Towards 6D Tracking: using fast-timing to determine track position, time, and angles

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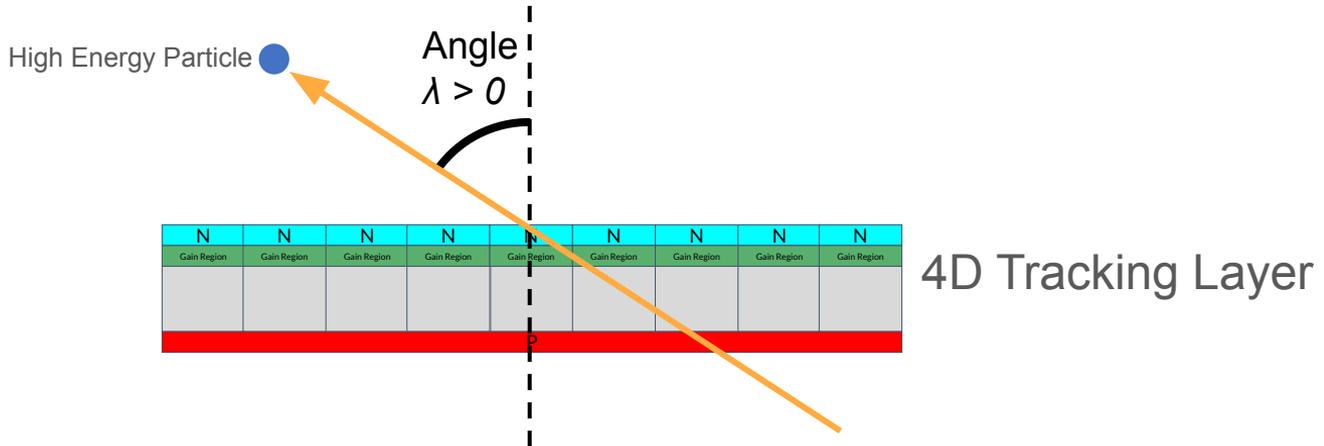
Victor Turbiner, Michael Cardiff, Abhiraj Gupta, Elena Villhauer, Julie Segal, Christopher J. Kenney, Ariel Schwartzman, Angelo Dragone
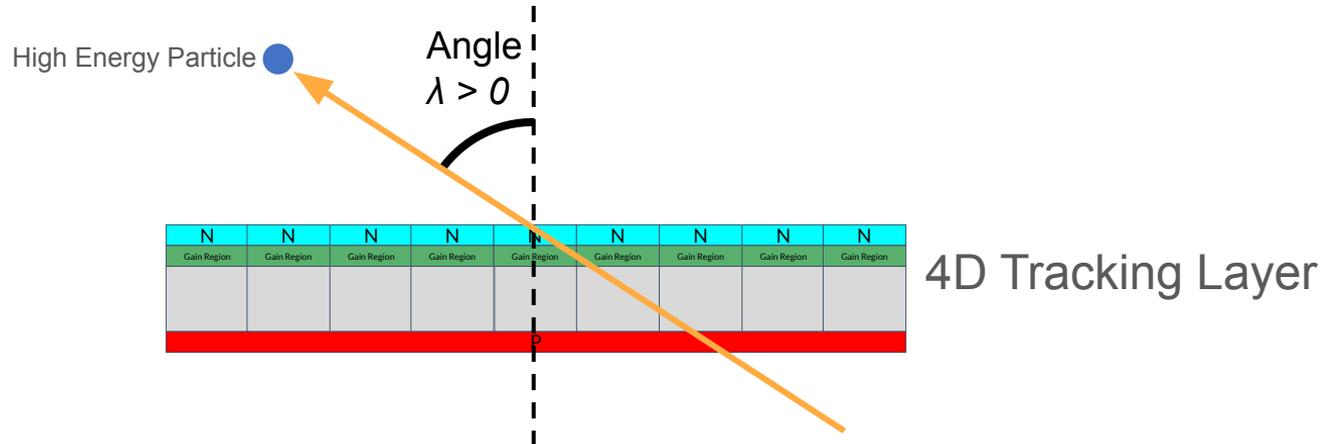
10/09/25

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University

U.S. DEPARTMENT of ENERGY

CLAIM

A single layer of a LGAD-based 4D tracker can also measure the angle of a track

HOW?

The angle of track can change the measured time by O(100ps) in detectors with O(10ps) resolution

High Energy Particle

Angle
$\lambda > 0$

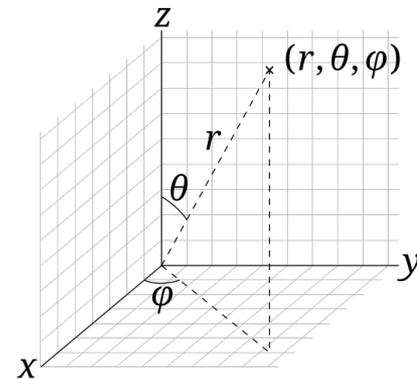4D Tracking Layer

IDEA: LGADs Can Enable 6D Tracking

POSITION
X,Y,Z

TIME
T

ANGLES
θ,ϕ

Jorge Stolfi, Public domain, via Wikimedia Commons

Courtesy of MS Copilot

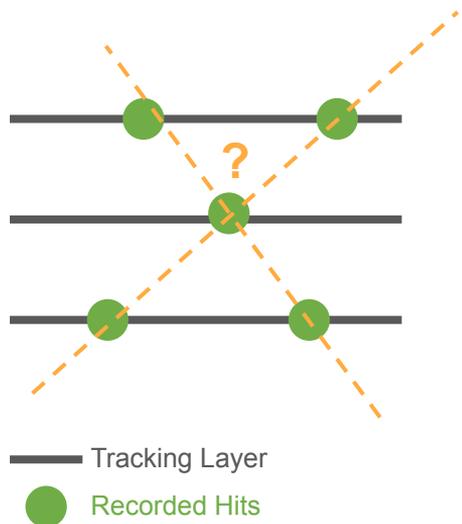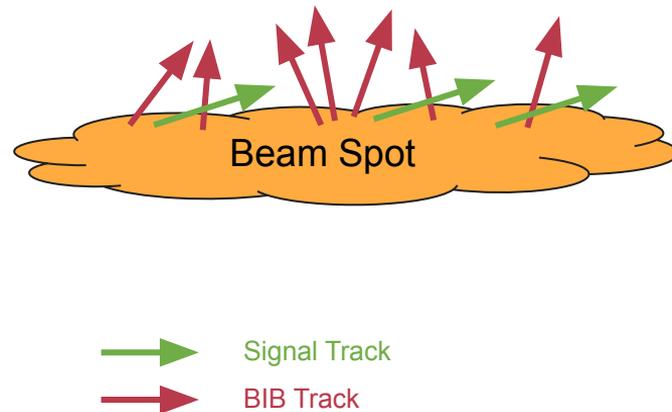Andeggs, Public domain, via Wikimedia Commons

3D

4D

6D

MOTIVATION: Measuring Angles Has Multiple Uses

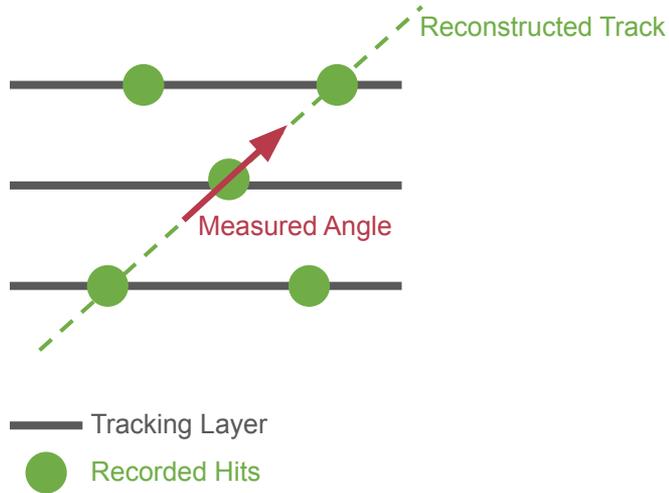Knowing the track angle and direction can simplify track-finding.

In a muon collider, the tracker layer could filter BIB from signals based on the angle of track.

Tracking Layer

Recorded Hits
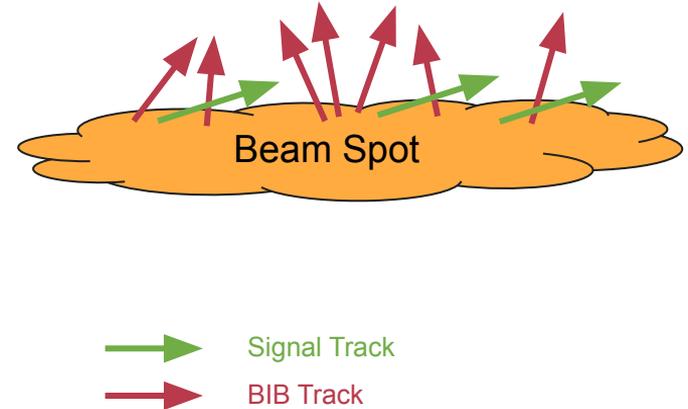
Beam Spot

Signal Track

BIB Track

MOTIVATION: Measuring Angles Has Multiple Uses

Knowing the track angle and direction can simplify track-finding.

In a muon collider, the tracker layer could filter BIB from signals based on the angle of track.

Reconstructed Track

Measured Angle

Beam Spot

—— Tracking Layer
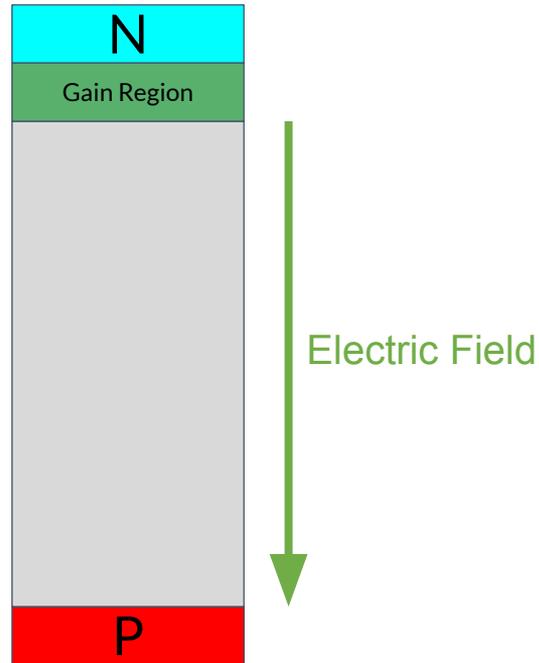
● Recorded Hits

⟶ Signal Track

⟶ BIB Track

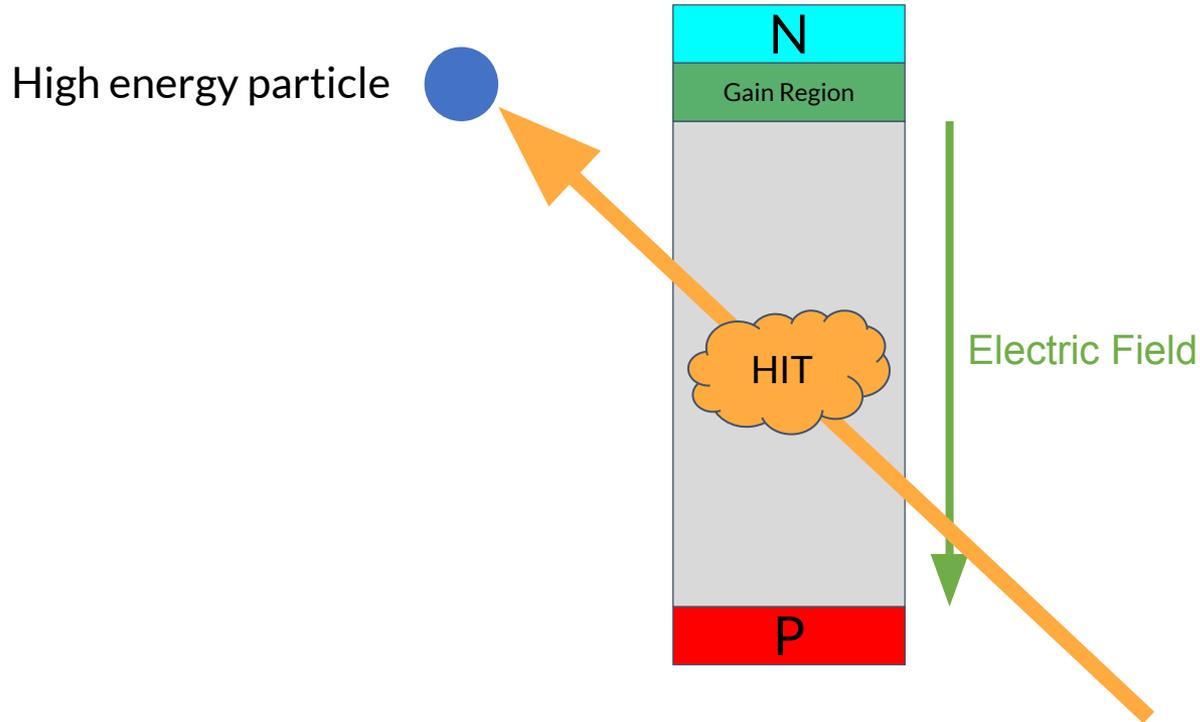# BACKGROUND

How LGADs Work

BACKGROUND: How LGADs Work

An LGAD is a Si diode detector with a built in gain region that amplifies its current.

BACKGROUND: How LGADs Work

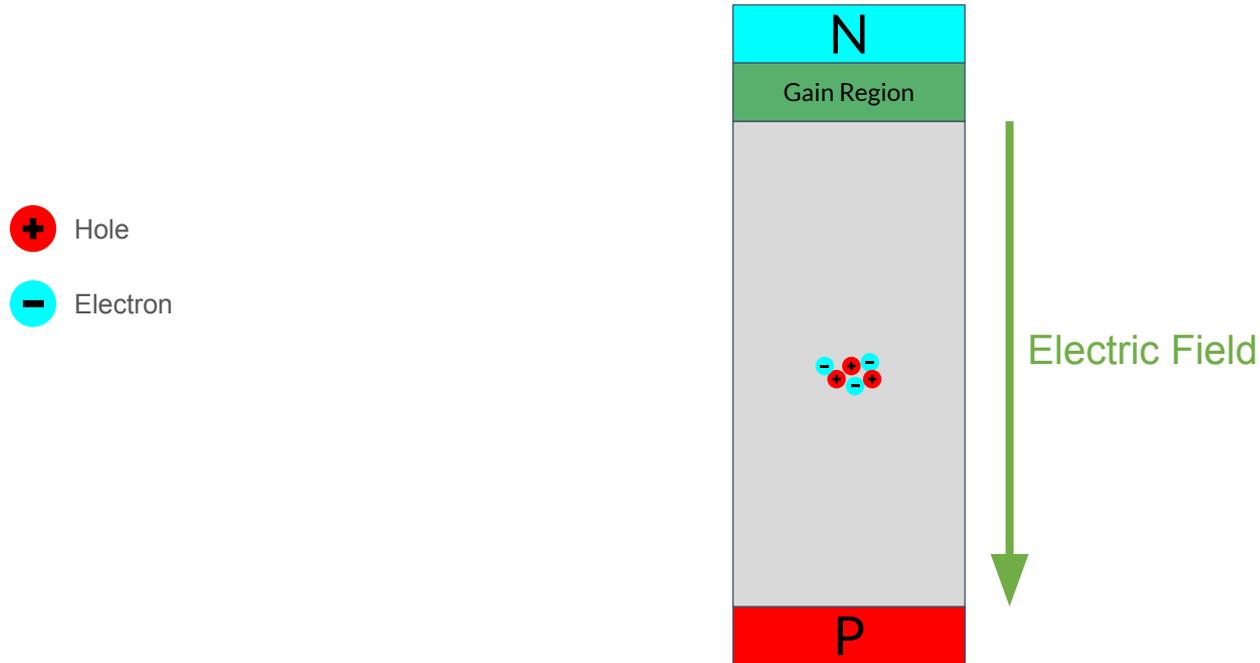An LGAD is hit by a high energy particle

High energy particle

N

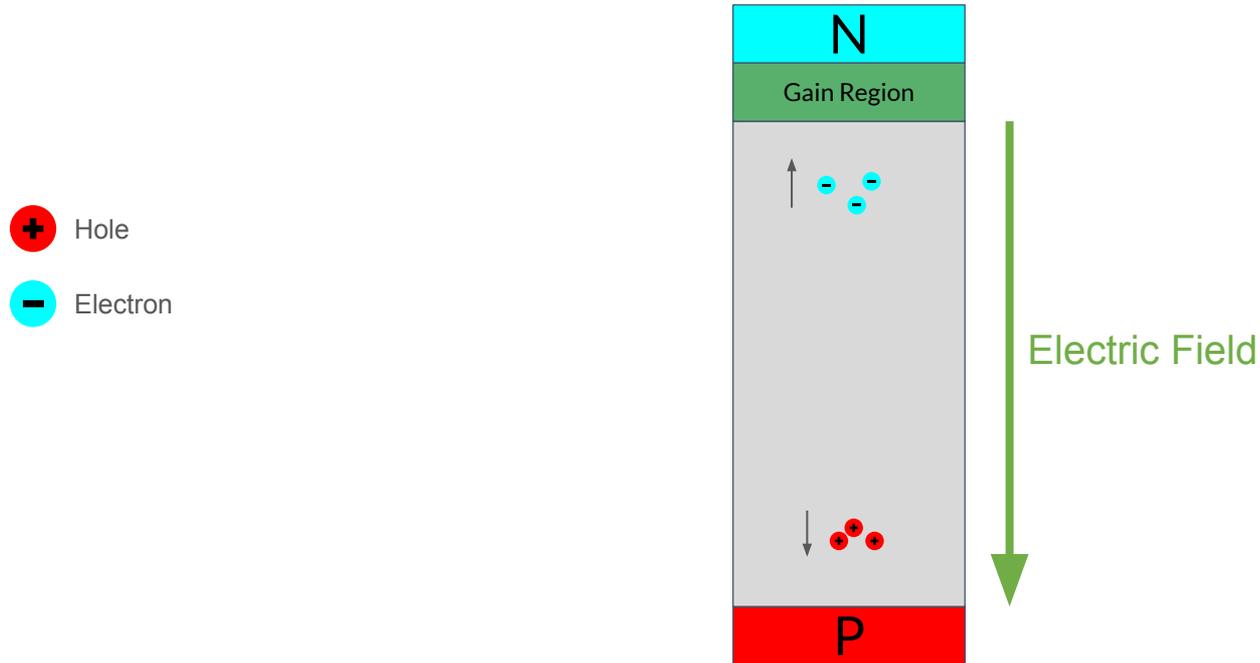Gain Region

HIT

Electric Field

P

BACKGROUND: How LGADs Work

The hit creates electron-hole pairs

BACKGROUND: How LGADs Work

The electrons and holes drift

Hole

Electron

N

Gain Region
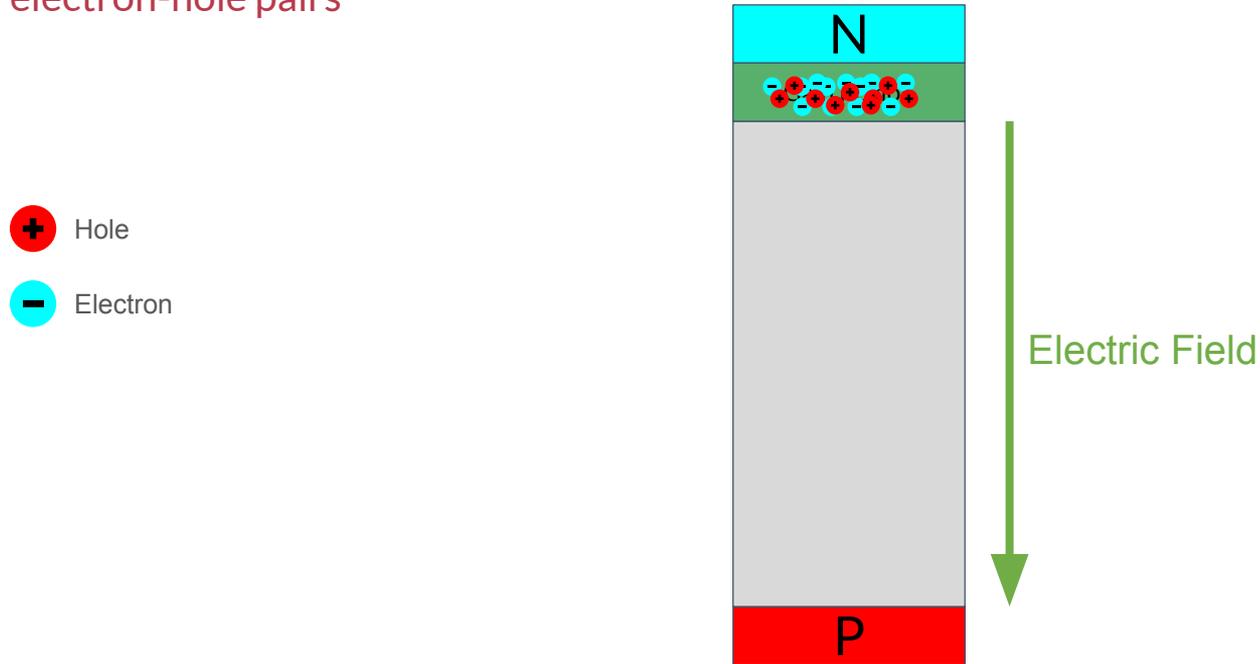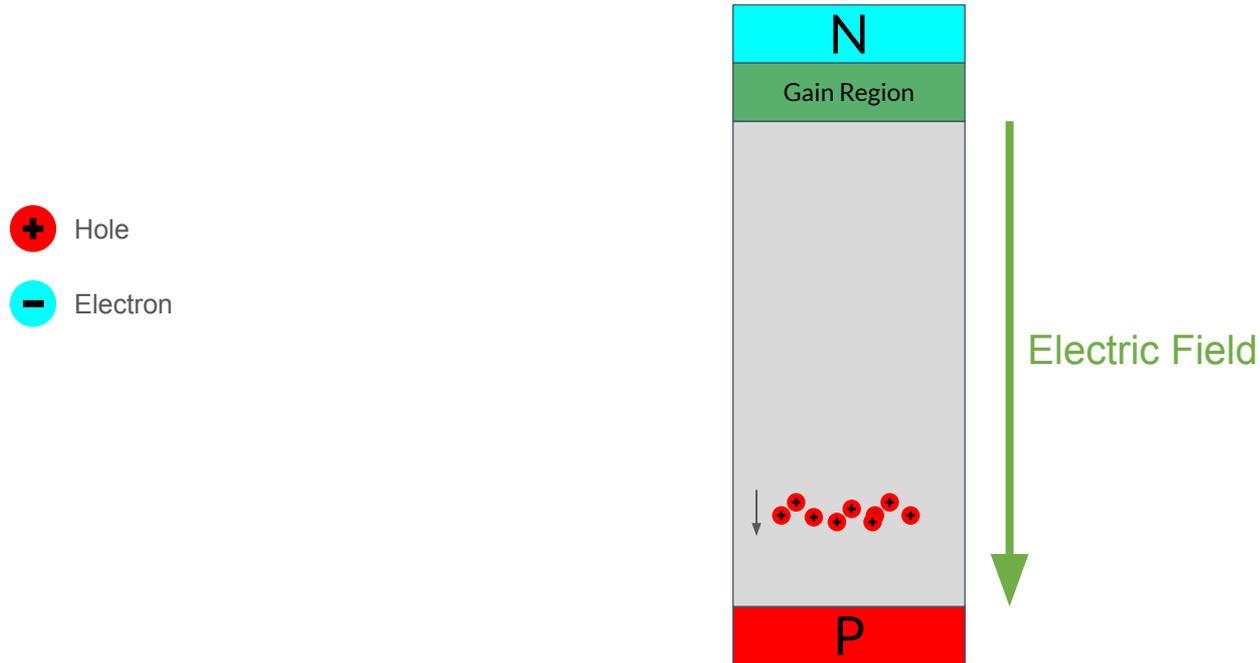
Electric Field

P

BACKGROUND: How LGADs Work

When the electrons reach the gain region, they get amplified by creating many new electron-hole pairs

BACKGROUND: How LGADs Work

The electrons get collected, the holes drift down and also get collected

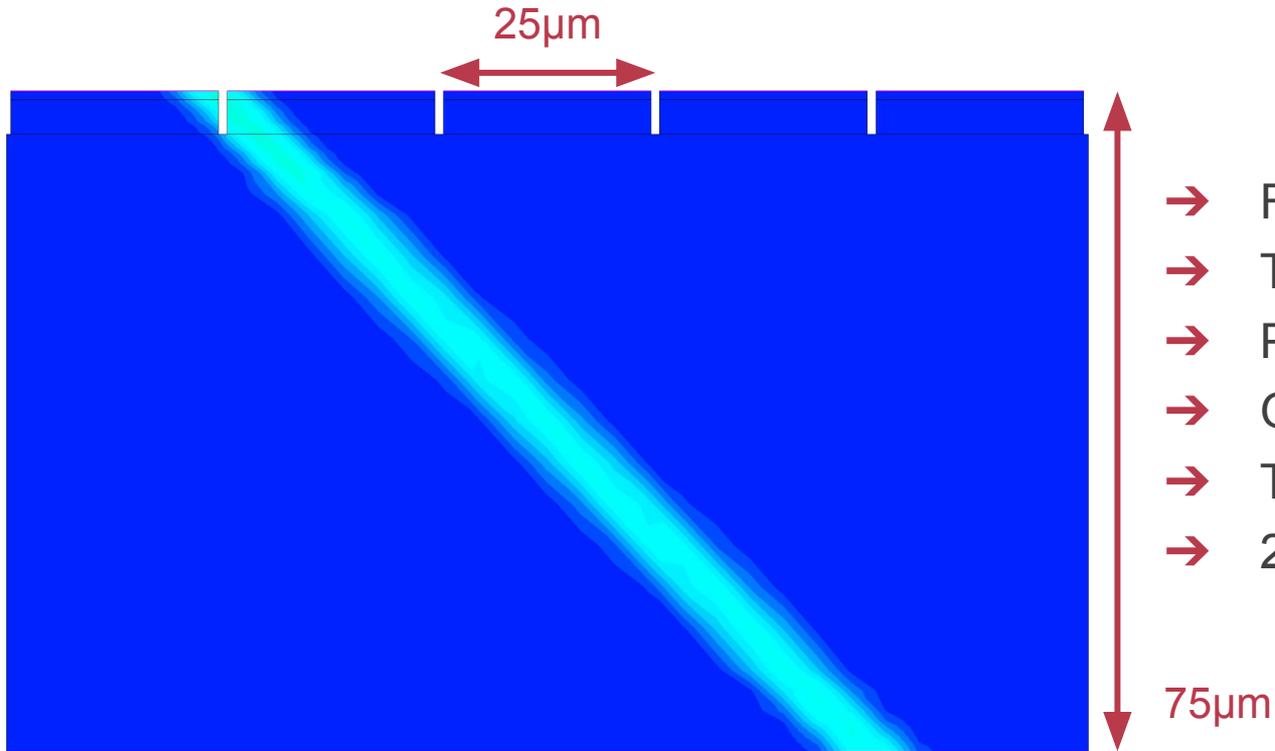# OBSERVATIONS

Qualitative overview of the link between timing and track angles.

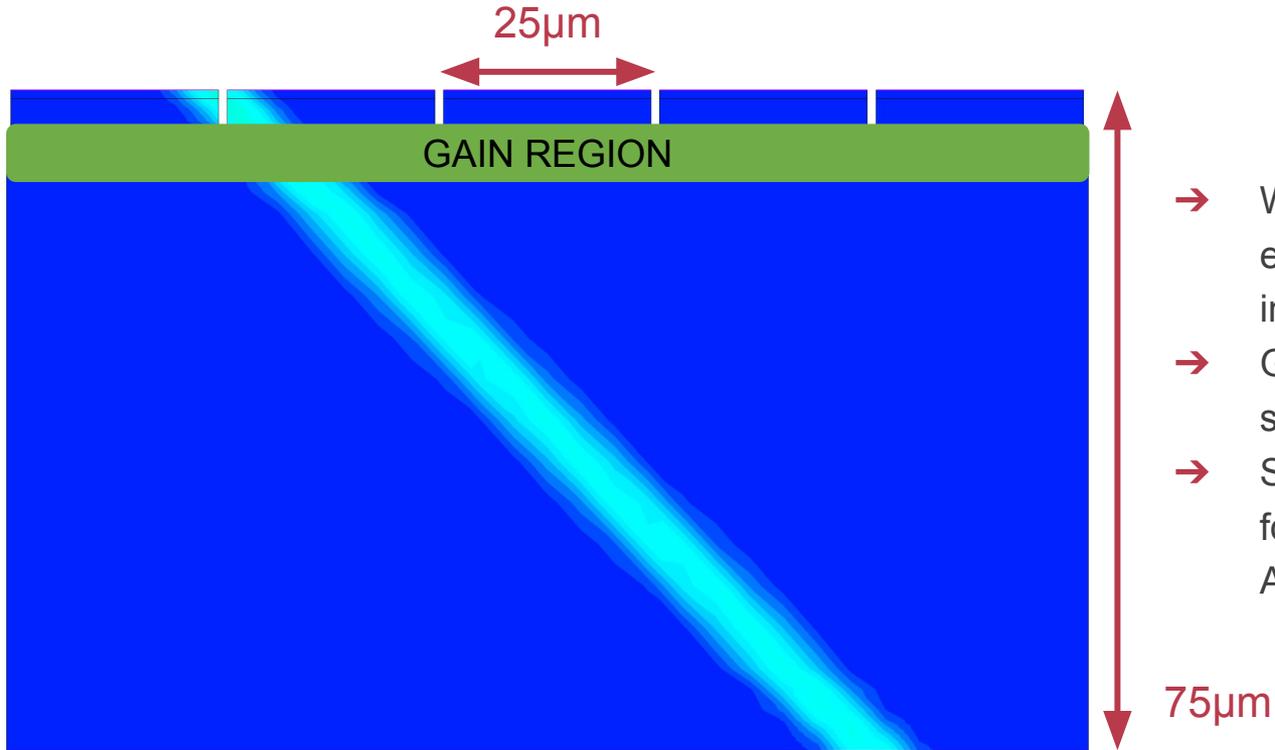# Structure Used For Analysis

25μm

75μm

→ Five Pixels

→ Thickness: 75μm

→ Pitch: 25μm

→ Gain: ~10x

→ Timing Resolution: ~20ps

→ 2D Sentaurus Simulation

Structure Used For Analysis

25μm

GAIN REGION

75μm
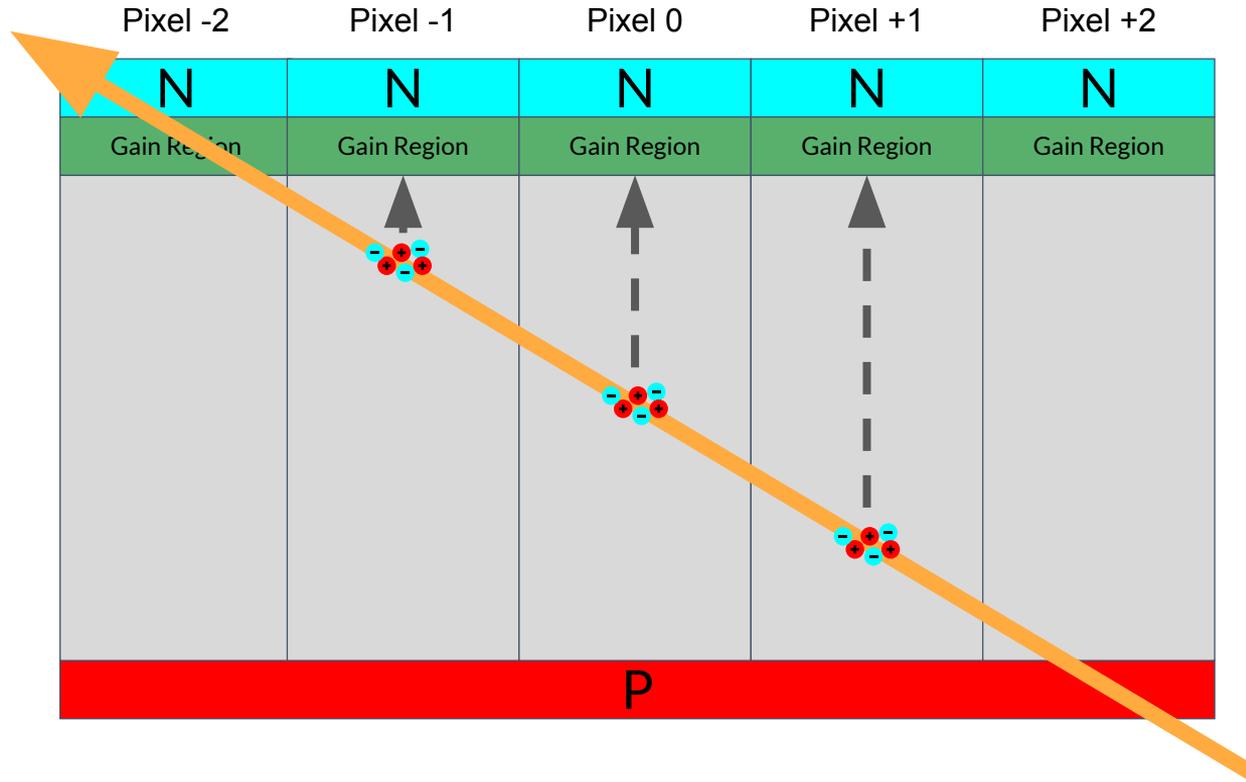
→ We use the device model for an epi-LGAD currently being investigated at SLAC.

→ Gain region is on the pixelation side.

→ Similar behaviors are expected for other types of LGADs such as AC LGADs, DJ LGADs, etc.
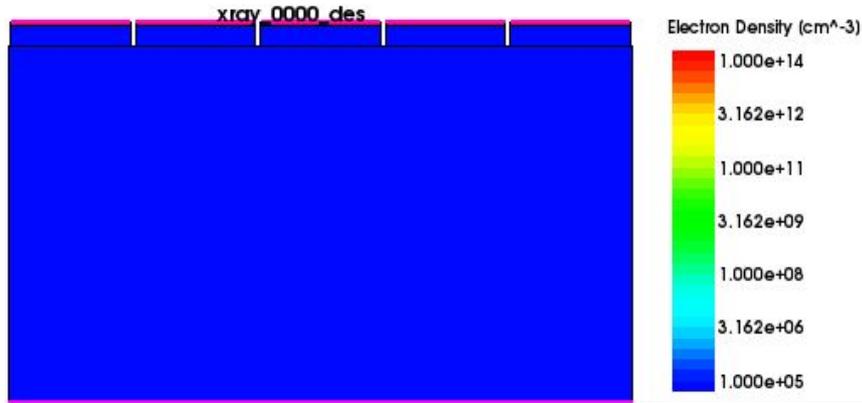
OBSERVATION: A Tilted Track Has Timing Variations

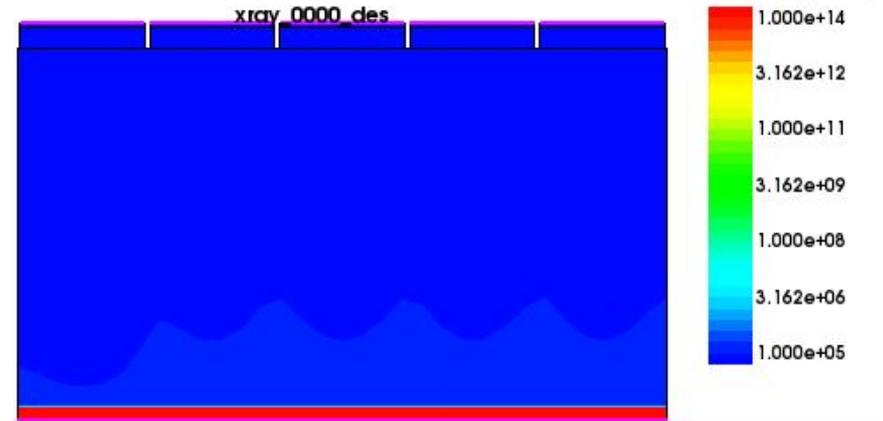The electrons in the right pixels have to travel a longer distance than the electrons in the left pixels.
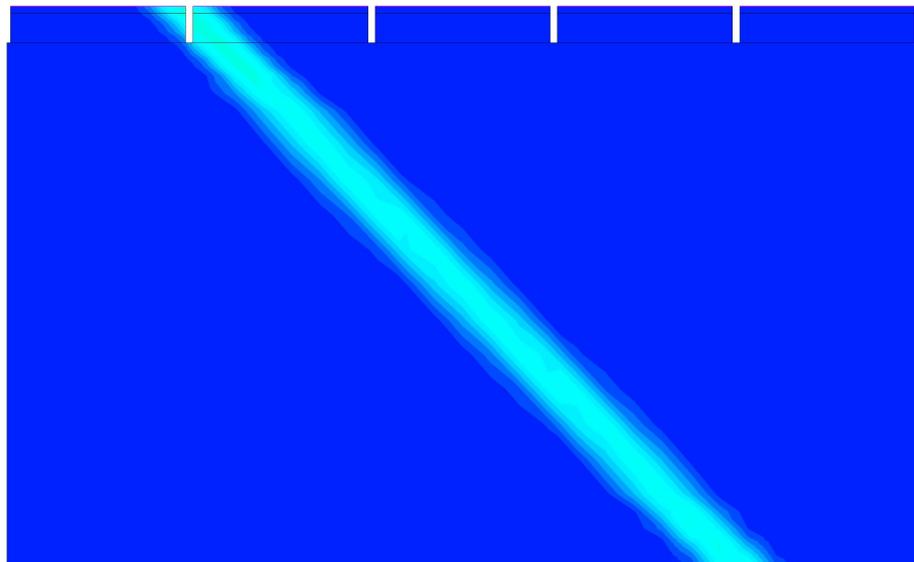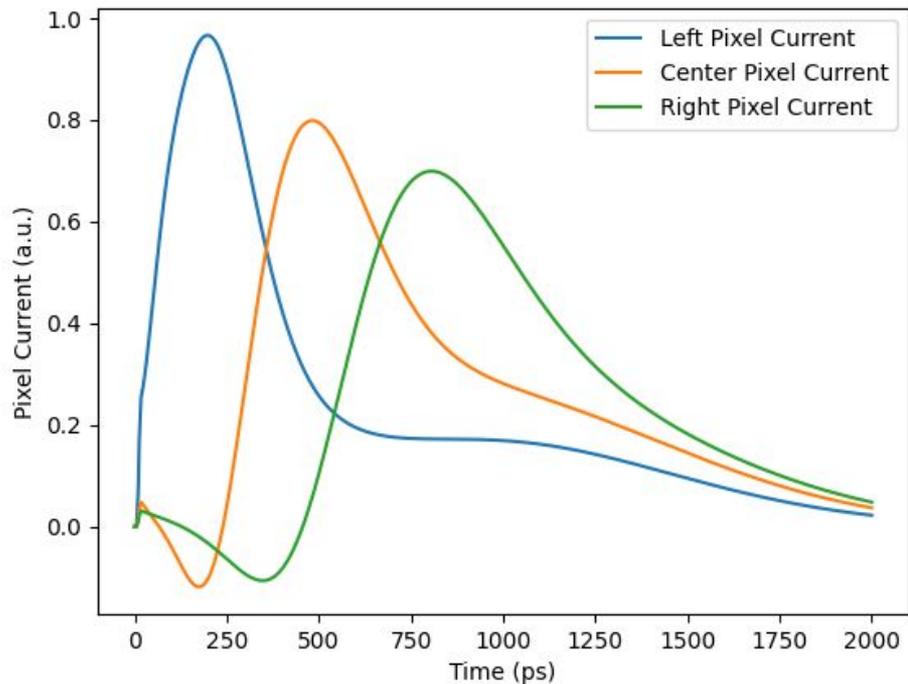
Electron and Hole Drift Animation

Electron Density

Hole Density

OBSERVATION: Track Angle Visibly Affects Timing

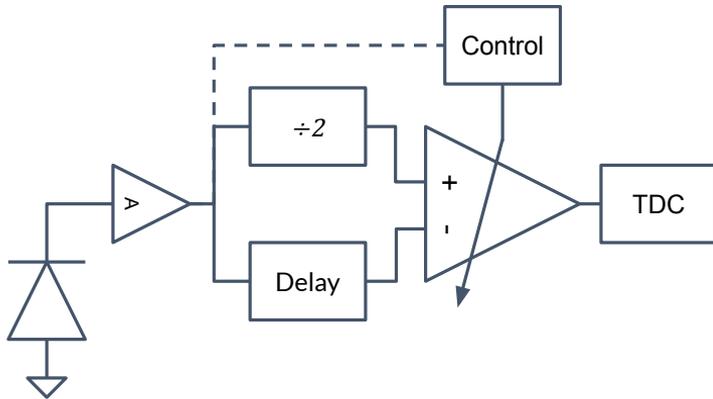A 45 degree track has a ~500 ps variation between peak times

ANALYSIS

A Geometric Model For The Relationship Between Timing And Track Angles

ELECTRONICS: Record The Time Of The Leading Edge

We use a Constant Fraction Discriminator to record the time of the leading edge without timewalk.

Note: Such circuits are under active development. For example, Fermilab produced a CFD which can achieve 10ps timing resolution, see S. Xie *et al.*, "Design and performance of the Fermilab Constant Fraction Discriminator ASIC," *Nuclear Instruments and Methods in Physics Research Section a Accelerators Spectrometers Detectors and Associated Equipment*, vol. 1056, p. 168655, Sep. 2023, doi: 10.1016/j.nima.2023.168655.

MODELING: Let's Use A Simple Model For The Current

The Geometric Model

N

Gain Region

d

Leading edge of the track

Distance between leading edge
of the track and gain region

$$t_{pixel} = t_{hit} + d/v_{drift}$$

Time recorded
by pixel

Time particle hit
the detector

Drift velocity of
the electrons

P

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RESULT: Measuring angles from timing

As an example, let's assume that 4+ pixels were hit by a track.
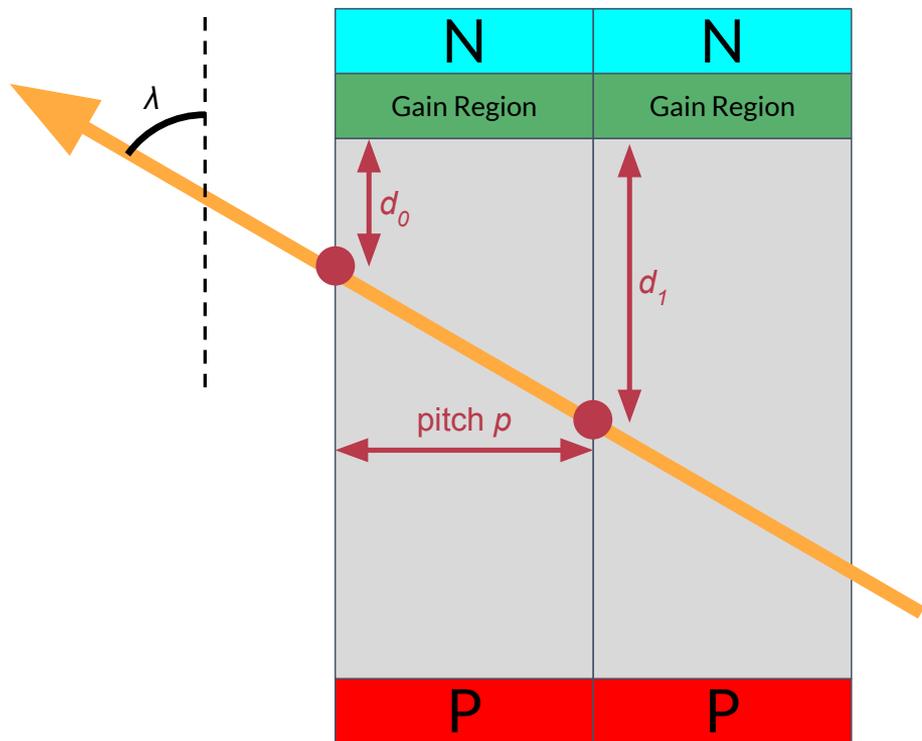

$$d_0 = (t_0 - t_{hit})\, v_{drift}$$
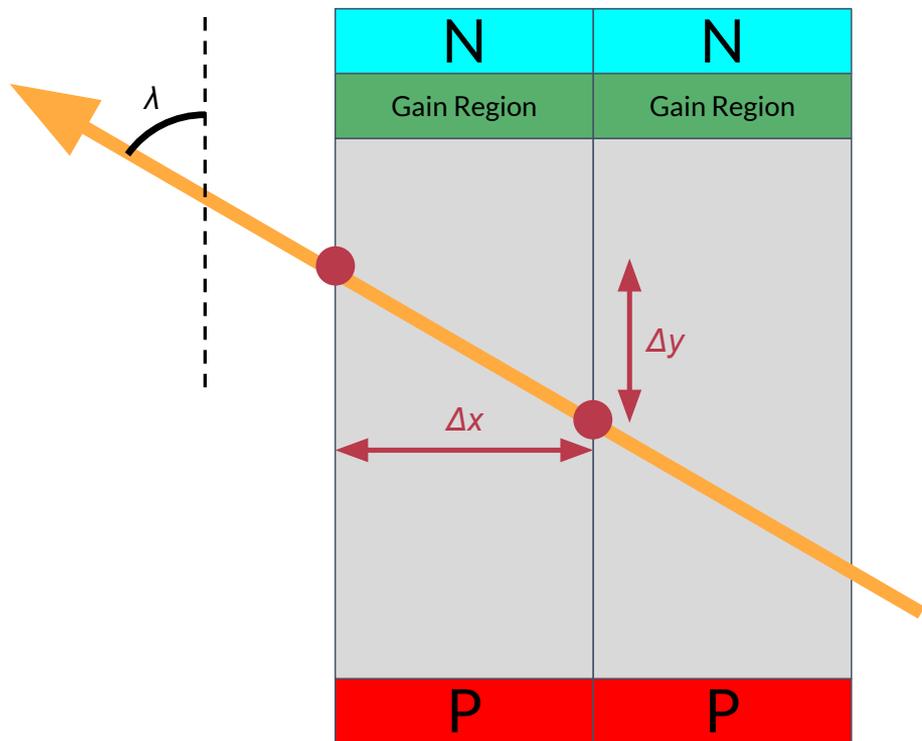
$$d_1 = (t_1 - t_{hit})\, v_{drift}$$

RESULT: Measuring angles from timing

As an example, let's assume that 4+ pixels were hit by a track.

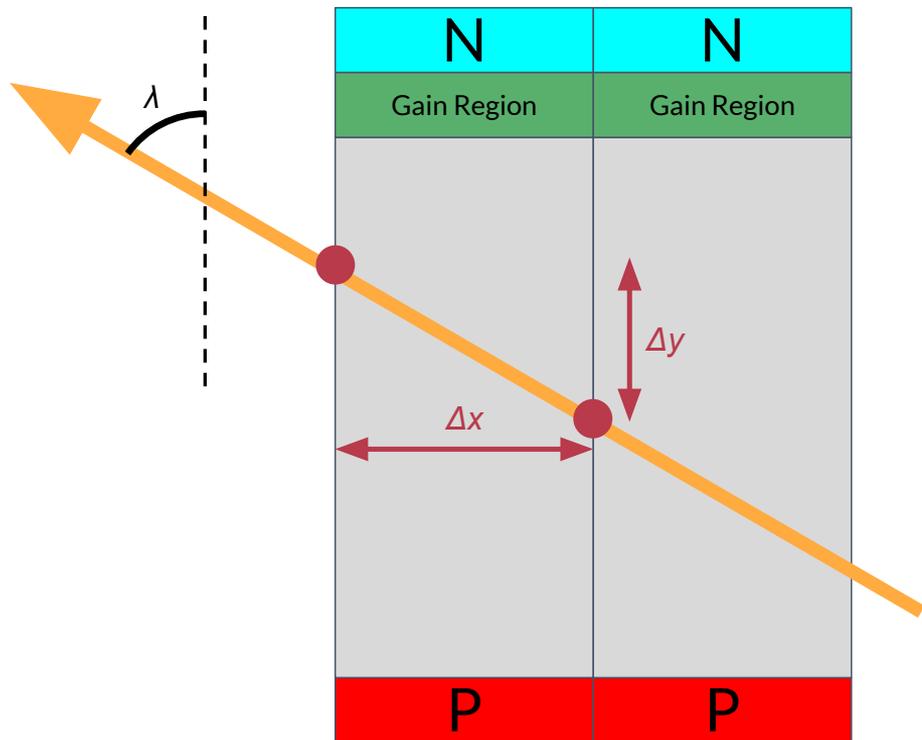

$$\Delta x = p$$

$$\Delta y = d_1 - d_0$$

$$\cot \lambda = \frac{\Delta y}{\Delta x}$$
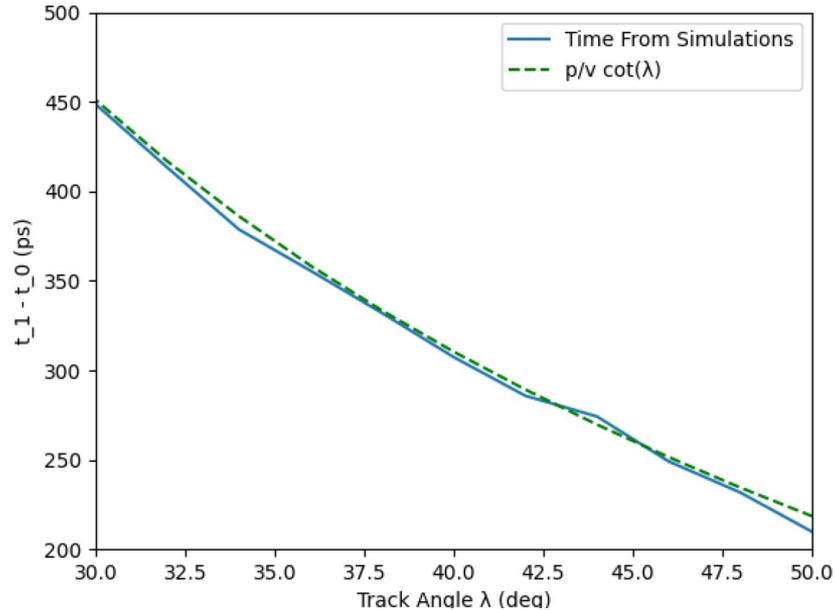
RESULT: Measuring angles from timing

As an example, let's assume that 4+ pixels were hit by a track.

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

RESULT: The Geometric Model Is Very Accurate

The below curve is obtained with $v_{drift} = 10^7$ cm/s, the saturation velocity of carriers in Si.

Angle Reconstruction Does Not Depend On The Track Offset

Two track at the same angle with different offsets will give different timing results, but the difference in times will be the same.

N   N

Gain Region   Gain Region

Δy

Δy

P   P

Same t_1 - t_0 for both tracks

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

≥3 Pixels Need To Be Hit To Determine The Angle

The two different tracks shown below have the same timing.

TIMING UNCERTAINTIES

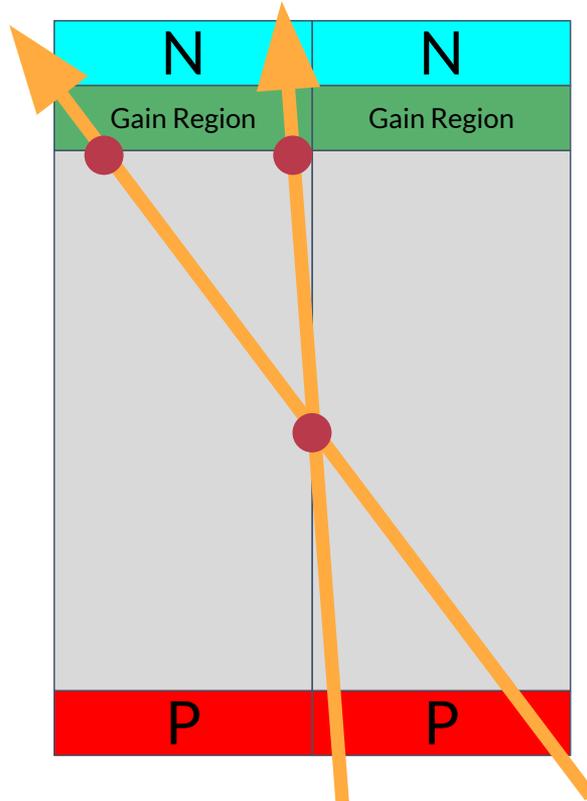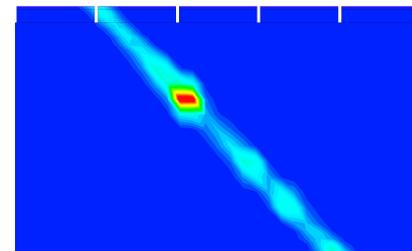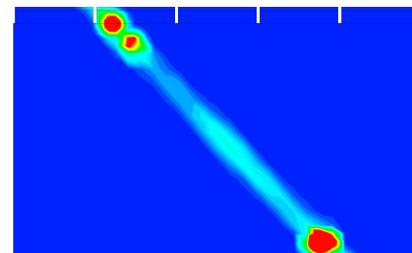Landau fluctuations and electronic noise contribute to timing uncertainty.

Landau Fluctuations

A high energy particle deposits electron-hole pairs by randomly interacting with the Si lattice.

This leads to fluctuations in the despotied charge density

HeavyIonChargeDensity (cm^-3)

0.000e+00   8.333e+11   1.667e+12   2.500e+12   3.333e+12   4.167e+12   5.000e+12

Ensemble of charge deposition patterns for the same track.

Fluctuations follow a Landau distribution fit to FIG.11 from: H. Bichsel, "Straggling in thin silicon detectors," *Reviews of Modern Physics*, vol. 60, no. 3, pp. 663–699, Jul. 1988, doi: 10.1103/revmodphys.60.663.

Landau Fluctuations Have A Long Tail

Sometimes, the high energy particle may hit an Si atom head on and create a very large amount of electron-hole pairs in a very small region.

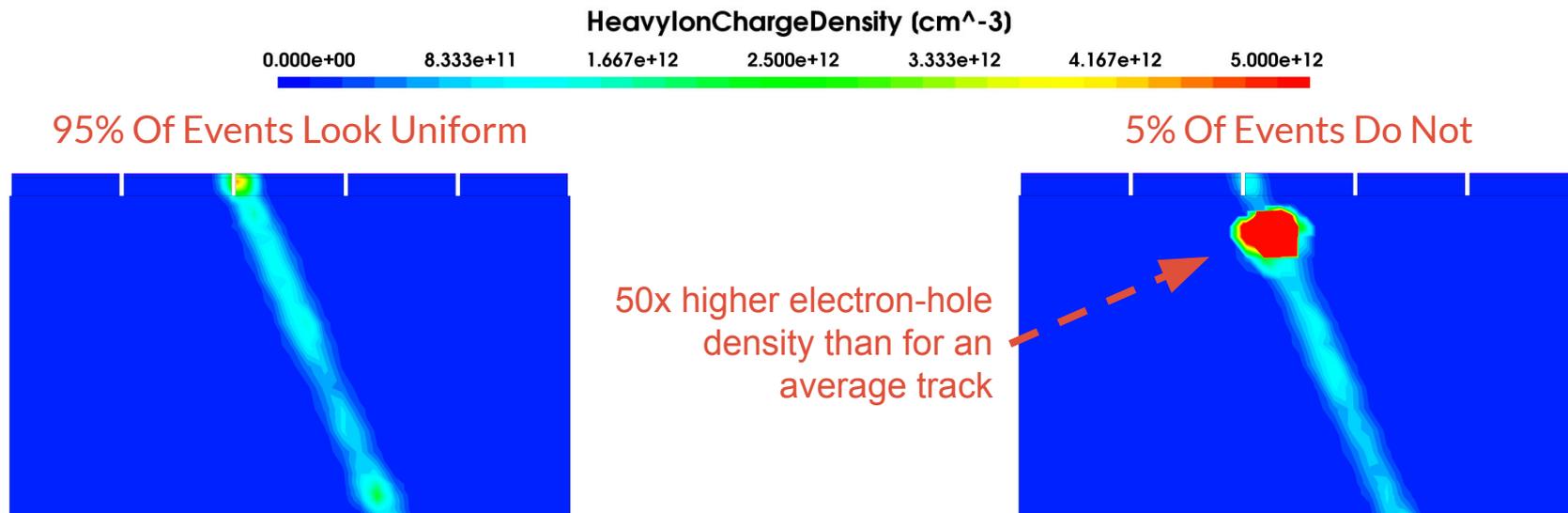**HeavyIonChargeDensity (cm^-3)**

| 0.000e+00 | 8.333e+11 | 1.667e+12 | 2.500e+12 | 3.333e+12 | 4.167e+12 | 5.000e+12 |

95% Of Events Look Uniform

5% Of Events Do Not

50x higher electron-hole density than for an average track

In tracking studies, there is a similar long-tail event known as a **delta-ray**, where the high energy particle hits a Si atom so hard that it ionizes an electron which escapes the tracker and acts like a new high energy particle which must be tracked.

Landau Fluctuations Have Long Tails

In tilted tracks, long tail events significantly affect the measured time.

"Normal" tracks with ~20ps RMS jitter

Long tail events that significantly change the shape of the track

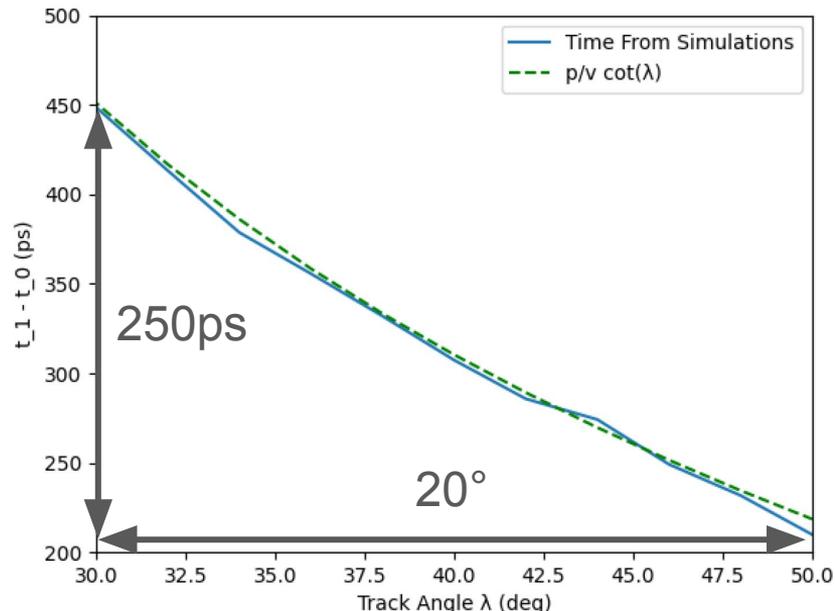# We Have Two Types Of Events

95% of events are normal
- We can measure the angle of the tracks using timing.

5% of events are long tail events
- Our analysis assuming a uniform track no longer applies.
- But, we can at least flag these events.

Estimating The Resolution

We assume a normal event, with 20ps RMS of Landau jitter and 10ps RMS of electronic noise.

$$\lambda \approx \frac{20^\circ}{250ps}(t_1 - t_0)$$

$$\sigma_\lambda \approx \frac{20^\circ}{250ps}\sqrt{2}\sqrt{(10ps)^2 + (20ps)^2}$$

Two Measurements Electronic Noise Landau Fluctuations
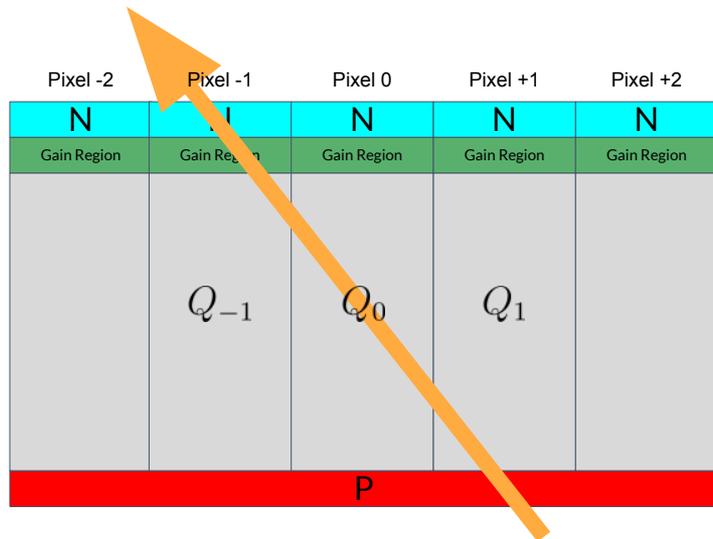
$$\sigma_\lambda \approx 2.5^\circ$$

ALGORITHM

We find the angle of a track in 4 steps

Step 1: Clustering & Long-Tail Event Finding Using Charge

We flag the 5% of events with the most deposited charge as long-tail events. This gets rid of 99.5% of long-tail events.

Pixel -2	Pixel -1	Pixel 0	Pixel +1	Pixel +2
N	N	N	N	N
Gain Region	Gain Region	Gain Region	Gain Region	Gain Region
	Q_{-1}	Q_0	Q_1	

P

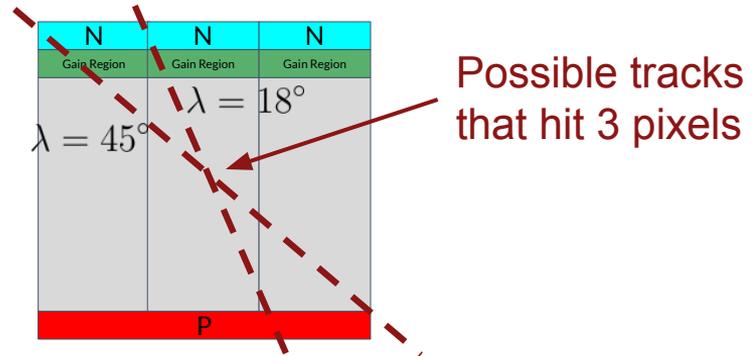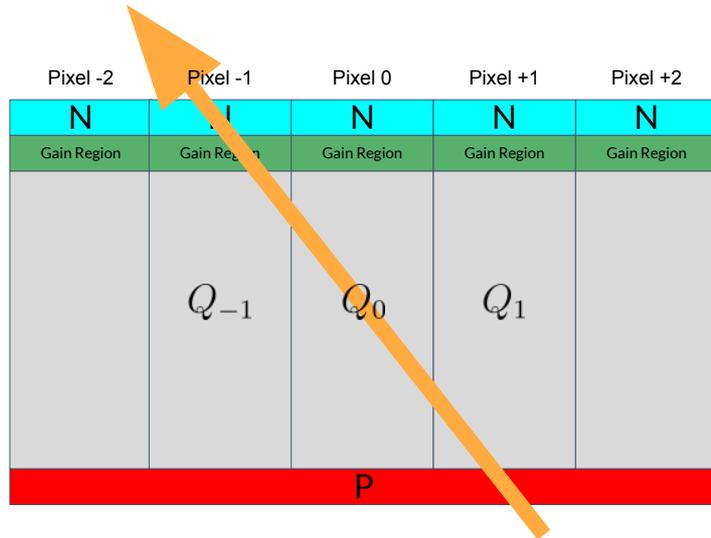A pixel is marked as hit if its deposited charge is above a threshold.

$$Q_i \geq Q_{thr}$$

Only tracks whose total charge is below a threshold are marked as normal tracks.

$$\sum_i Q_i \leq Q_{long-tail}$$

Step 2: Angle Estimation Using Pixel Counting

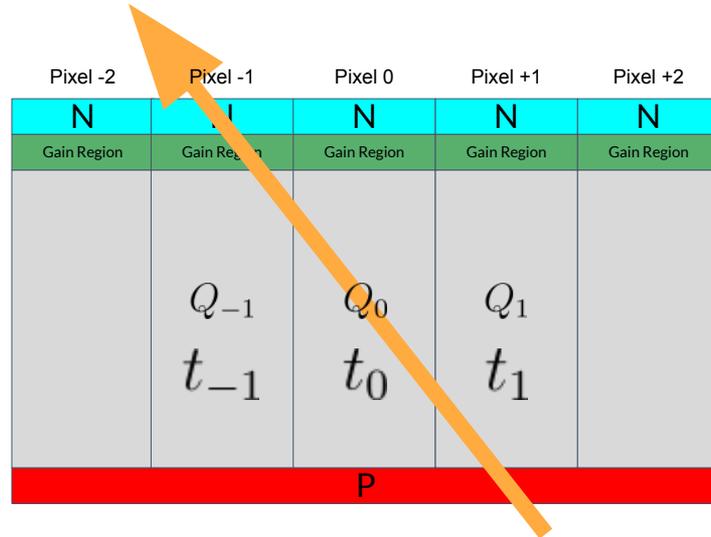We can estimate the angle of track by counting how many pixels were hit.

Pixel -2	Pixel -1	Pixel 0	Pixel +1	Pixel +2
N	N	N	N	N
Gain Region	Gain Region	Gain Region	Gain Region	Gain Region

Q_{-1} $\quad Q_0 \quad$ Q_1

P

N	N	N
Gain Region	Gain Region	Gain Region

$\lambda = 18°$

$\lambda = 45°$

P

Possible tracks that hit 3 pixels

The following set of angles could hit three pixels:

$$18° \leq \lambda \leq 45° \quad \text{OR} \quad -45° \leq \lambda \leq -18°$$

Step 3: Finding The Sign Of The Angle

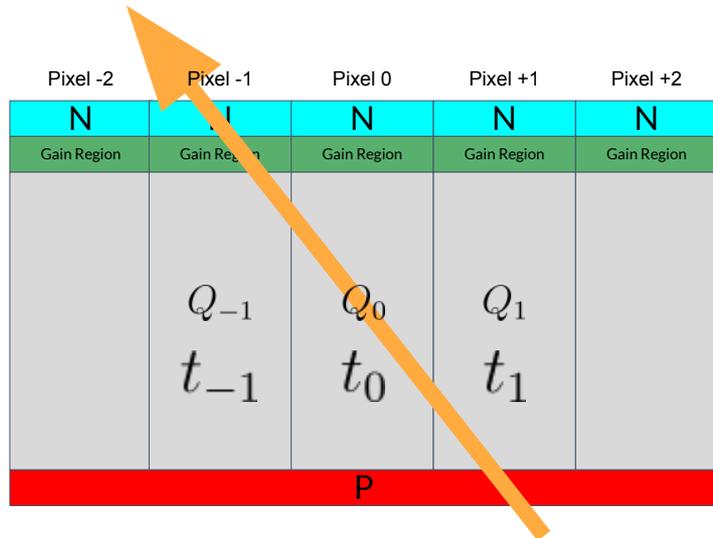Look at whether the timing increases or decreases with position.

$$t_{-1} \leq t_0 \leq t_1 \implies \lambda \geq 0$$

Thus, the angle must be in the interval:

$$18° \leq \lambda \leq 45°$$

Step 4: Linear Fit For cot(λ)

Our geometric model states that the cotangent of the angle should be a linear functions of the recorded times.

Pixel -2	Pixel -1	Pixel 0	Pixel +1	Pixel +2
N	N	N	N	N
Gain Region	Gain Region	Gain Region	Gain Region	Gain Region

Q_{-1} Q_0 Q_1

t_{-1} t_0 t_1

P

$$\cot \lambda = b + \sum_i c_i t_i$$

We find the coefficients by running a linear regression on the simulator data while enforcing time-translation invariance (adding the same constant to all t_i should always yield the same angle):
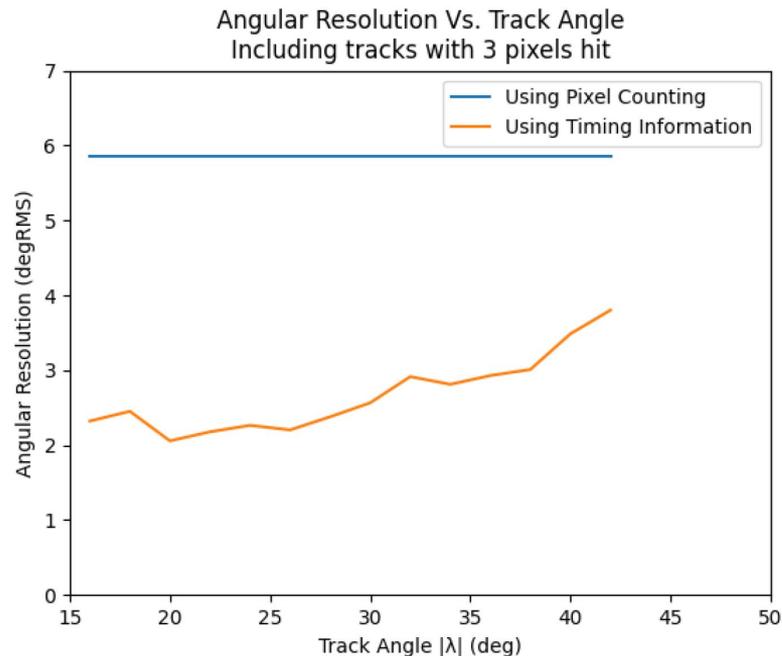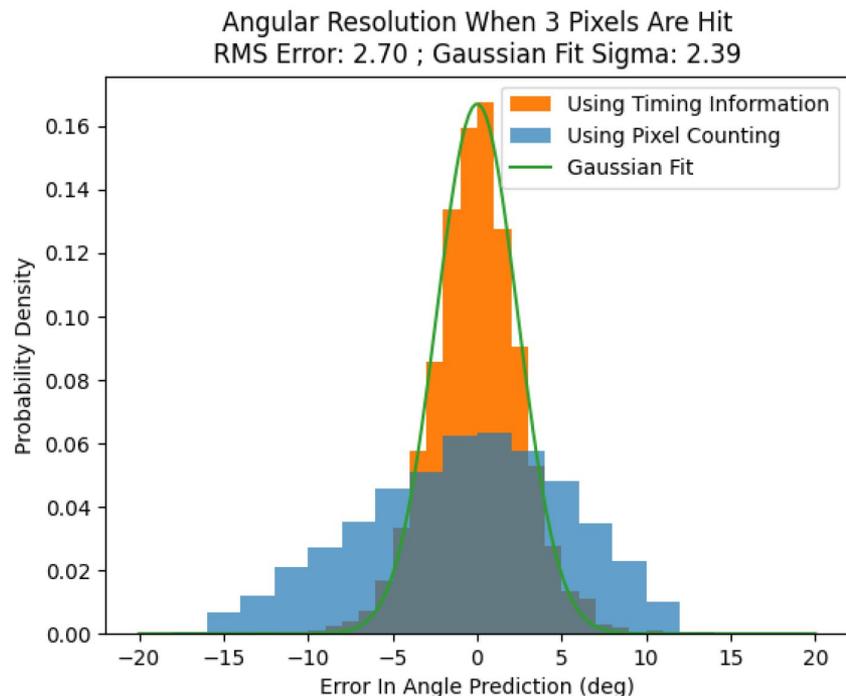
$$\sum_i c_i = 0$$
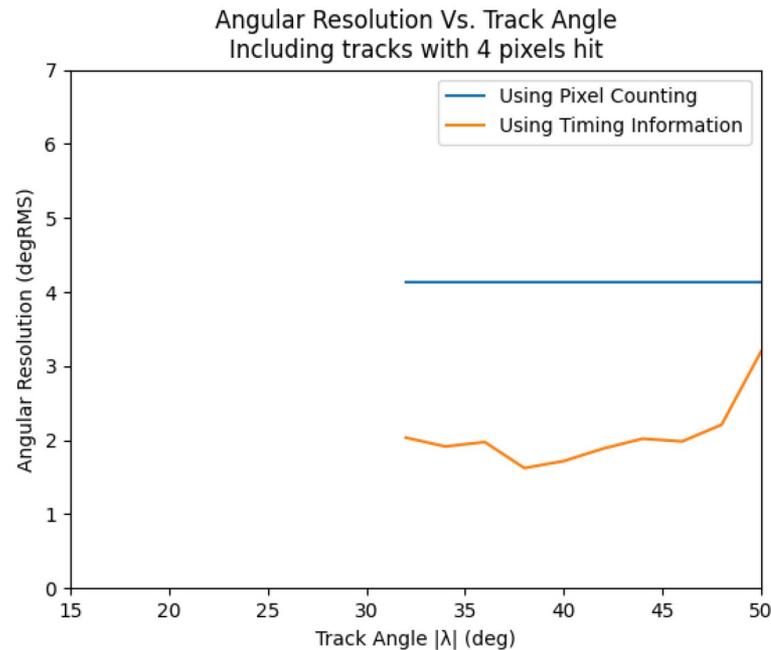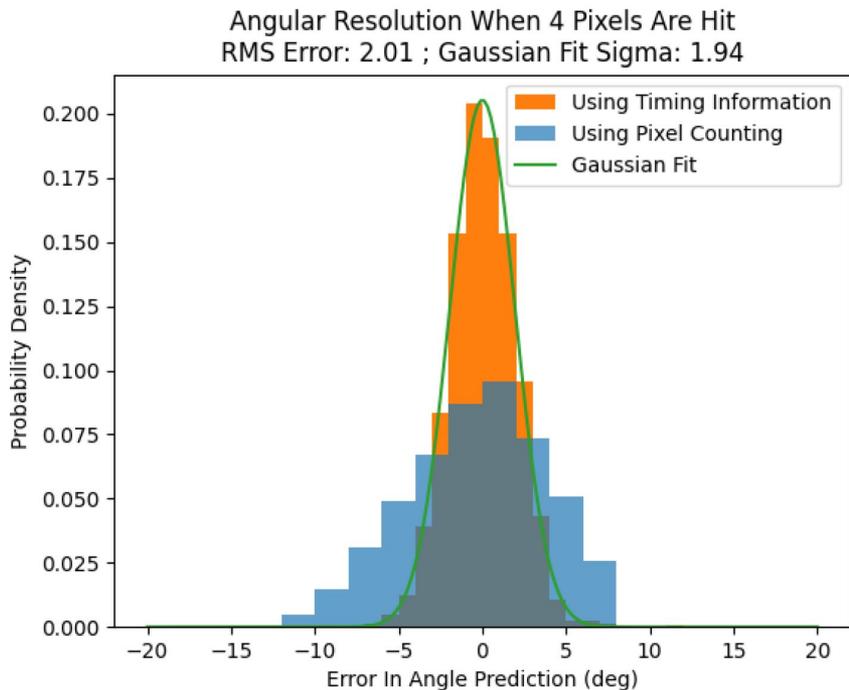
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RESULTS

Does it work?

Three Pixels Hit

Compared to counting pixels, we can get over twice the angular resolution using timing information.
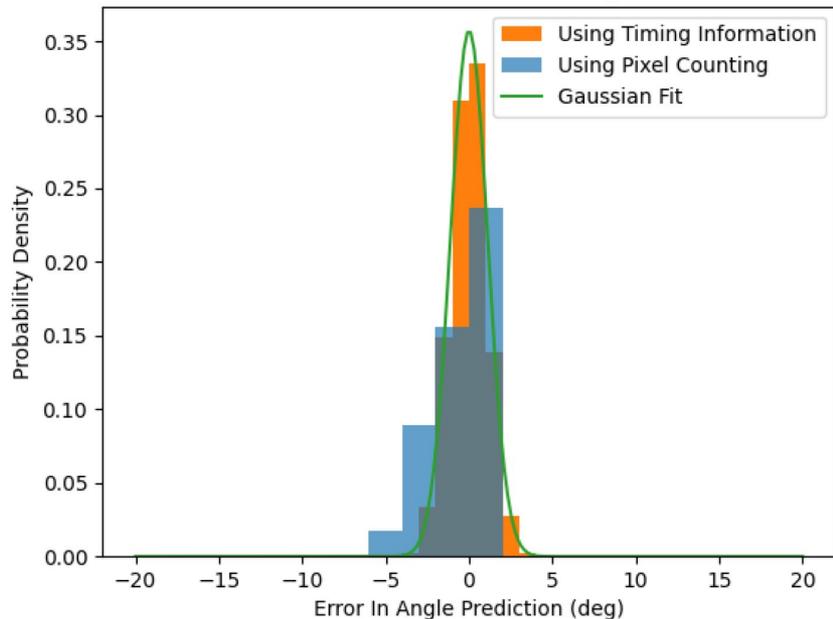
Four Pixels Hit

Compared to counting pixels, we can get twice the angular resolution using timing information.
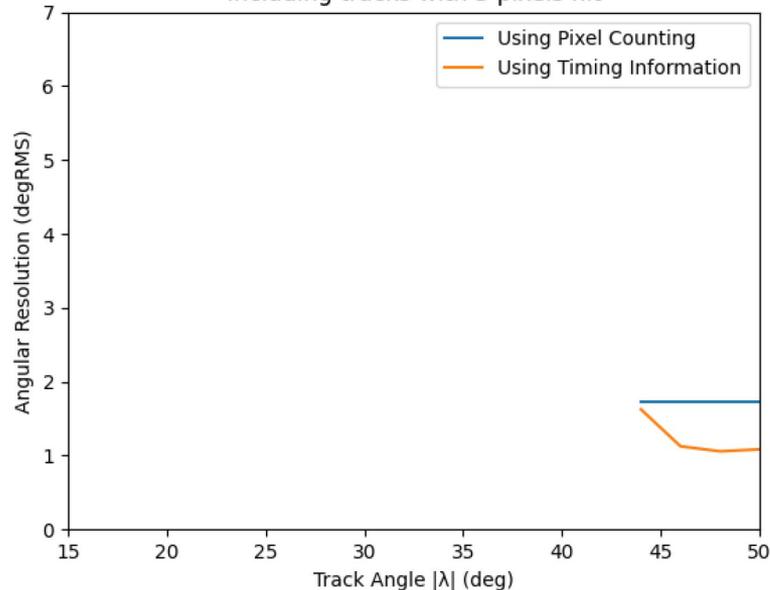
Five Pixels Hit

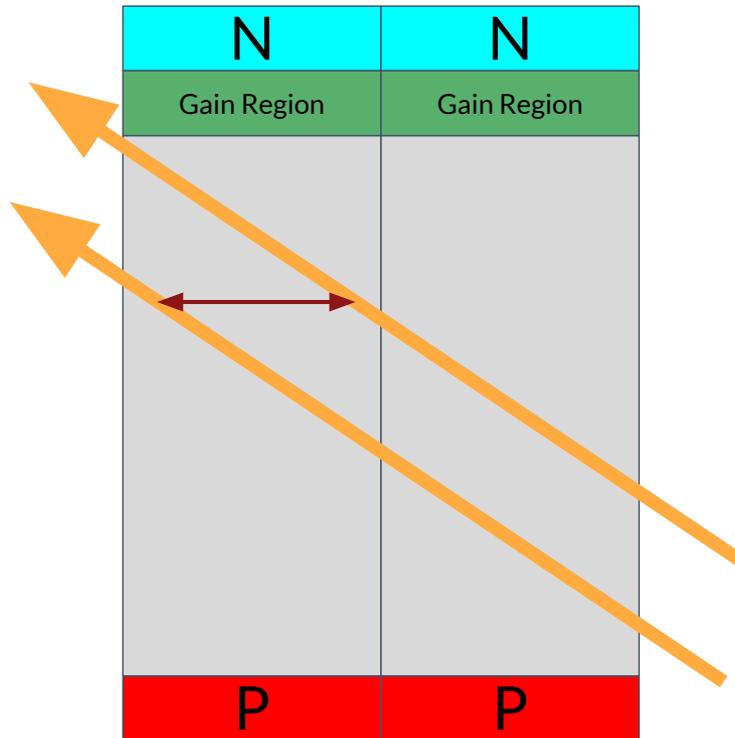Compared to counting pixels, we can get twice the angular resolution using timing information.
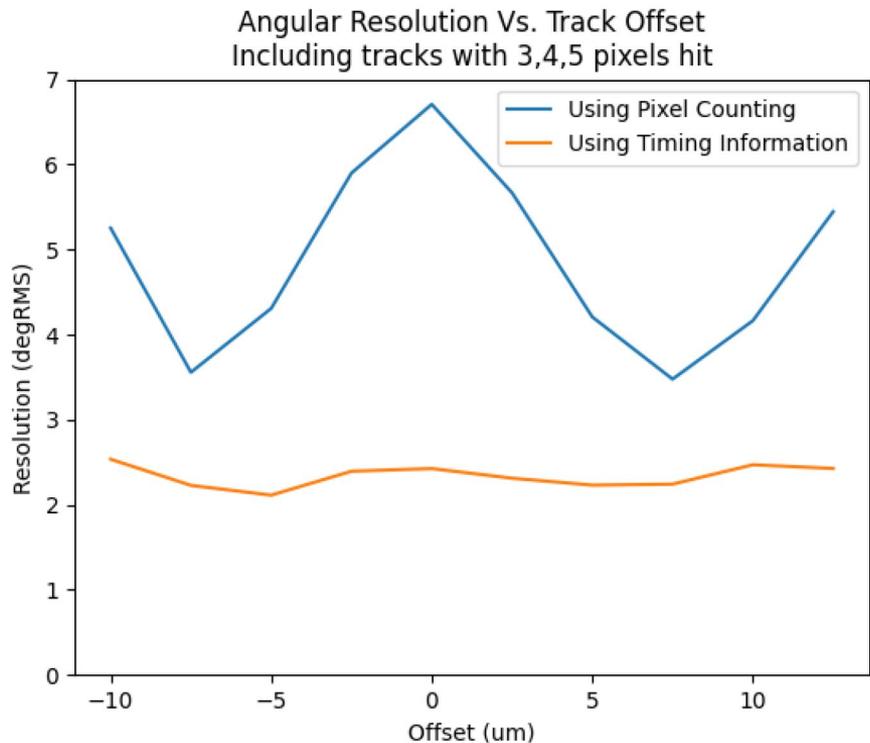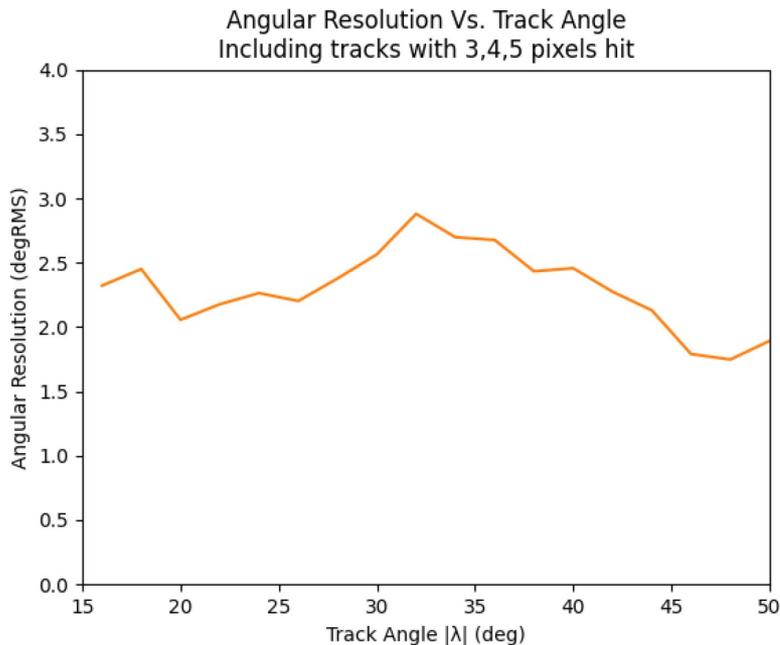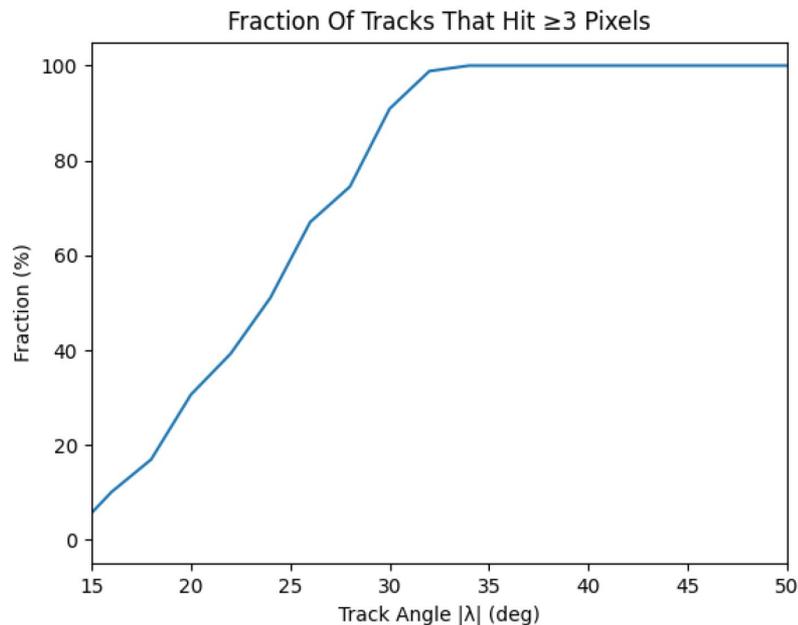
Track Offset Does Not Affect Angular Resolution

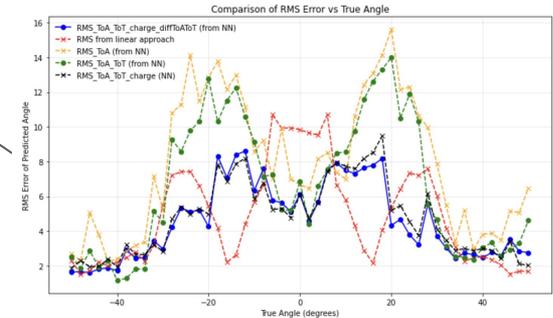# If ≥3 Pixels Are Hit, We Can Measure The Track Angle

Changing the ratio of pixel pitch to width can change the probability of hitting three pixels.
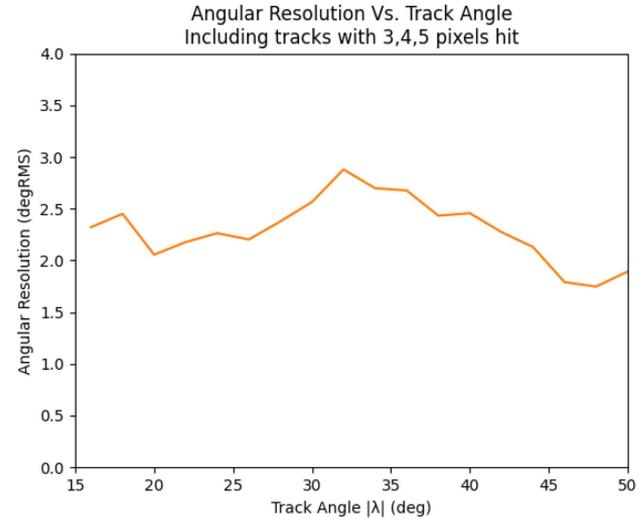
There Is Still Room To Improve

- Improving the angle-reconstruction algorithm.
  - Can we measure track angles if only two pixels are hit?
  - Could combining timing with charge information increase the angular resolution?
  - Could a neural network give better resolution than a linear regression?
- What are the physics implications of 6D tracking?
  - How should clustering and tracking algorithms account for track angles?
  - What new tracking algorithms could be enabled using 6D trackers?

Very preliminary studies show that the answer could be yes to some of these questions!

Comparison of RMS Error vs True Angle

Summary

1. The angle of a track can significantly affect the times read out by a 4D tracker. This lets us measure angles with ~2.5° of resolution if ≥3 pixels are hit.
2. When thinking of a track, it is dangerous to think that the electron-hole pairs are distributed uniformly with small fluctuations. For 5% of cases, these fluctuations significantly change the shape of the track.

Angular Resolution Vs. Track Angle
Including tracks with 3,4,5 pixels hit

Acknowledgement