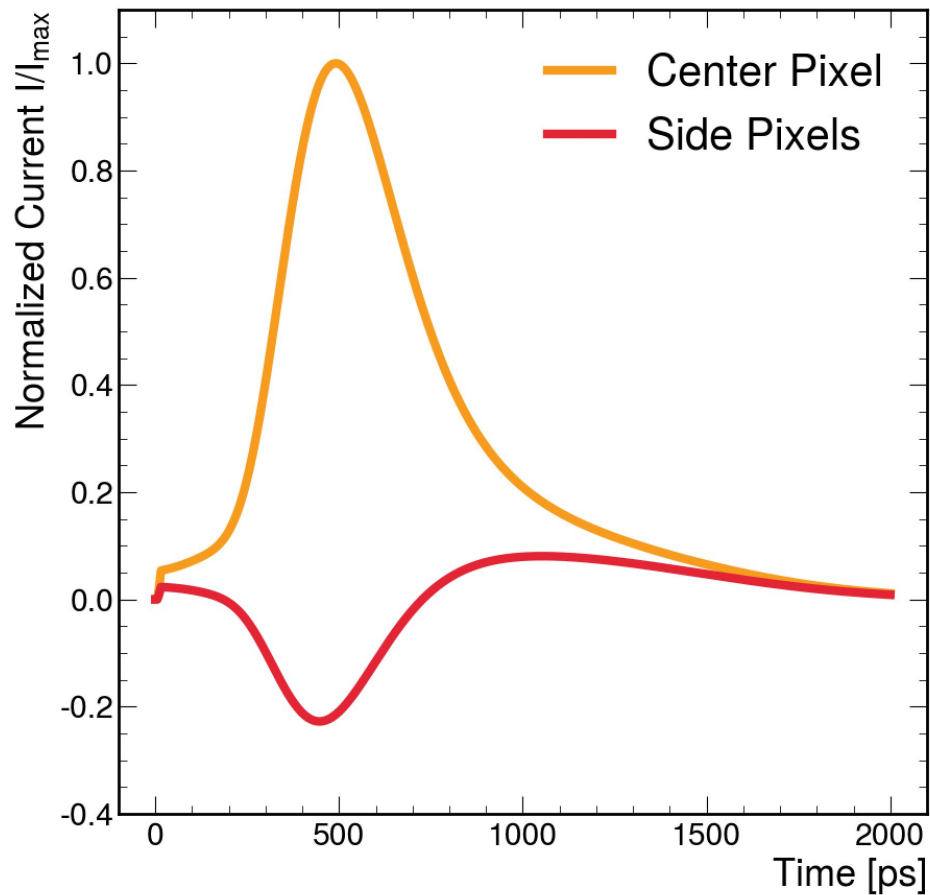


~10% of tracks



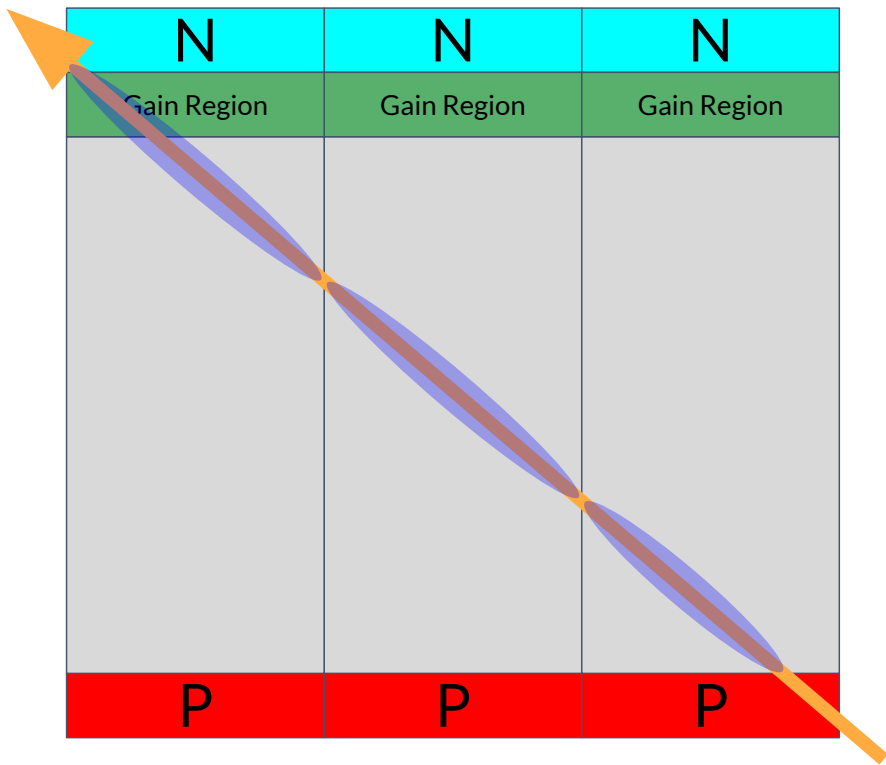
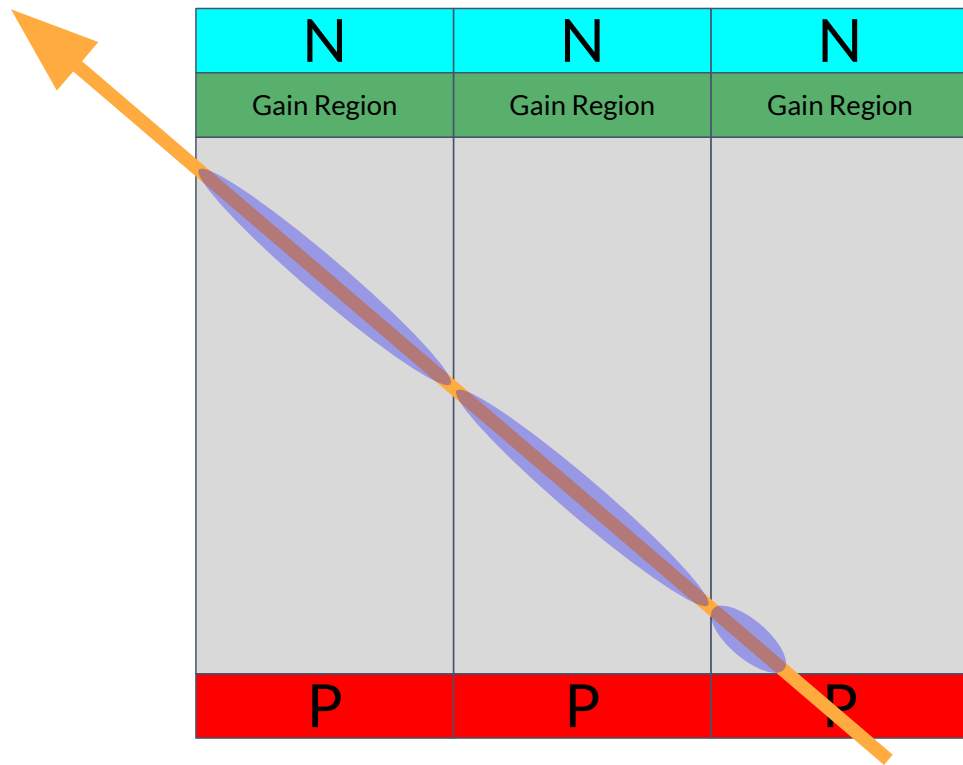
Crosstalk

22

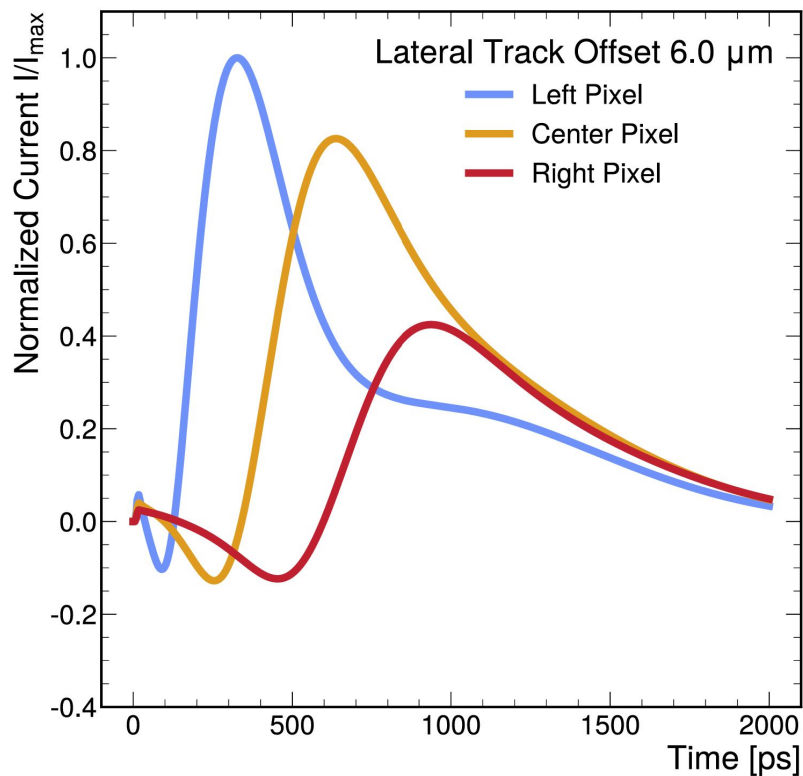
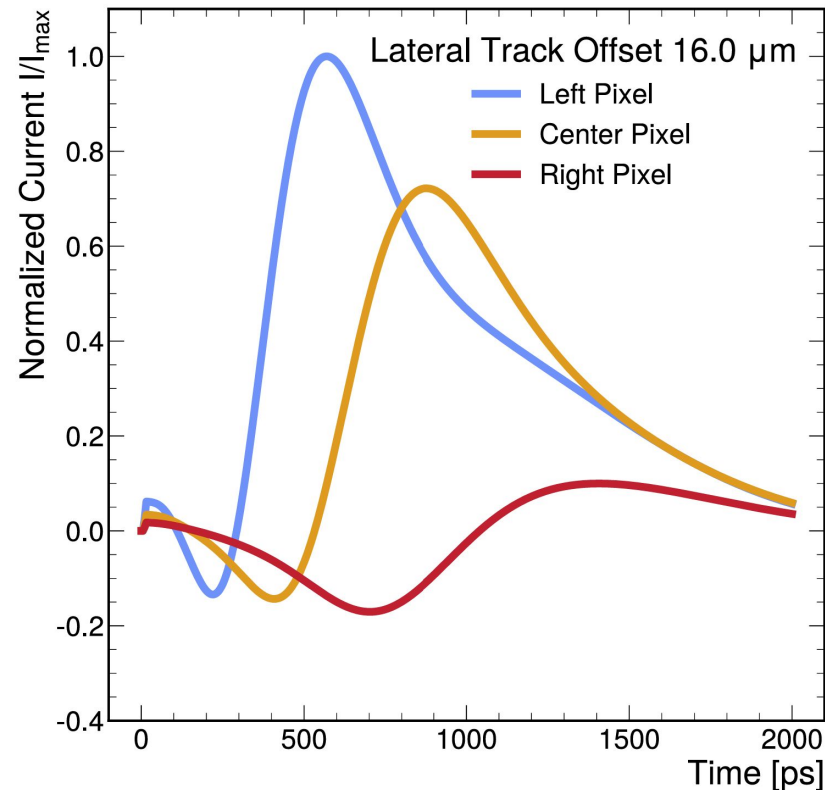


Lateral offset

23



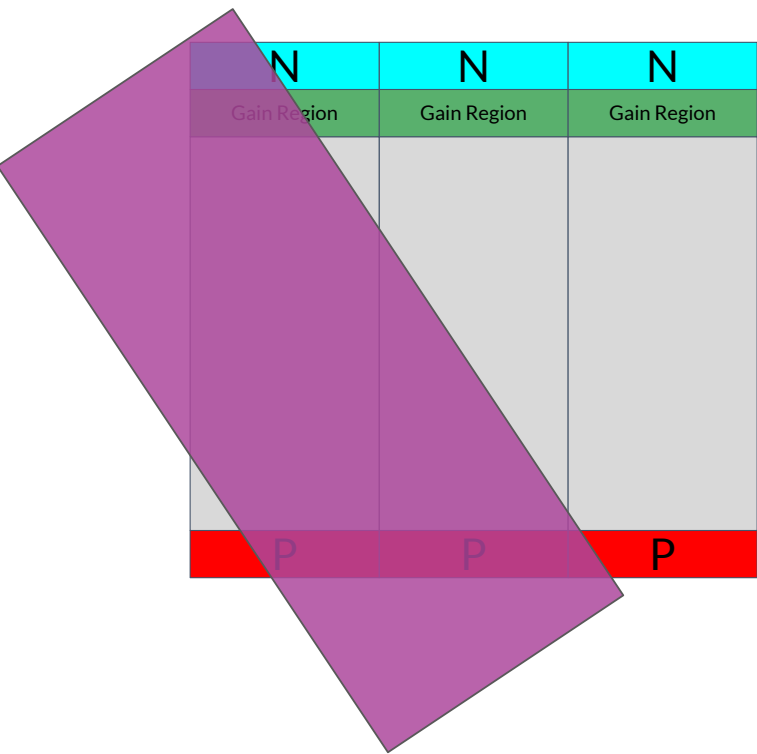
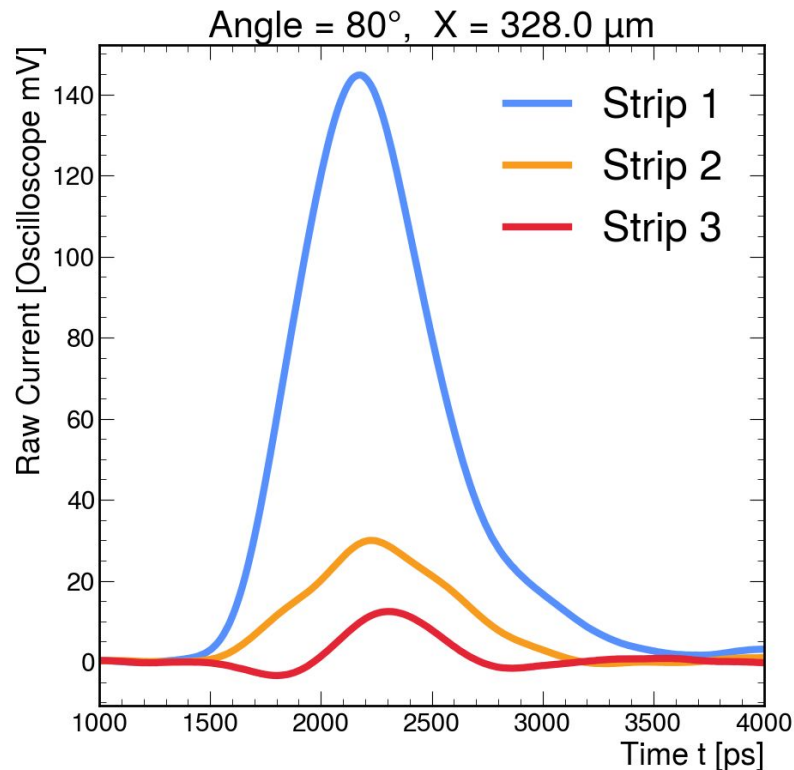
Lateral offset (simulation)



Solution: Weigh hits by pulse amplitude

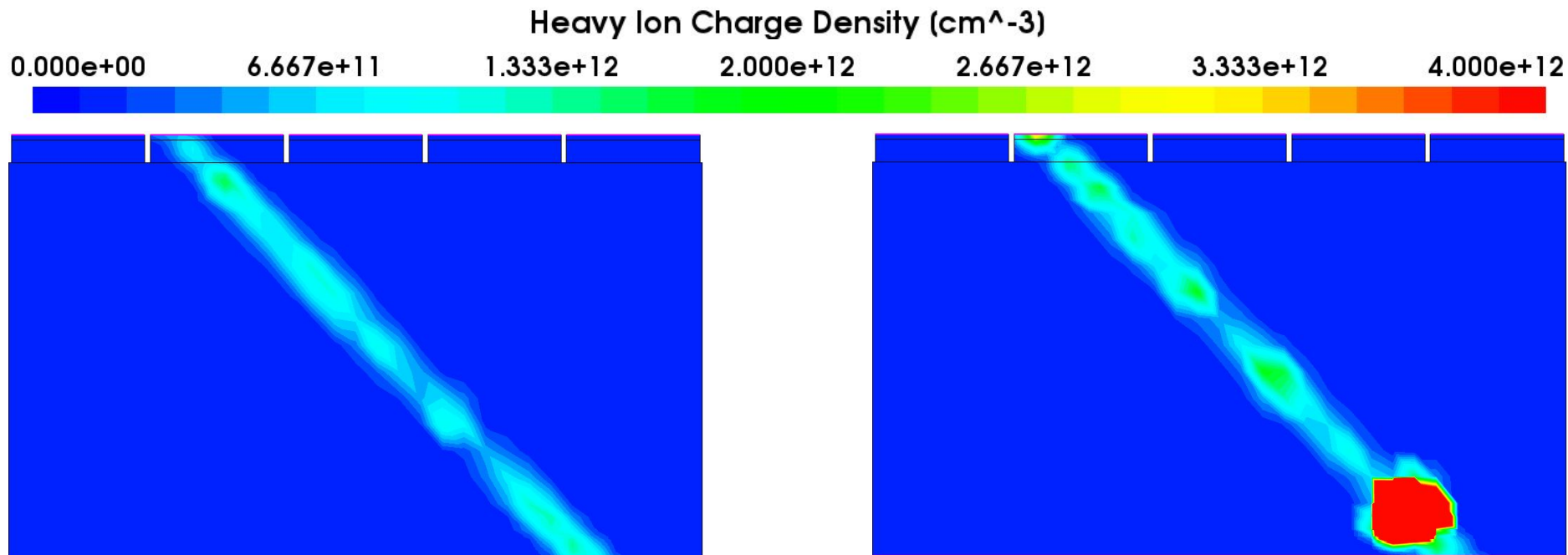
Lateral offset (preliminary measurements)

Strip 1 Strip 2 Strip 3



Solution: Weigh hits by pulse amplitude

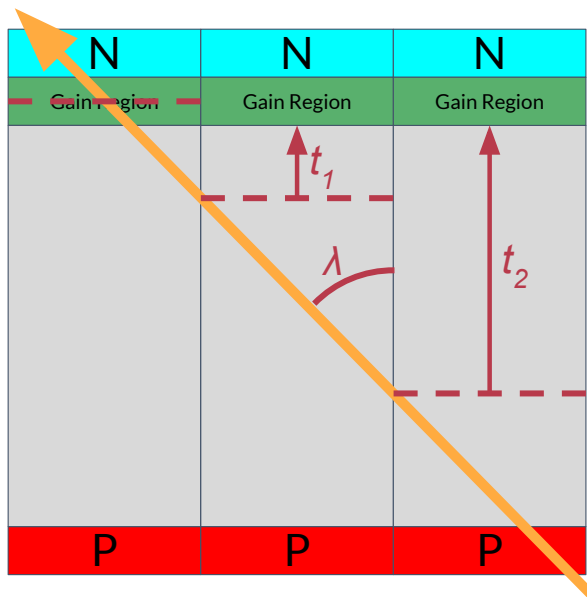
Large Landau fluctuations (simulation)



Solution: Filter tracks with very high charge deposition

Reconstruction algorithm

1. Weigh hits by amplitude to find the sign of the track angle
2. Filter tracks with high charge due to large Landau fluctuations
3. Compute track angles using the linear model

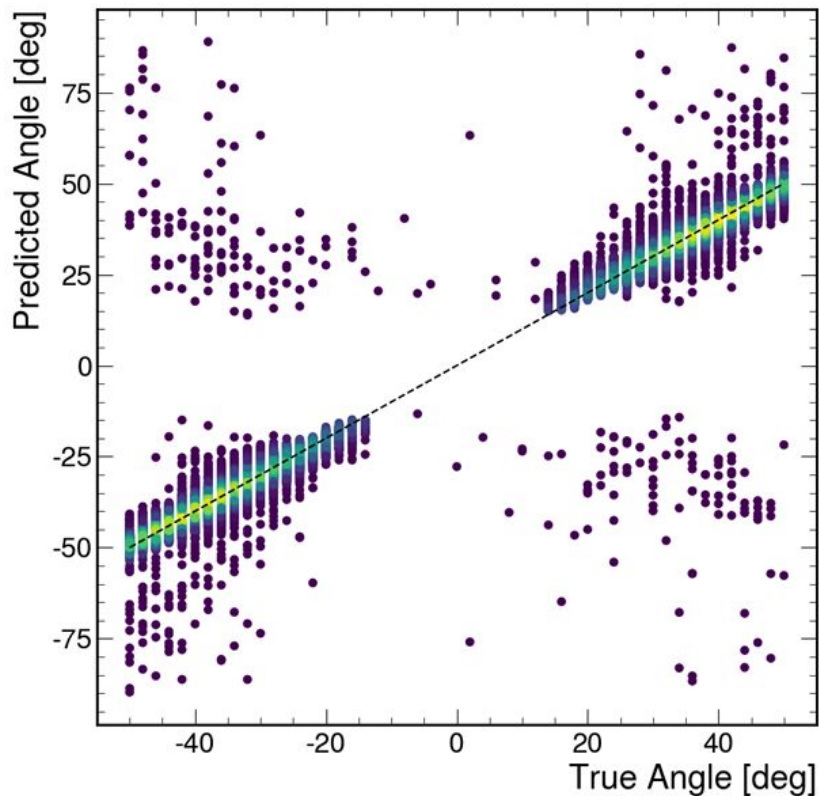


$$\widehat{\cot \lambda} = c_0 + \sum_i c_i (t_{i+1} - t_i)$$

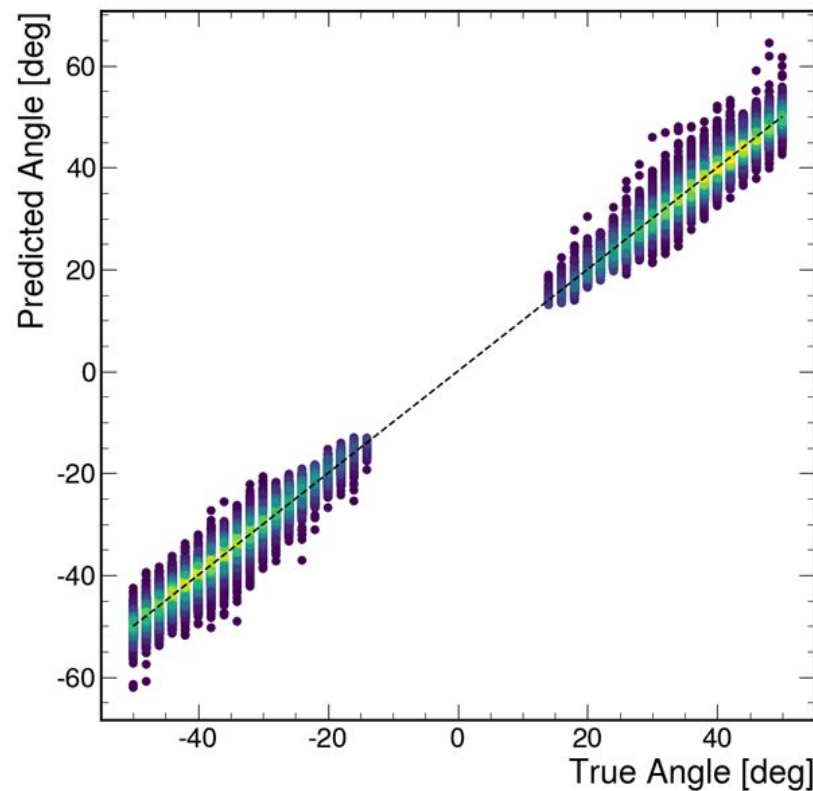
Results (simulation)

28

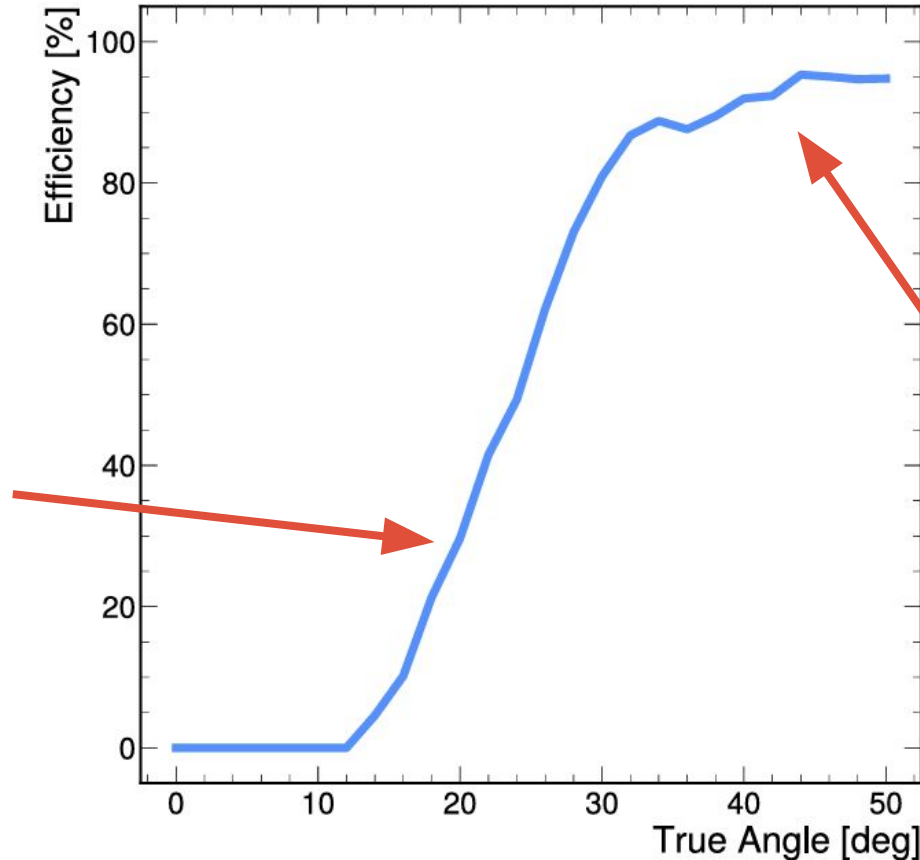
Before Landau filtering



After Landau filtering



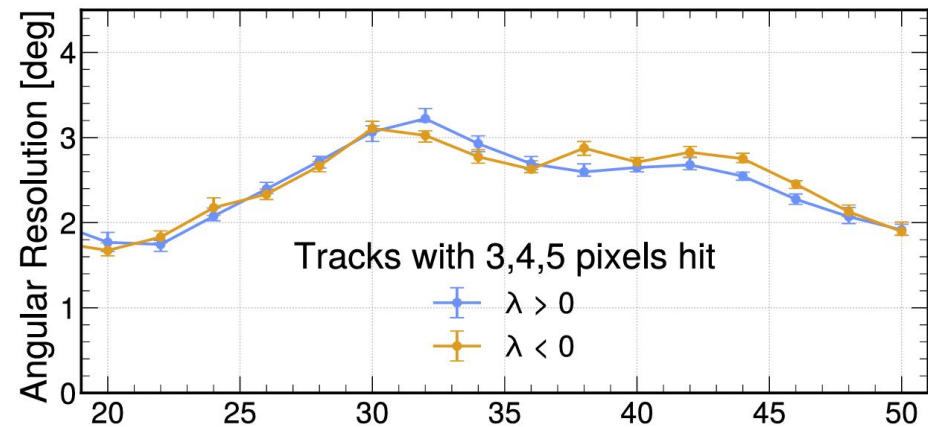
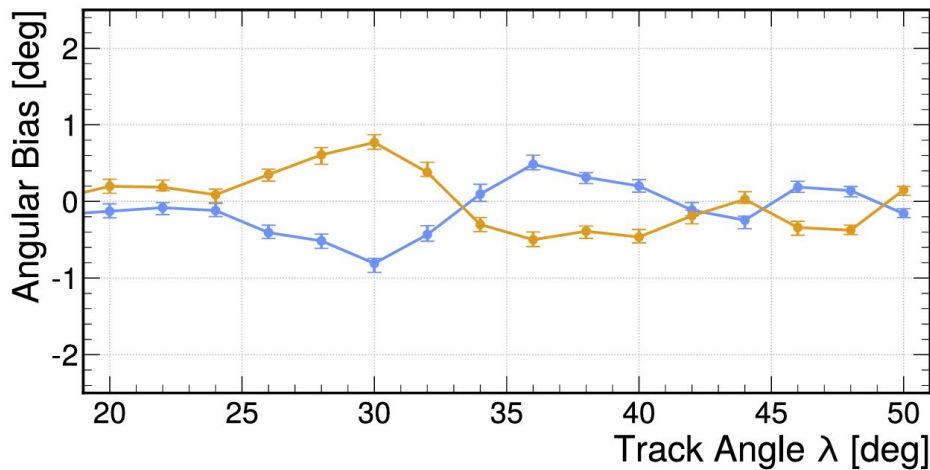
Efficiency (simulation)



At least 3 pixels
need to be hit to
reconstruct the
angle

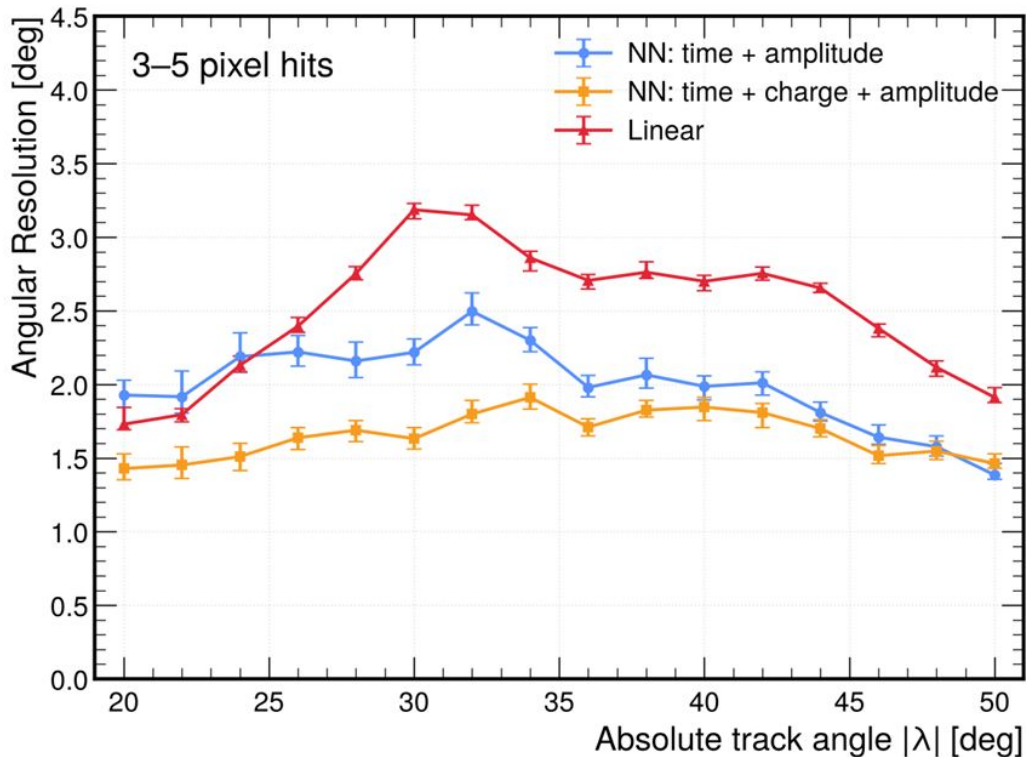
Tracks with high
charge are filtered
for large Landau
fluctuations

Results (simulation)



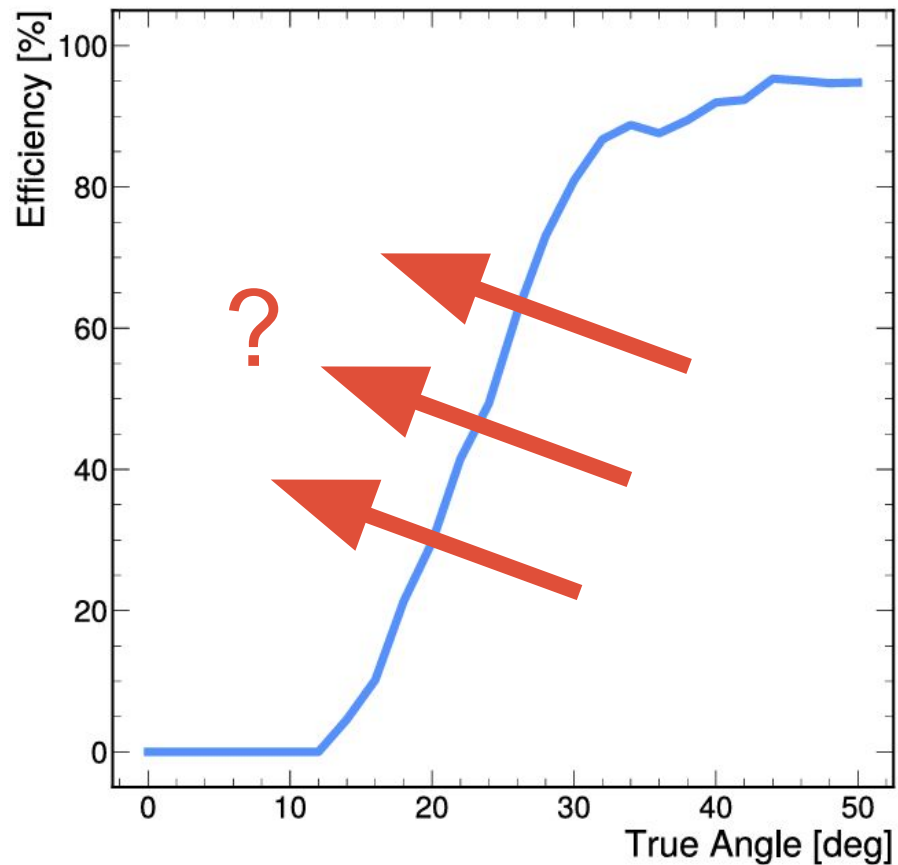
Neural networks (simulation)

31



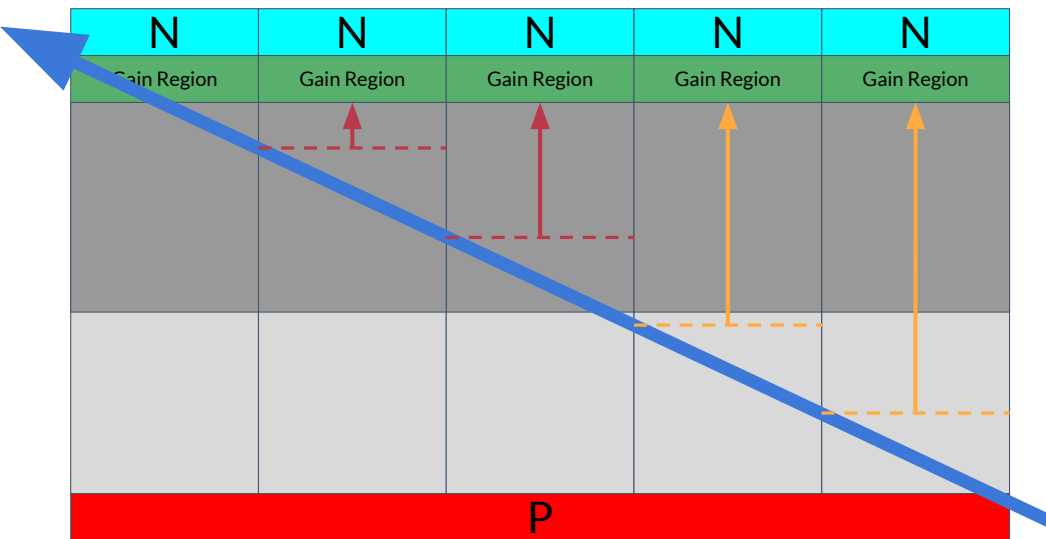
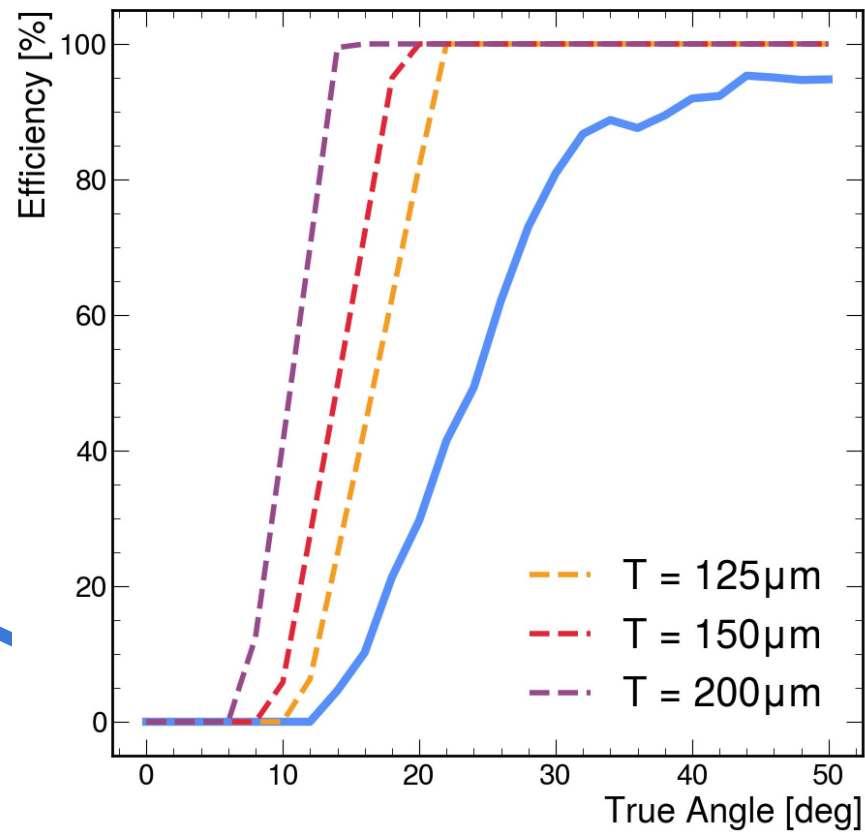
Trained on the same filtered simulation samples as the linear model

Improving efficiency



Thicker detectors

33



Towards 6D Tracking

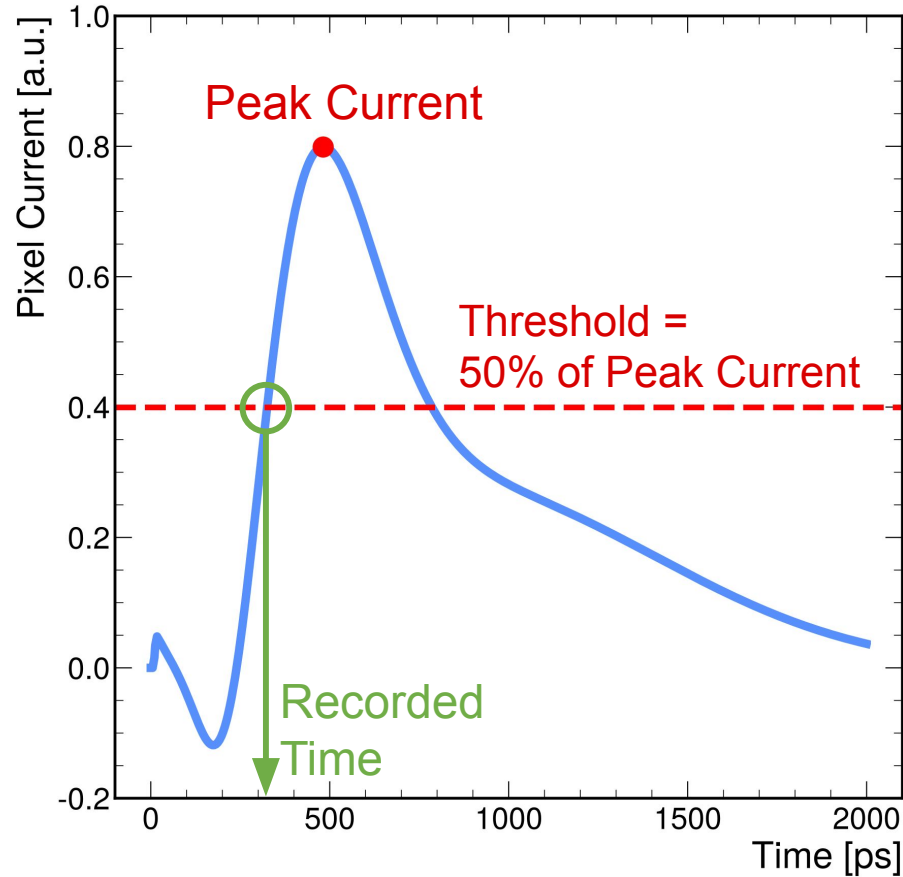
- 1 Tilted tracks spread hit times by hundreds of ps
- 2 Timing gives the angle and its sign from a single layer (with ≥ 3 pixels hit)
- 3 Simple analytic model: $2^\circ - 3^\circ$, bias $< 1^\circ$; neural networks reach $\sim 1.7^\circ$
- 4 Crosstalk from charge imbalance distorts waveforms
- 5 Laser scans confirm the drift-time slope and offset-driven crosstalk
- 6 Interesting possibilities for future optimization of 6D trackers

BACKUP

LGAD details

	Simulation	Laser measurement
Type	5 TI-LGAD Strips	TI-LGAD Strip Array
Method	2D Sentaurus TCAD	Tilted IR laser beam
Pitch × thickness	25 μm × 75 μm	50 μm × 50 μm
Gain	10×	10×
Charge	Landau-sampled	IR absorption
Statistics	110 events / config	100 shots averaged
Timing	Ideal 50% CFD	Ideal 50% CFD

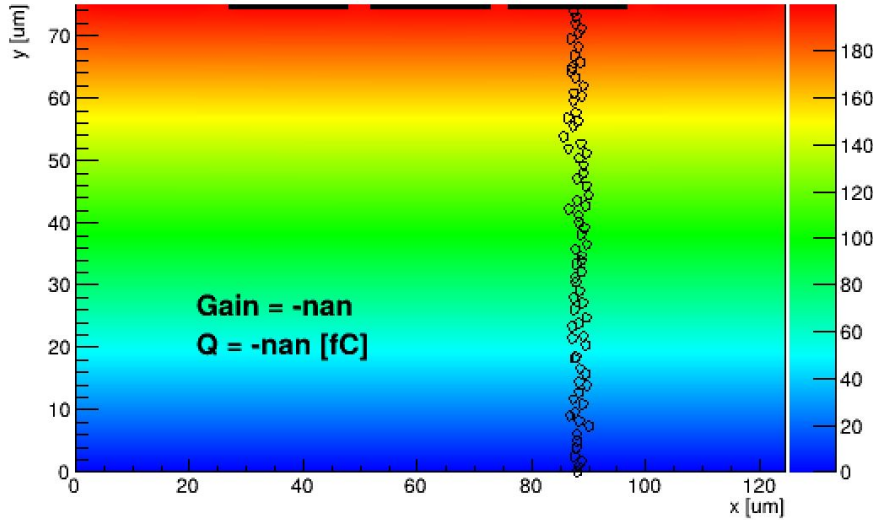
Constant Fraction Discriminator (CFD)



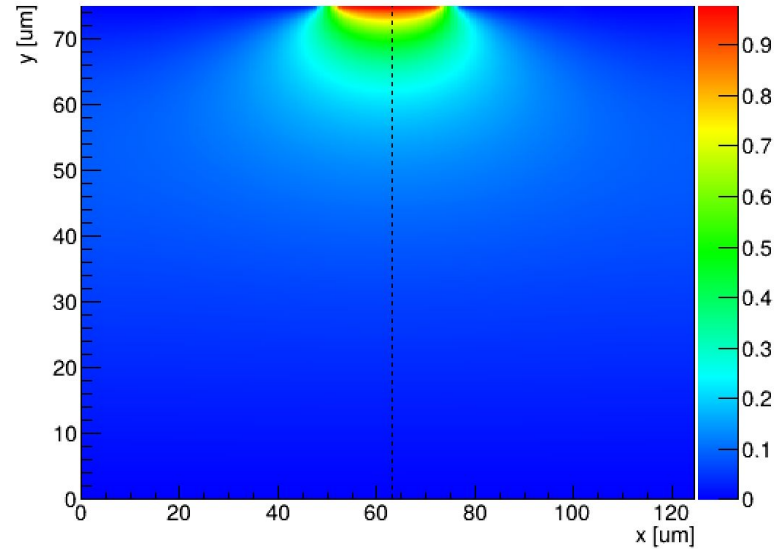
Shockley-Ramo and crosstalk

Waveform pixel

Hit pixel

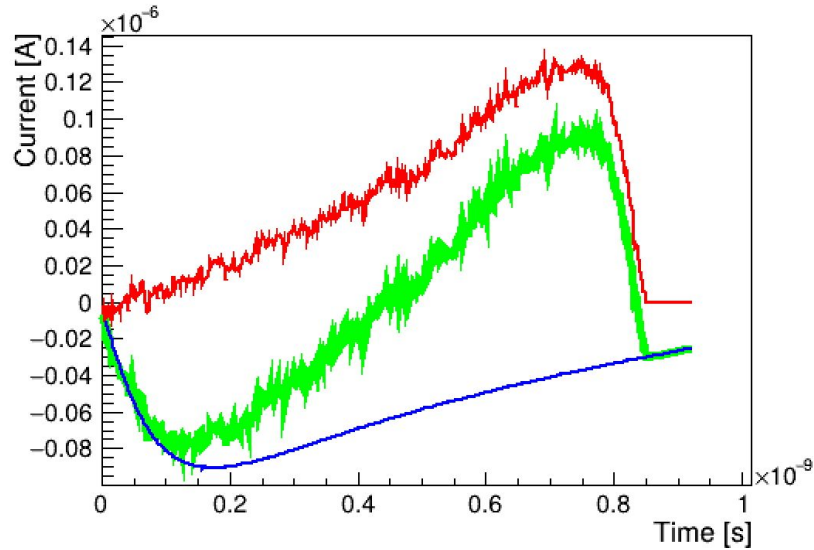


Weighting Potential

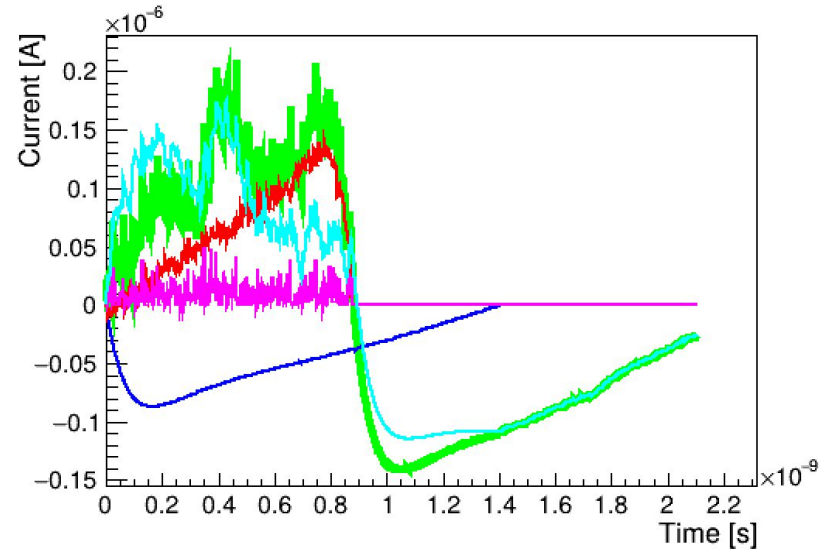


Weightfield2 diode simulation

Shockley-Ramo and crosstalk



No Gain



2x Gain

Track sign reconstruction

$$\bar{x} = \frac{\sum_i A_i x_i}{\sum_i A_i} \qquad \bar{t} = \frac{\sum_i A_i t_i}{\sum_i A_i}$$

$$C = \frac{\sum_i A_i (x_i - \bar{x}) (t_i - \bar{t})}{\sum_i A_i}$$

$$\widehat{\text{sgn } \lambda} = \text{sgn } C$$