Simulation and Measurement of the Shockley–Ramo Current from a Pixelated Silicon Detector

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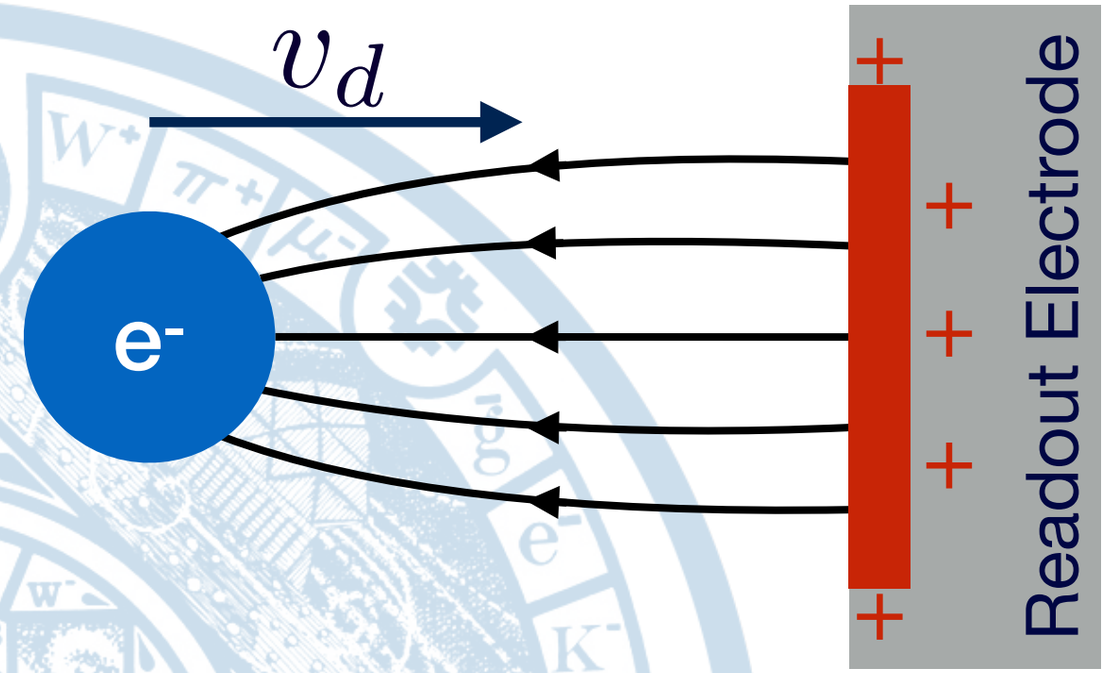
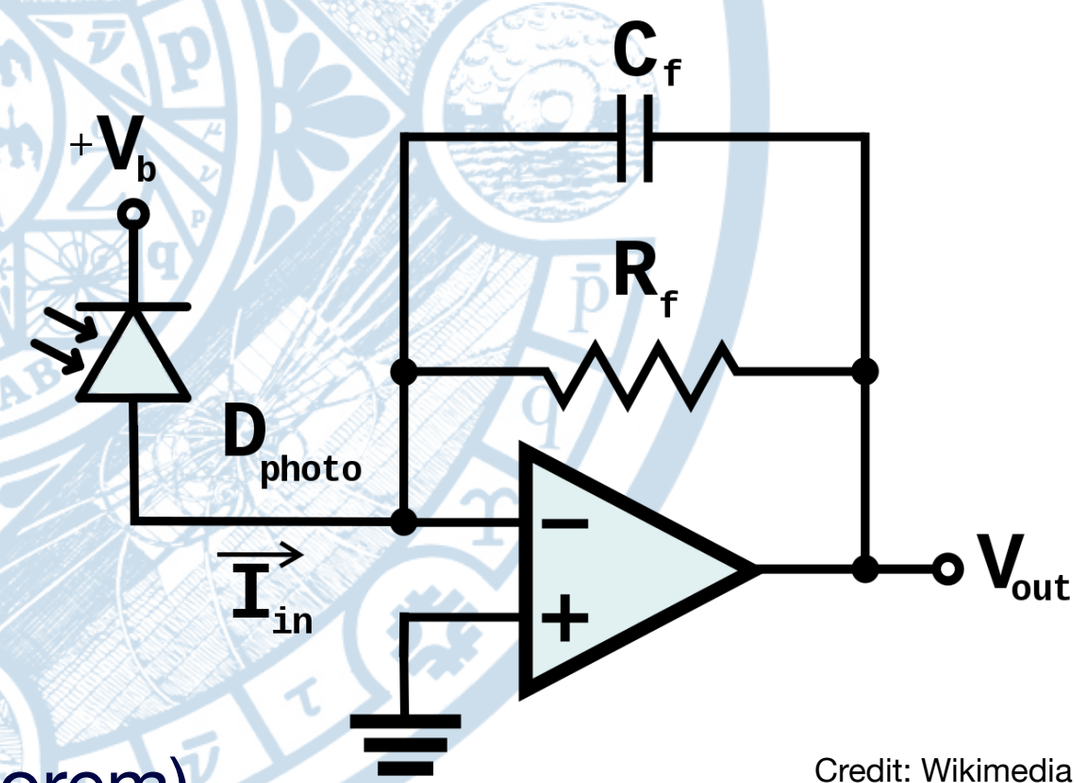
Shockley–Ramo Current

- Shockley–Ramo current or the induced current at a readout electrode from the instantaneous change of electrostatic flux lines
  - $Q = \oint_S \epsilon E \cdot dS$
  - Signal is distinct from the drift current measured in traditional silicon detectors
- Bipolar signal that will integrate to zero in a few nanoseconds
- Current from a moving point charge can be expressed as
- $i = E_v q v$ (Shockley-Ramo Theorem)





Credit: Wikimedia

Advantages of Shockley-Ramo Current

- There a several advantages of measuring the induced current
  - Very fast rise time
    - Signal begins as soon as the electrostatic flux changes at the readout electrode
    - No need to wait for the drift charge
  - Complex shape information
    - The shape of the induced current depends on the depth and position of the charge deposit
    - Angle of incidence information for charged particles

Challenges of Shockley–Ramo Current

- Small signal
  - Initial signal ~10% the size of the drift current's maximum amplitude
    - Requires a low threshold comparator
- Low Time Jitter

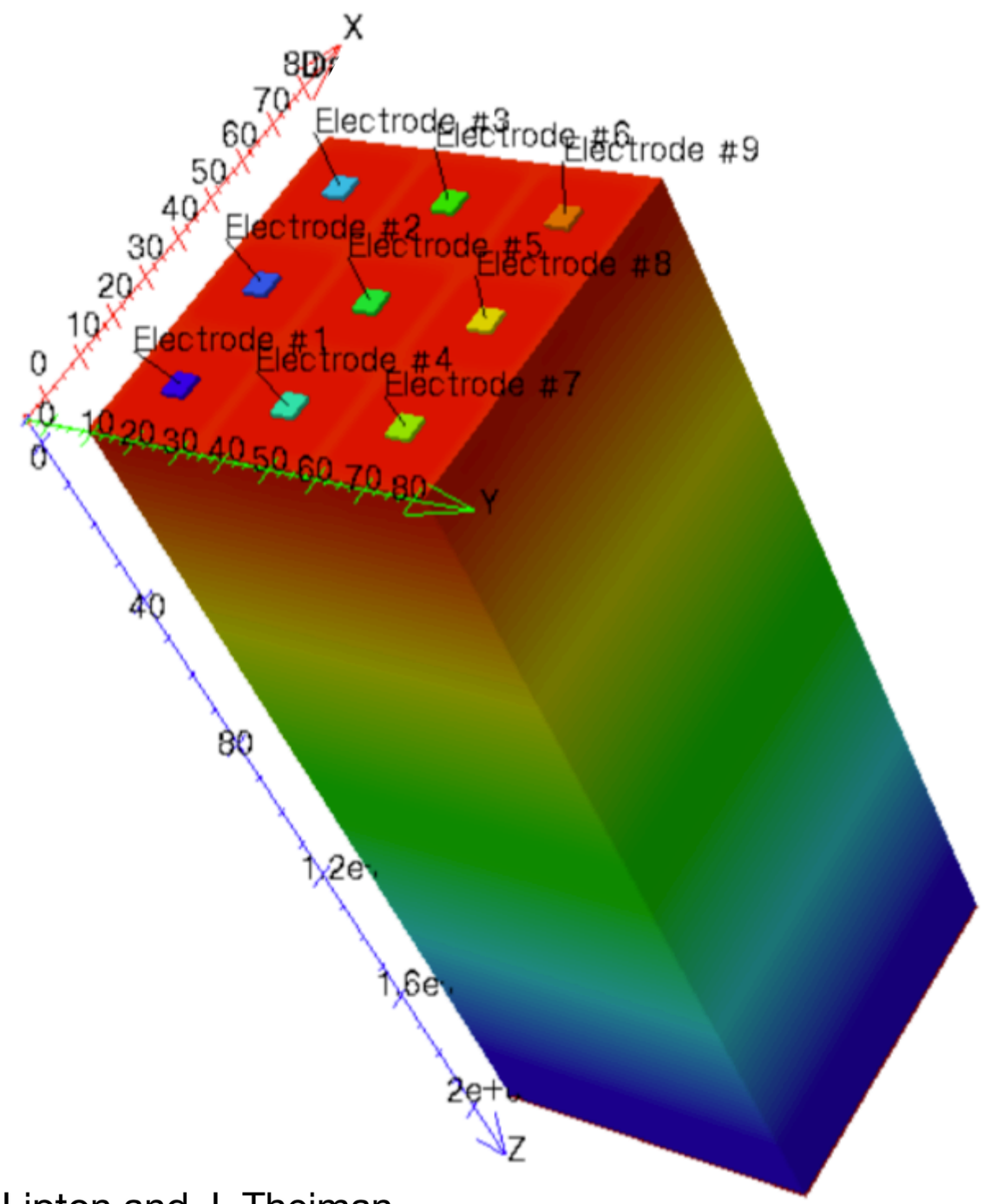
$$\sigma_t \approx \frac{C_L}{\sqrt{g_m t_a}} \frac{\sqrt{t_a^2 + t_d^2}}{signal} \qquad g_m = \frac{\Delta I_a}{\Delta V_i}$$

  - Requires a readout system with low capacitance and high front-end transconductance
    - Balance input current with pixel density and power/cooling limitations
- More details can be found in:
  R. Lipton and J. Theiman. "Fast timing with induced current detectors". In: Nucl. Instrum. Meth. A 945 (2019), p. 162423. doi: 10.1016/j.nima.2019.162423.

Sensor Parameters

- Requires sensor with a large (~10) pixel-pitch to sensor thickness ratio
- Small pitched 25x25 μm pixels
  - Lower pixel capacitance
    - Low Noise
    - Fast rise time
- 200-300 μm thick silicon sensor
  - Drift and induced current is distributed on multiple pixels
- n-on-p design nominally used

Biased 50μm sensor in TCAD

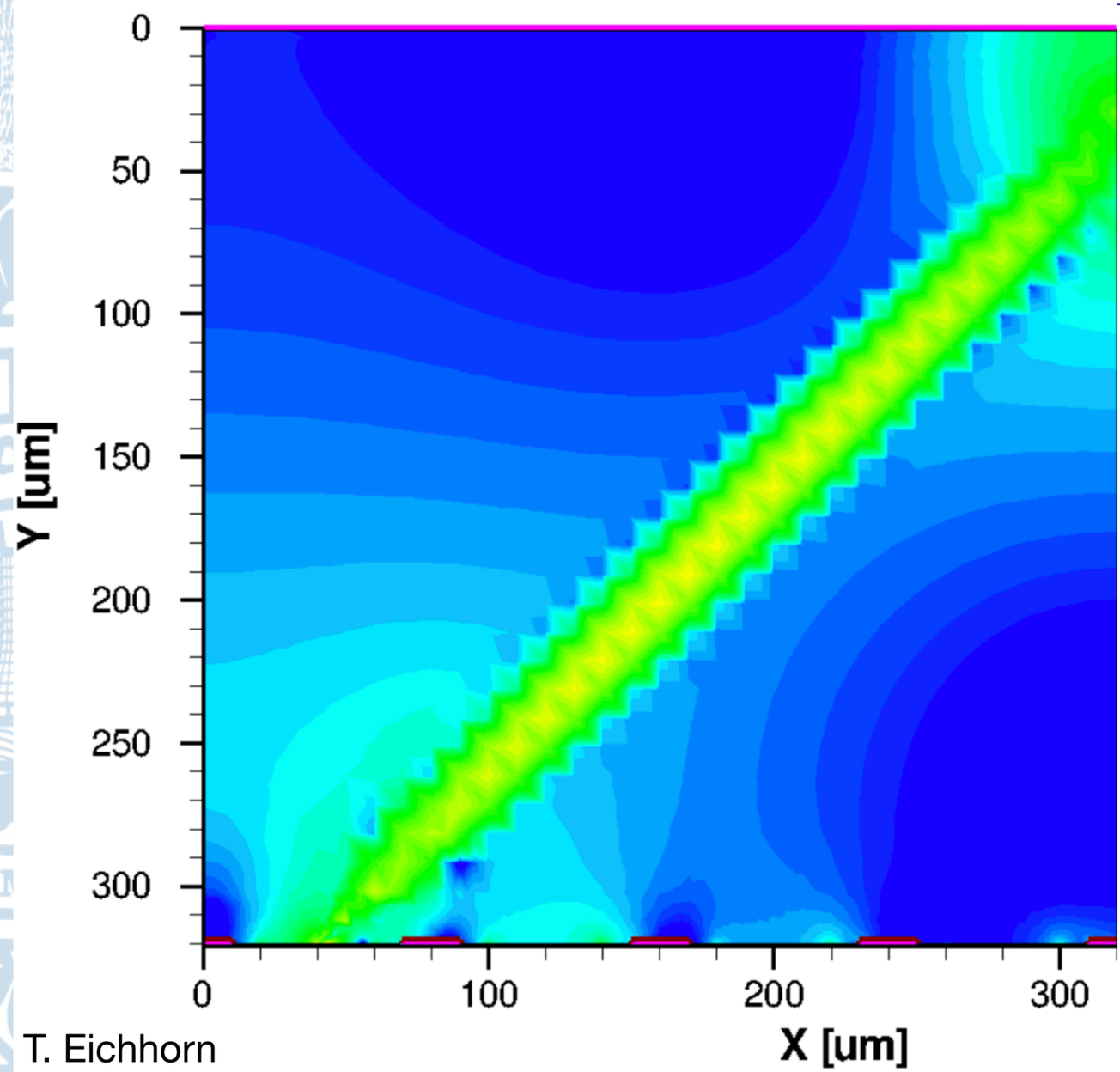


R. Lipton and J. Theiman

Sensor Simulation

- Sensor models built in TCAD
  - Two different signal types simulated
    - MIPs - 4fC uniformly distributed through sensor
    - Point - 4fC deposited at a specific depth
  - No time walk or ionization fluctuations

MIP Deposit in 320μm Silicon



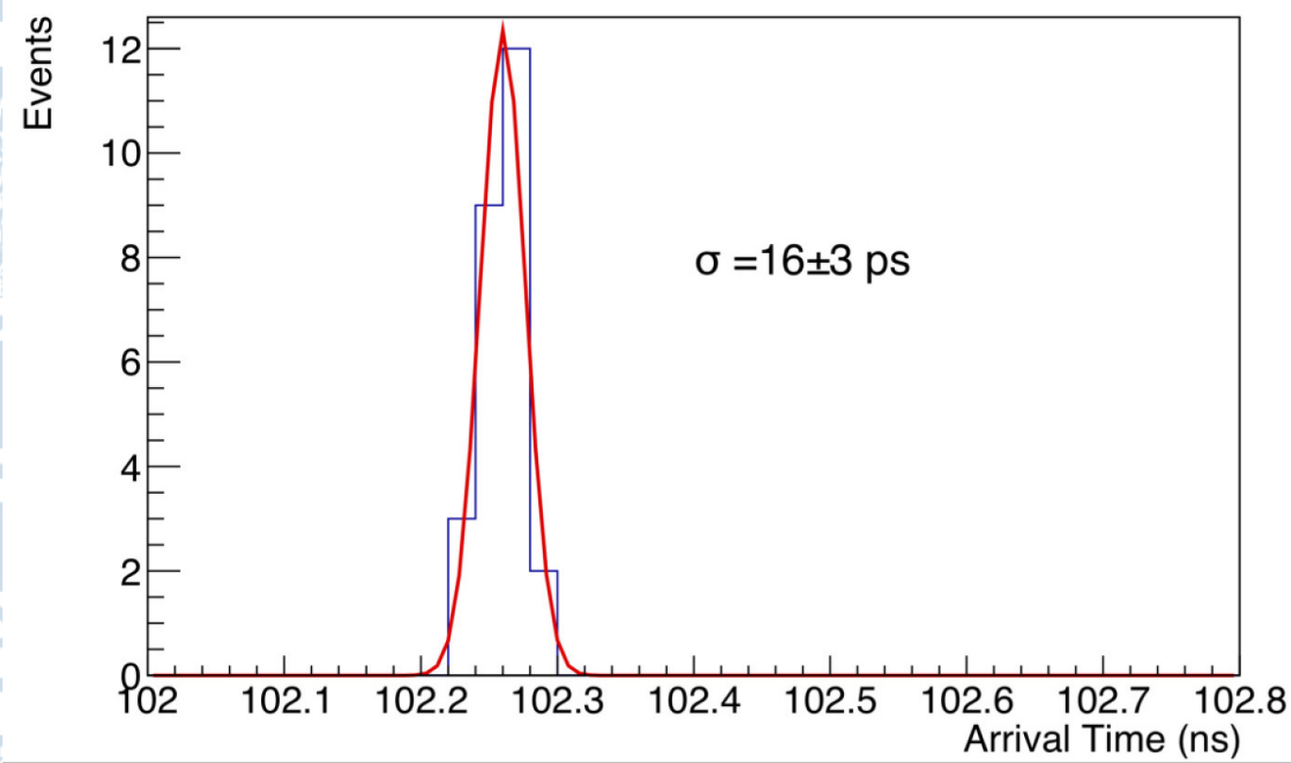
T. Eichhorn

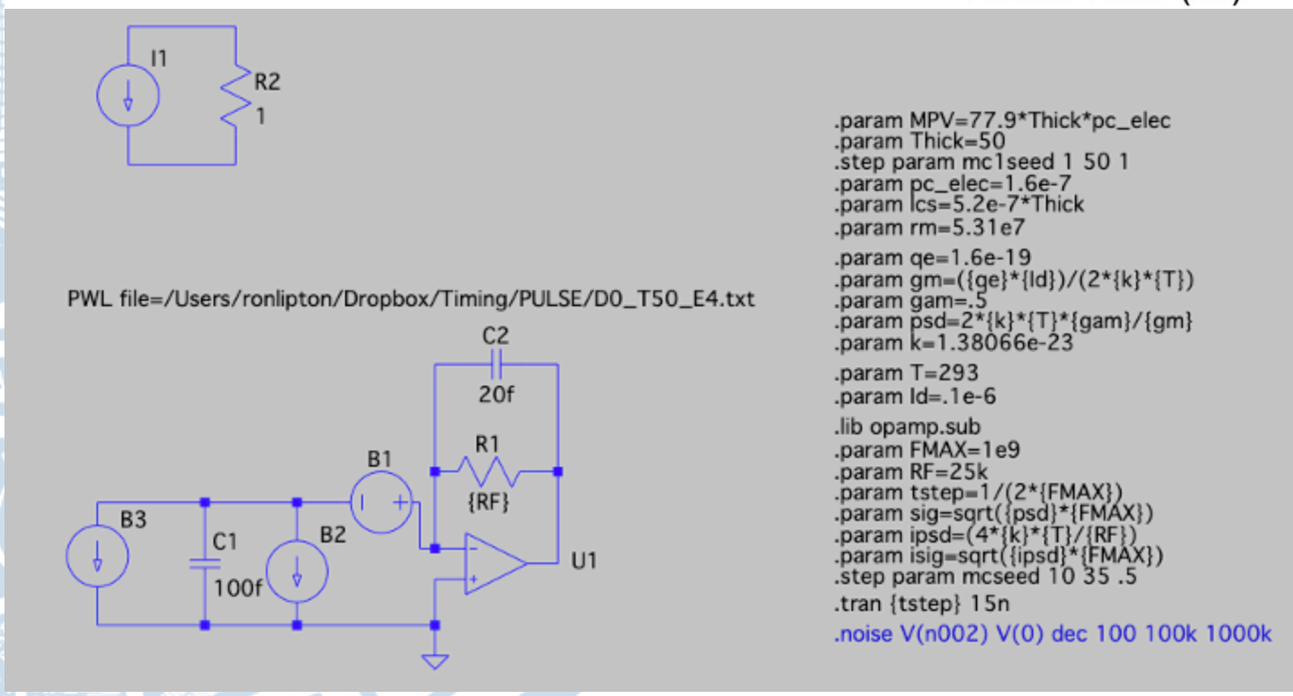
Readout Simulation

- Front end amplifier simulated in SPICE
  - Transimpedance amplifier with feedback resistor
    - 500 MHz Gain Bandwidth
    - 65nm feature size
    - Transimpedance amplifier consumes ~4μA

$$\sigma_t \approx \frac{C_L}{\sqrt{g_m t_a}} \frac{\sqrt{t_a^2 + t_d^2}}{signal} \qquad g_m = \frac{\Delta I_a}{\Delta V_i}$$

  - Noise and Landau fluctuations added to simulated signal from TCAD
    - Extracted noise induced jitter of ~16ps
  - ASIC will have to use 3D architecture to fit in 25μm pixel pitch
    - 3D integration will also minimize capacitive coupling



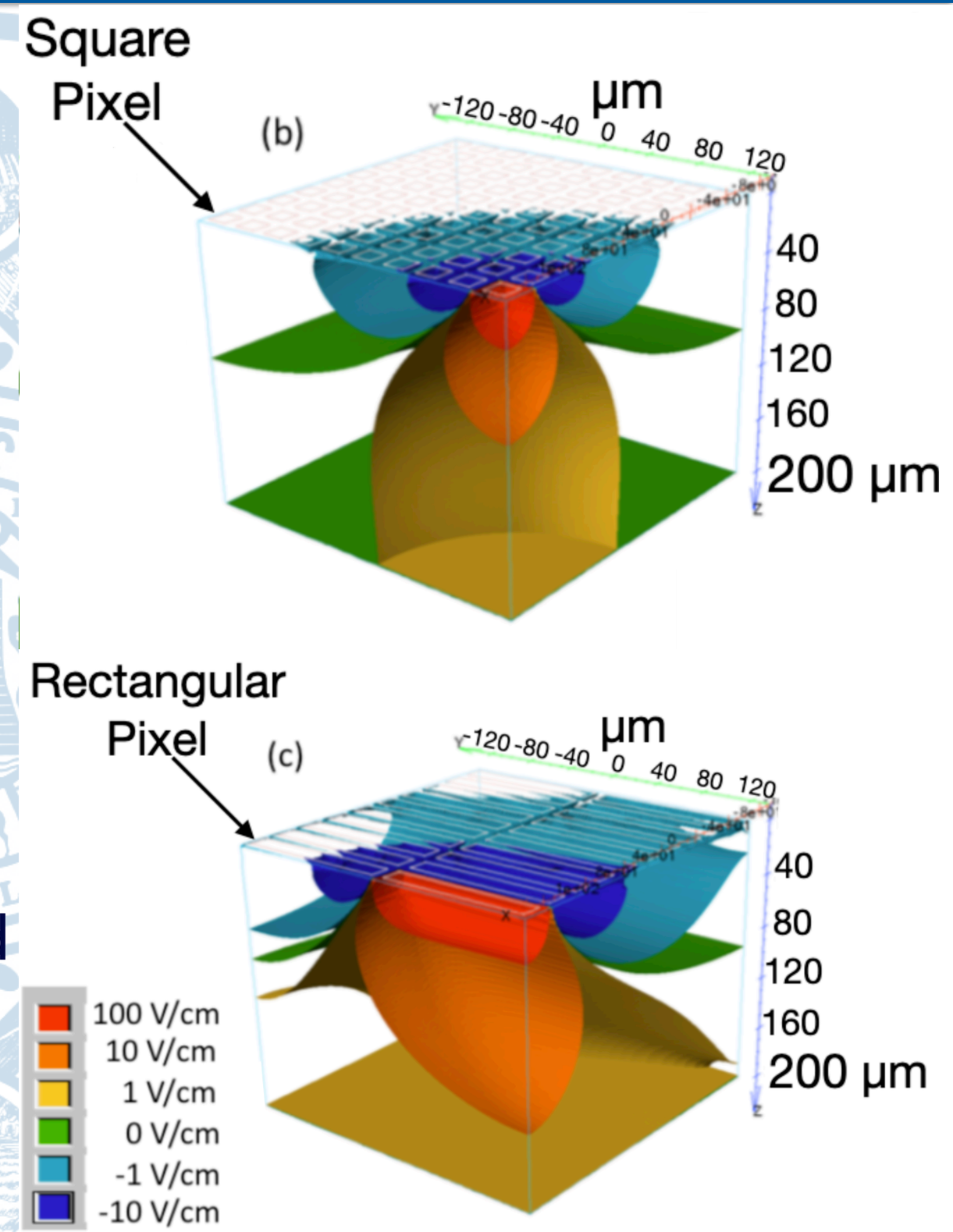


Weighting Field

- Shockley-Ramo current directly proportional to the weighting field

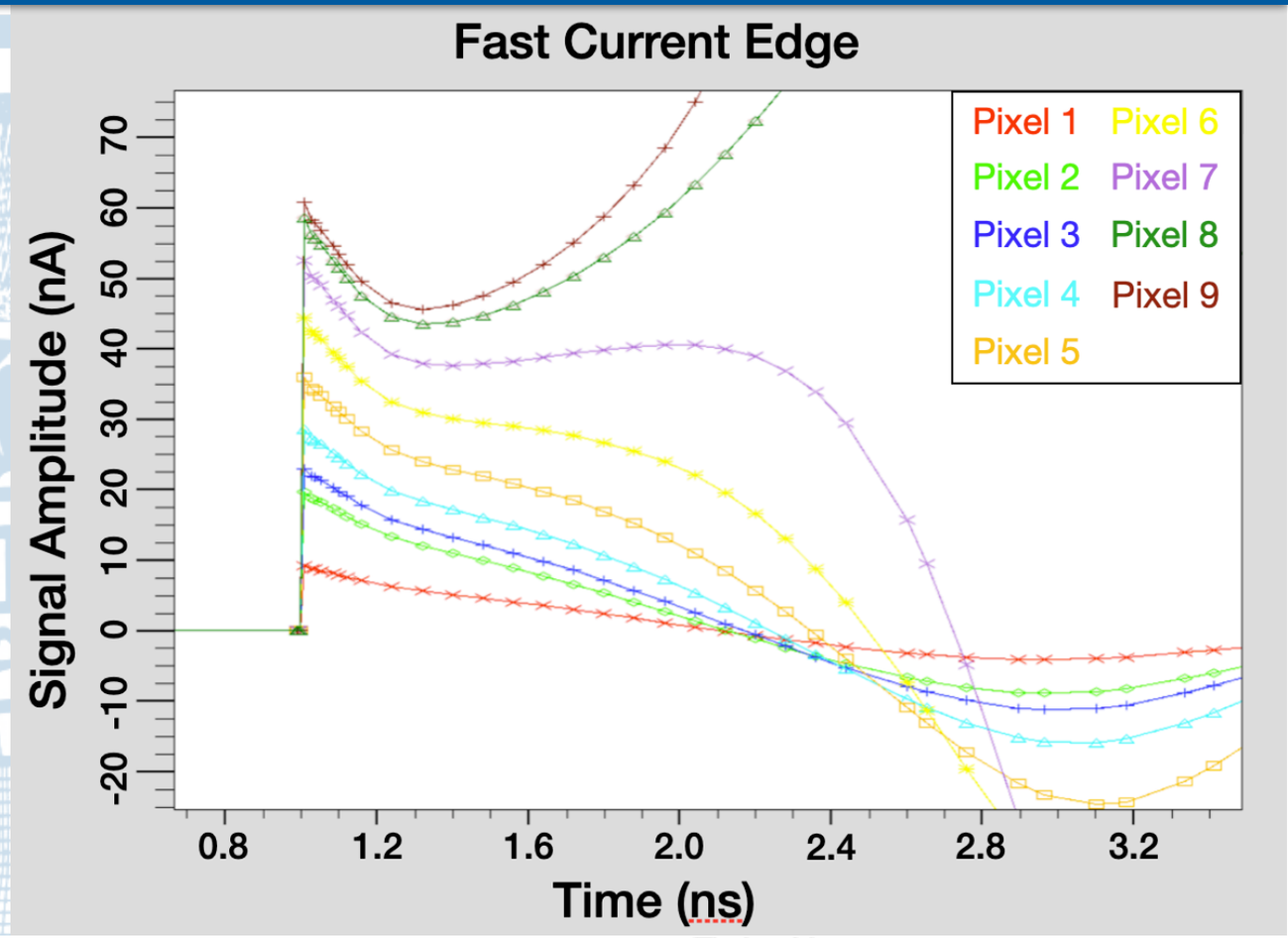
$$i = E_v q v$$

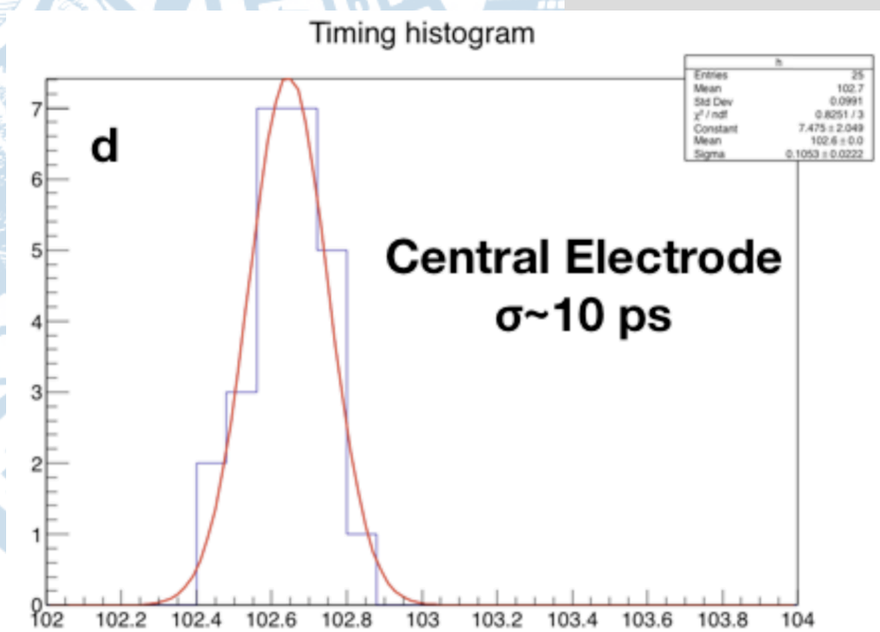
  - The direction of the electric field in the direction of the drift particles velocity
    - Free charge depleted
    - Readout electrode at unit potential
    - All other electrodes at ground
- The weighting field is highly dependent on pixel geometry

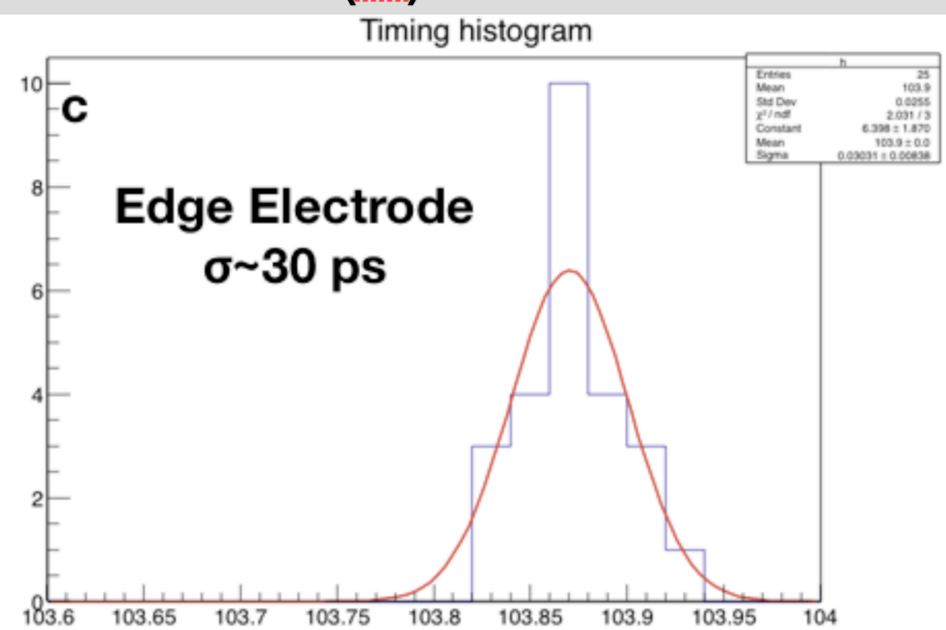


Initial Shockley–Ramo Current

- Shockley-Ramo current begins as drift charge starts moving
  - Very sharp rising edge
  - The central pixel time resolution is ~10ps
  - Low signal threshold
  - The initial Shockley-Ramo current amplitude is 2-14% of the maximum signal amplitude
    - Shape dependent on charge deposition location and depth
- Central pixel has larger initial current and better time resolution

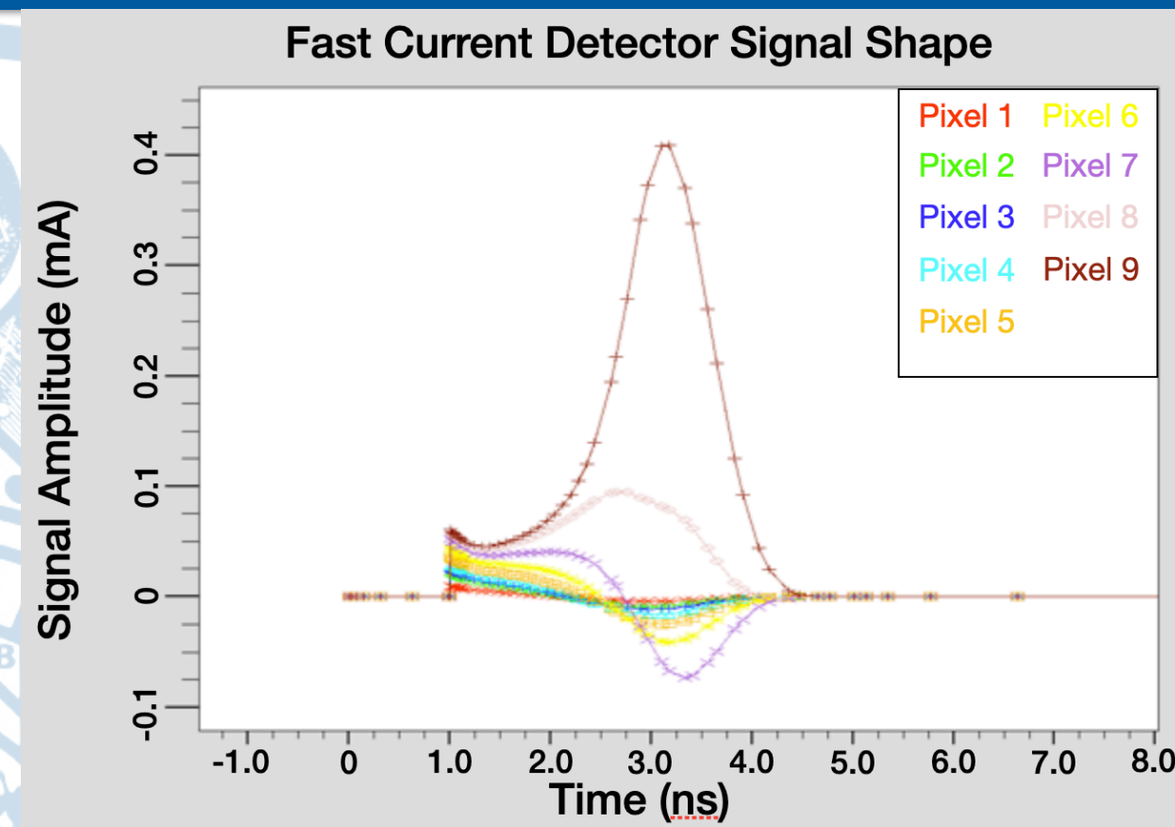


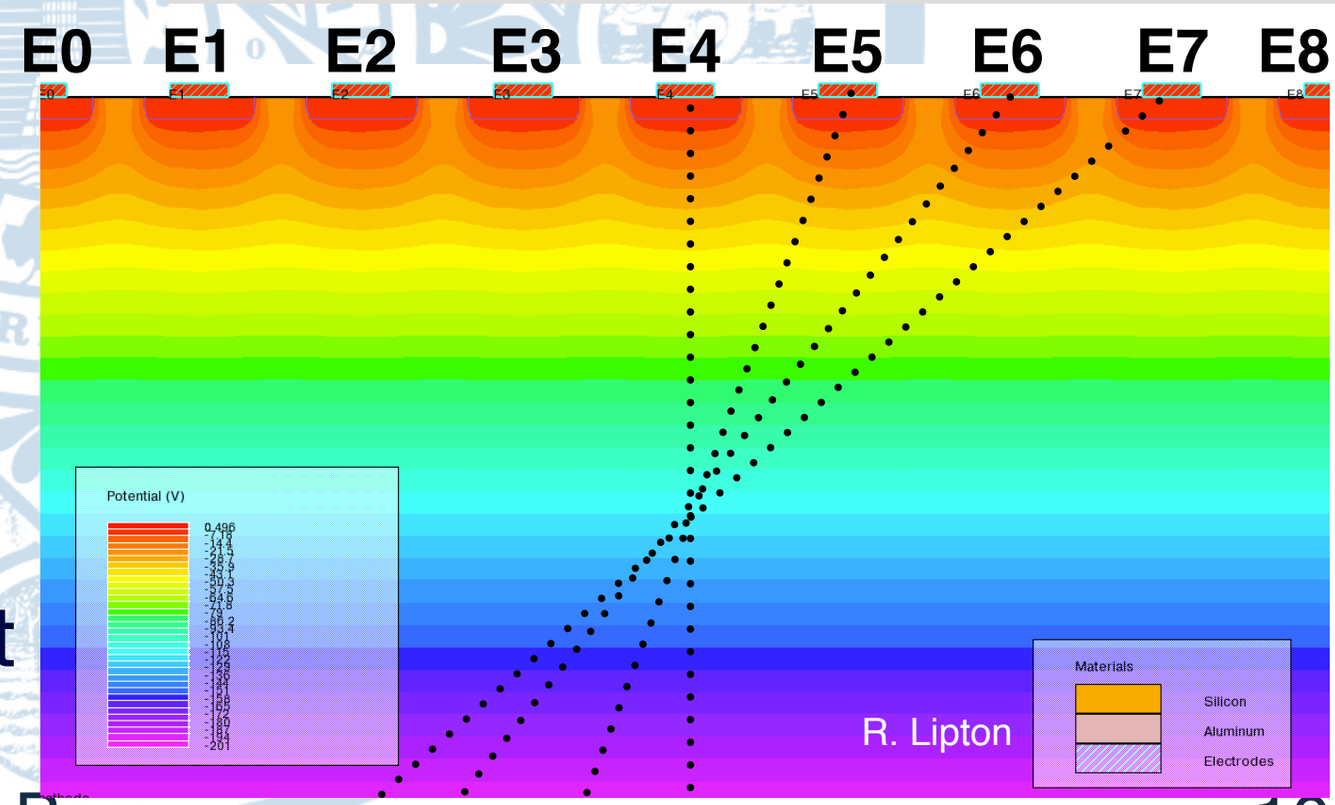




Pixel Hit Pattern

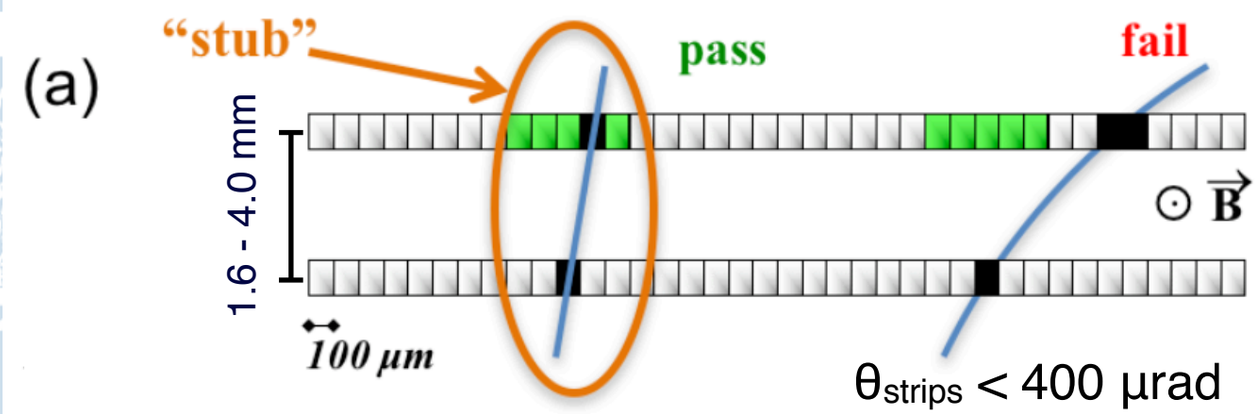
- Shockley-Ramo current has a time dependent signal shape
  - Sums to 0 over a few nanoseconds
  - Only pixels that readout drift current will have a position charge integral
- Signal shape on neighboring pixels dependent on particles incident angle
  - Central and edge pixels receive different fractions of the drift and induced current

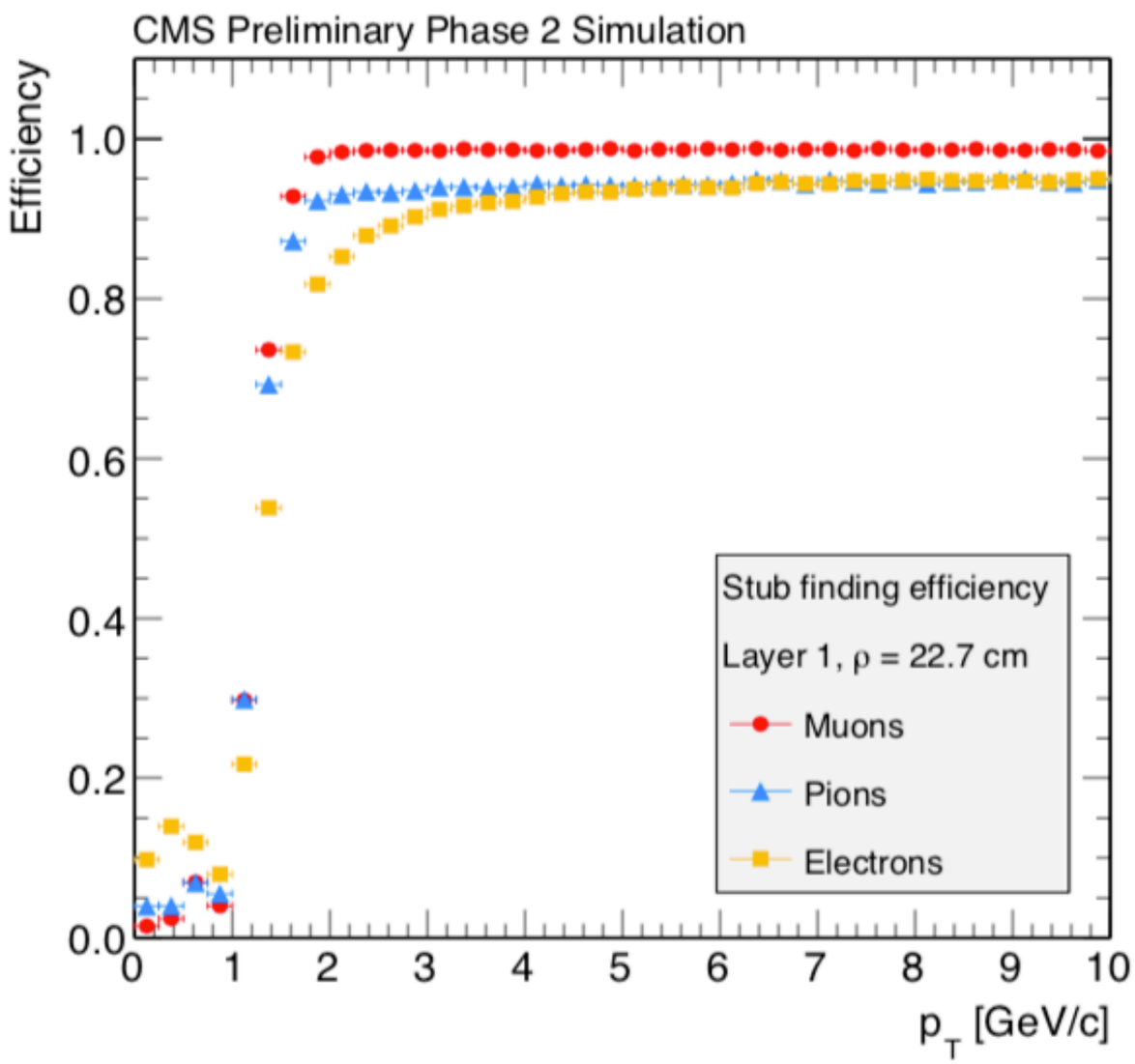


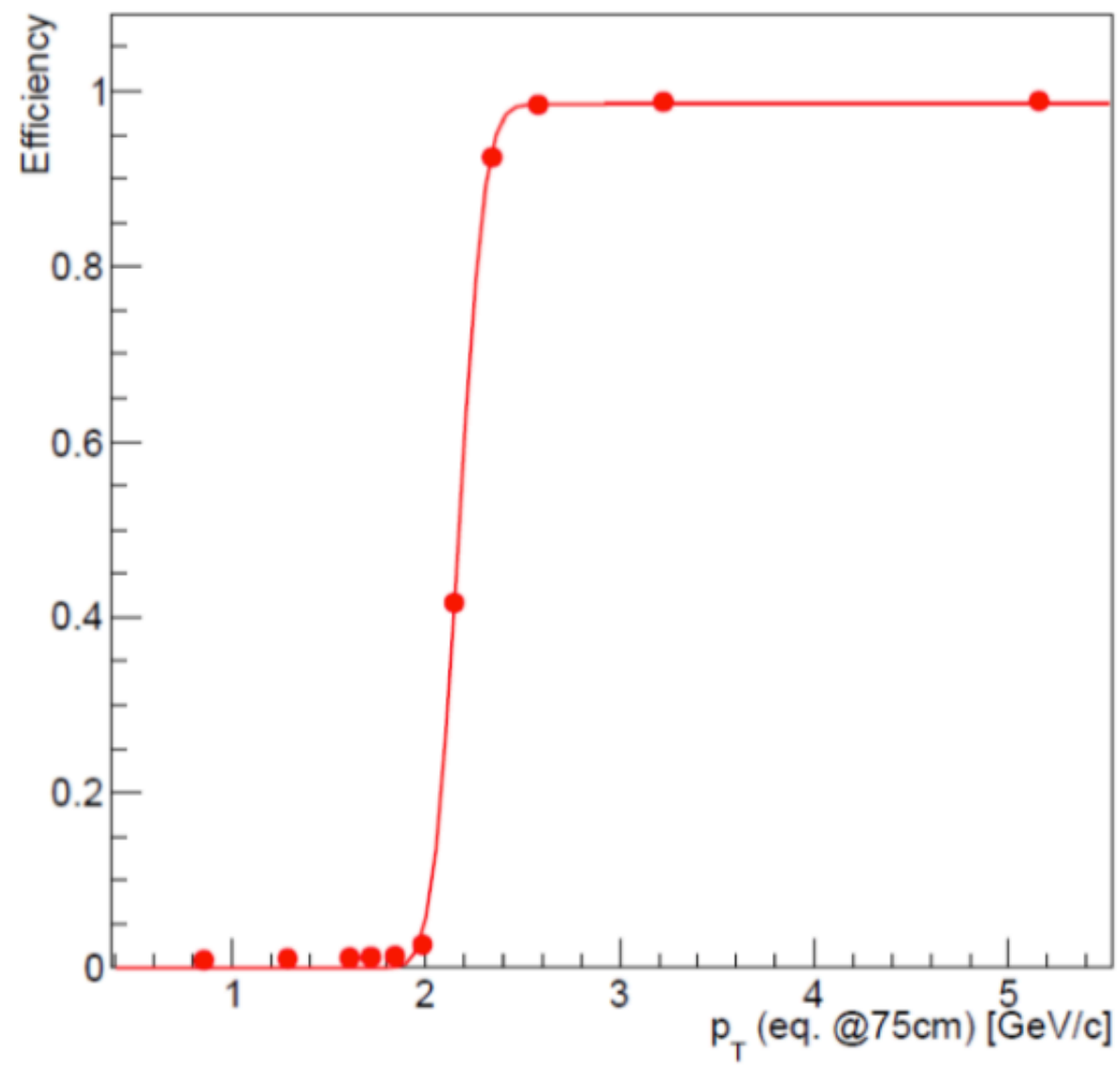


CMS Outer Tracker Trigger

- CMS is currently building a dual layer module to trigger at L1 on "high" p_T tracks

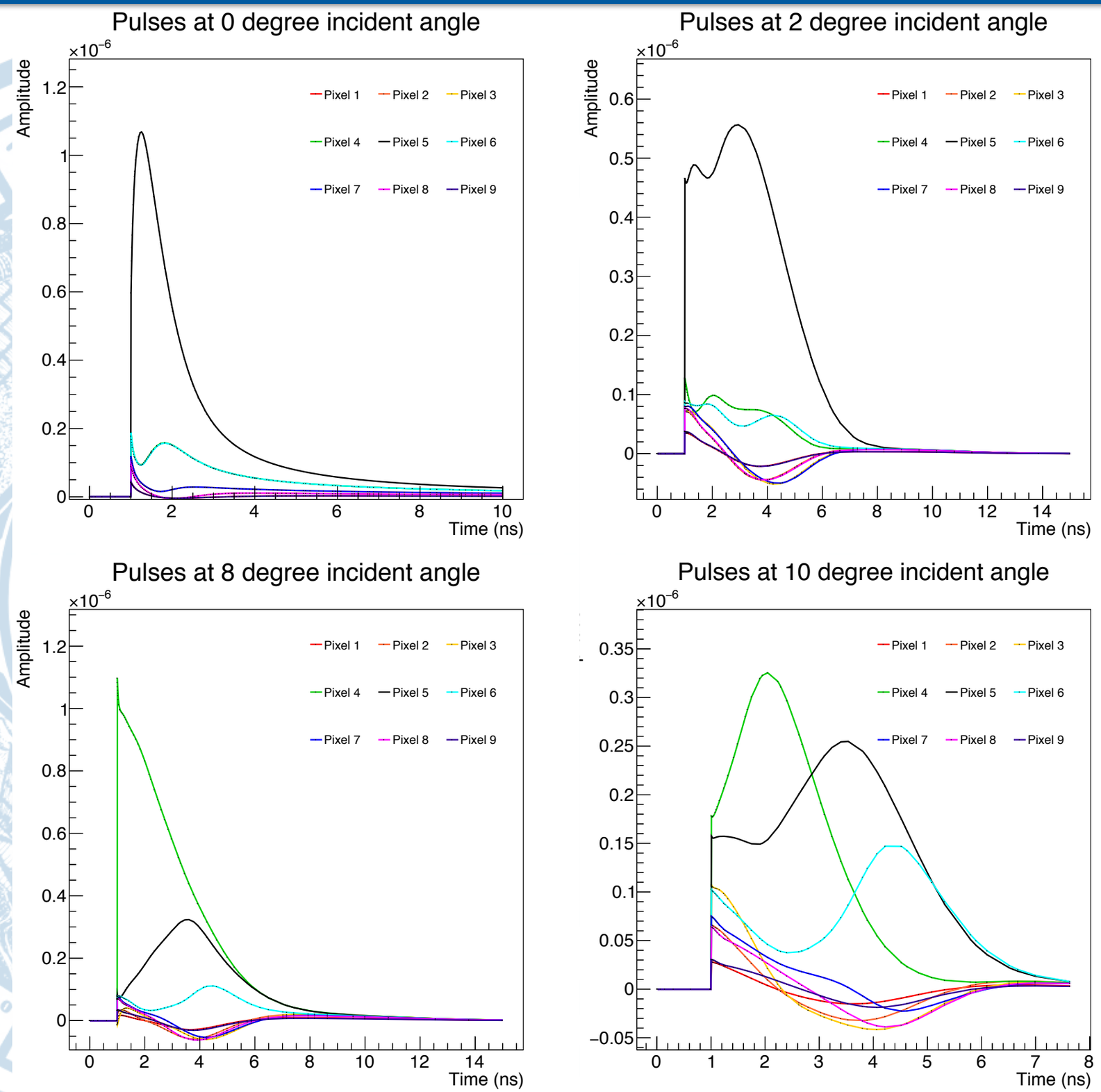






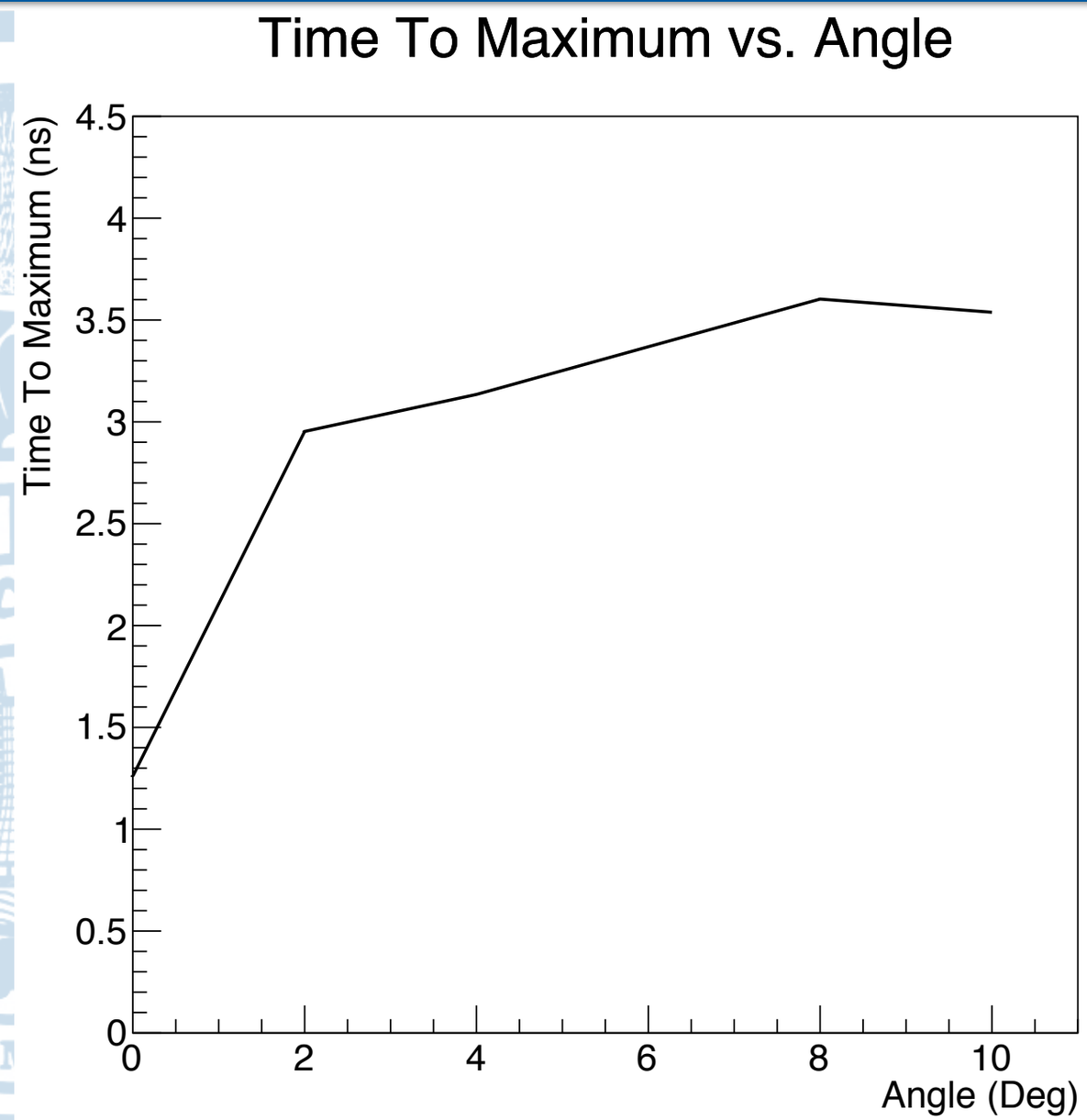
Angular Dependent Signal

- Charged particles with large incident angles have significant drift and Shockley-Ramo currents in neighboring pixels
- An ASIC with periodic current sampling could perform an on-chip angle measurement



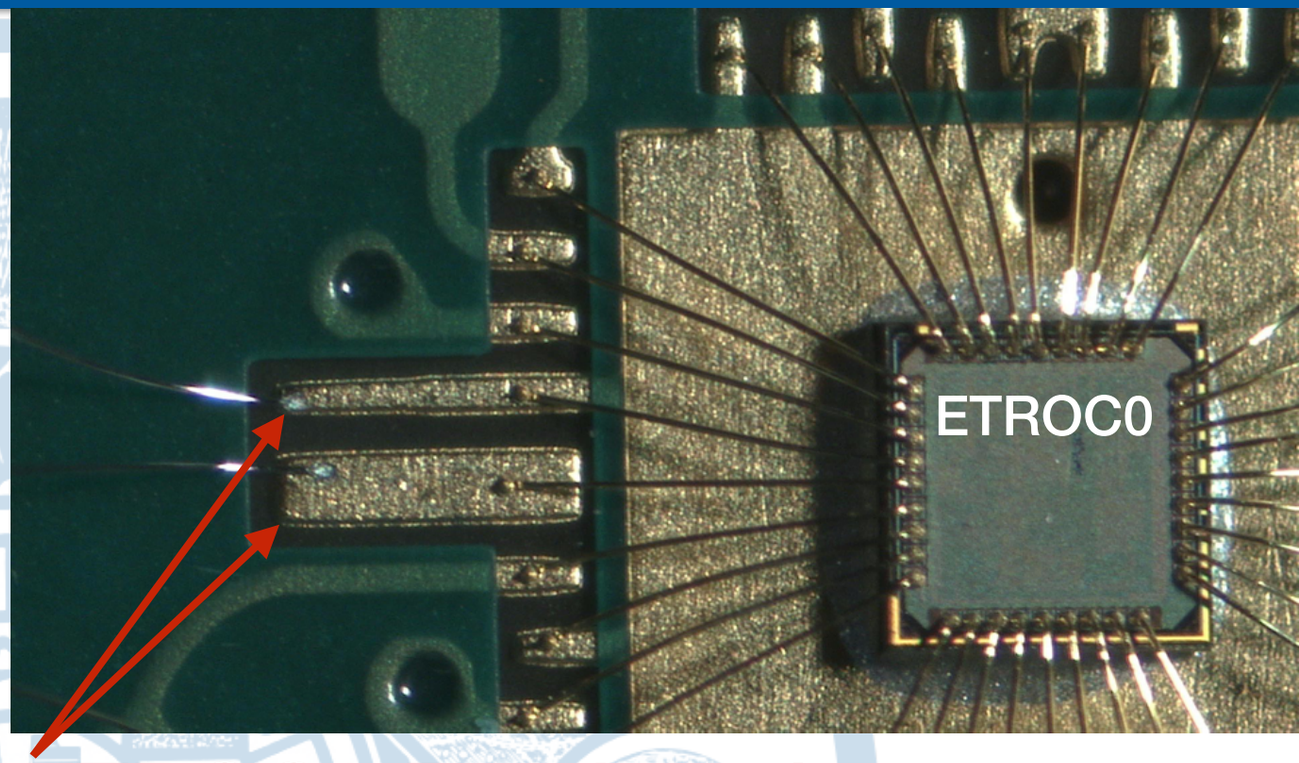
Angular Variables

- Investigating dedicated variables to extract angular information
  - Time to Maximum
  - Total relative amplitudes
  - Cluster width
    - Small (25μm) pixel-pitch
- Need ASIC to calculate simple quantities for triggering
  - Trigger could use multivariate (MVA) techniques
  - Possible to integrate MVAs into the ASIC as well



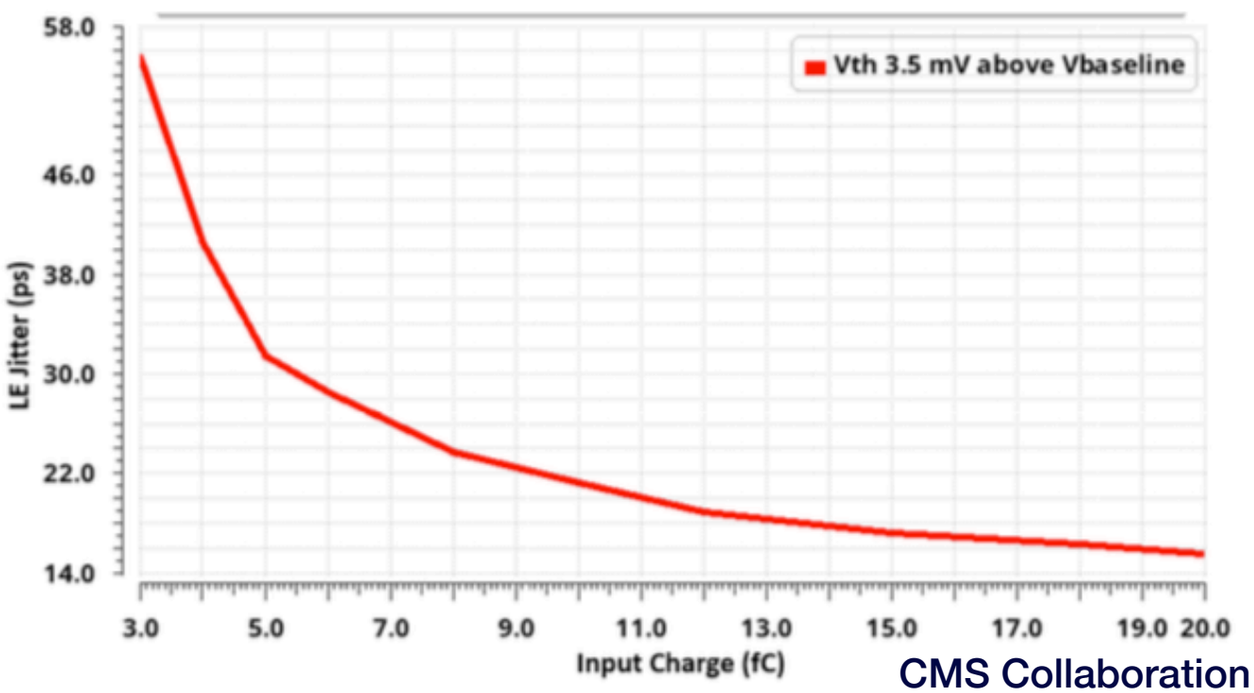
Proposed Measurement Setup

- Novati Wafer with 30x100 μm pitch left over from an 8” wafer development project
- Possible to connect sensor to ETROC0
  - ETROC designed for LGAD sensor
  - Operating at the edge of the chips capabilities (~3 fC)
- Wire bonding seems to be the lowest capacitance connection scheme

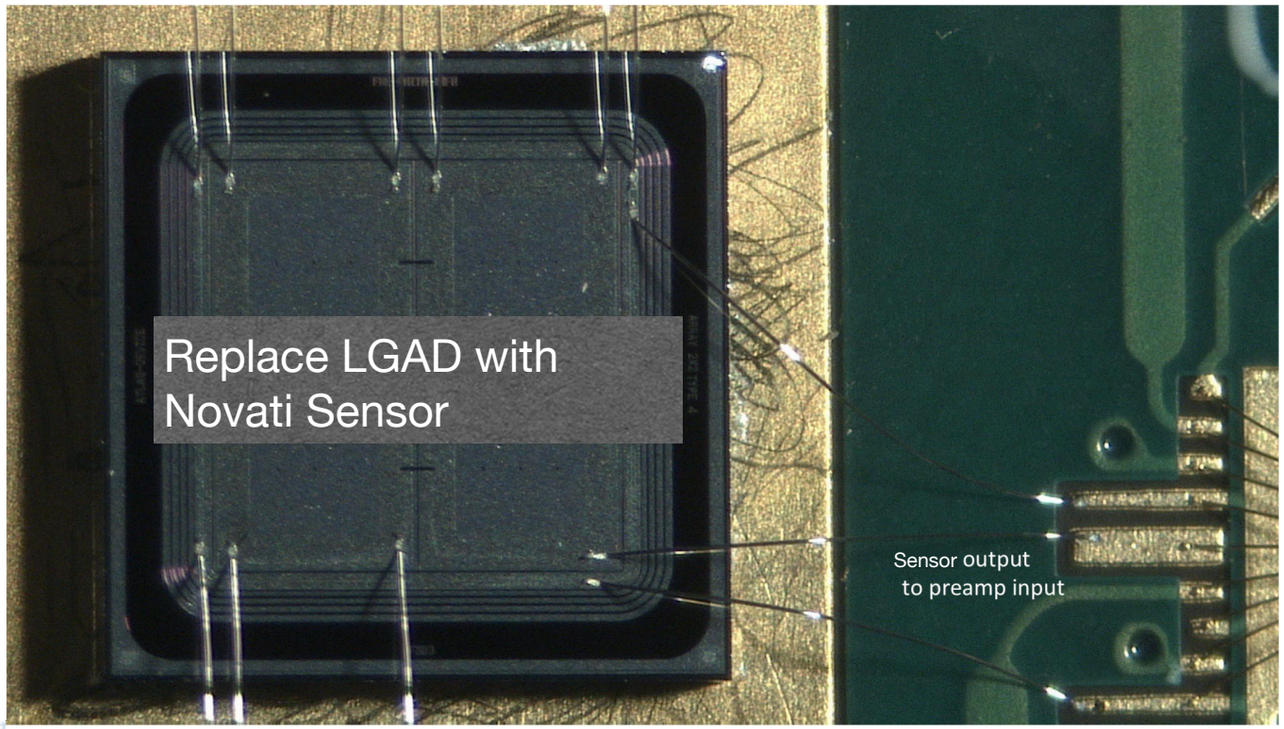


ETROC0 Pre-Amp Inputs

Simulated ETROC Performance

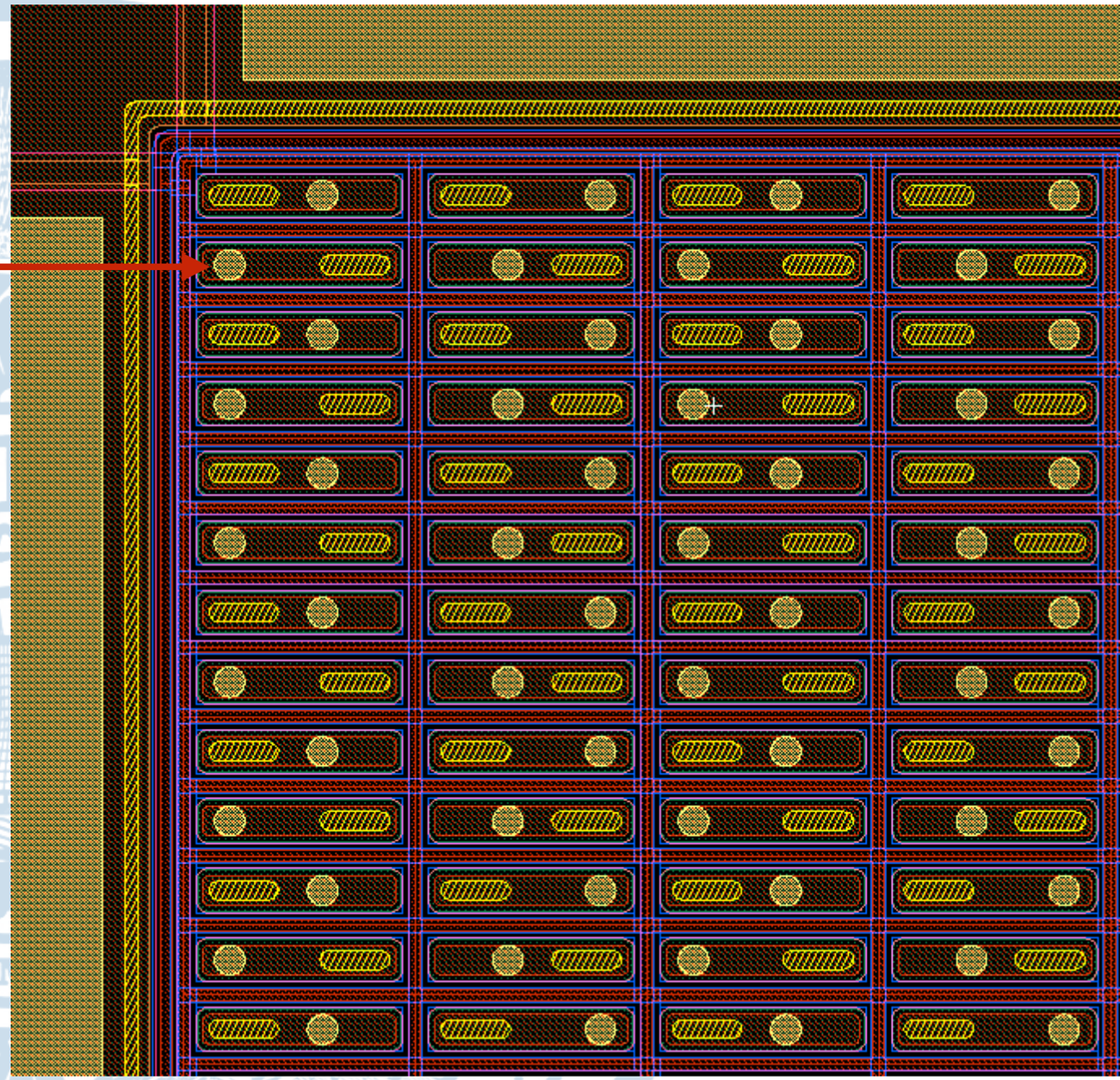


CMS Collaboration



Measurement Setup

- Novati wafer has a small contact area intended for bump bonds
  - 13μm bump bond pad
  - Investigated bump bond fanout
    - Parallel fanout lines will likely have excessive capacitance
  - Will be challenging to land a wire bond in such a small area



Summary

- Introduced a Shockley–Ramo current detector
  - Traditional silicon detector with large (~10) pitch-to-thickness ratio
    - Excellent time resolution (<20ps)
    - Requires low capacitance readout chain
      - 3D integration
    - Small Signal Threshold
      - Pixel geometry can be adjusted to enhance weighting field
    - Has the capability to measure a particle's incident angle
      - Can be used to create a track trigger at Level-1
  - Simple bench setup in the works to detect Shockley-Ramo signal