# Characterization of the Front-End Electronics for the Pixel-Strip Module of the Phase 2 CMS Tracker

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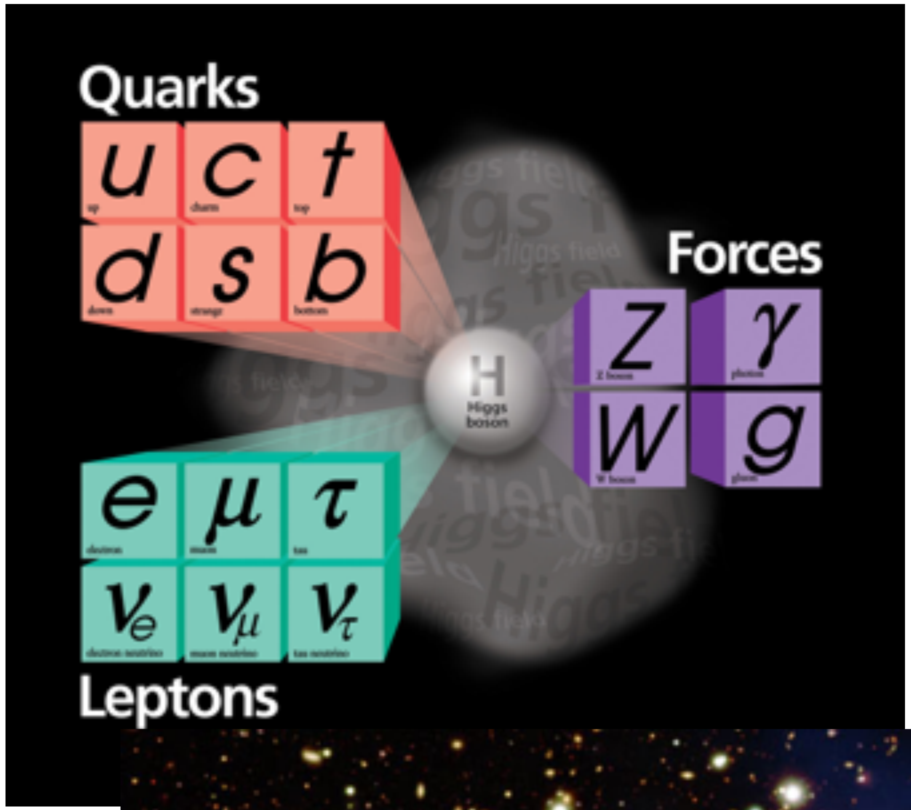
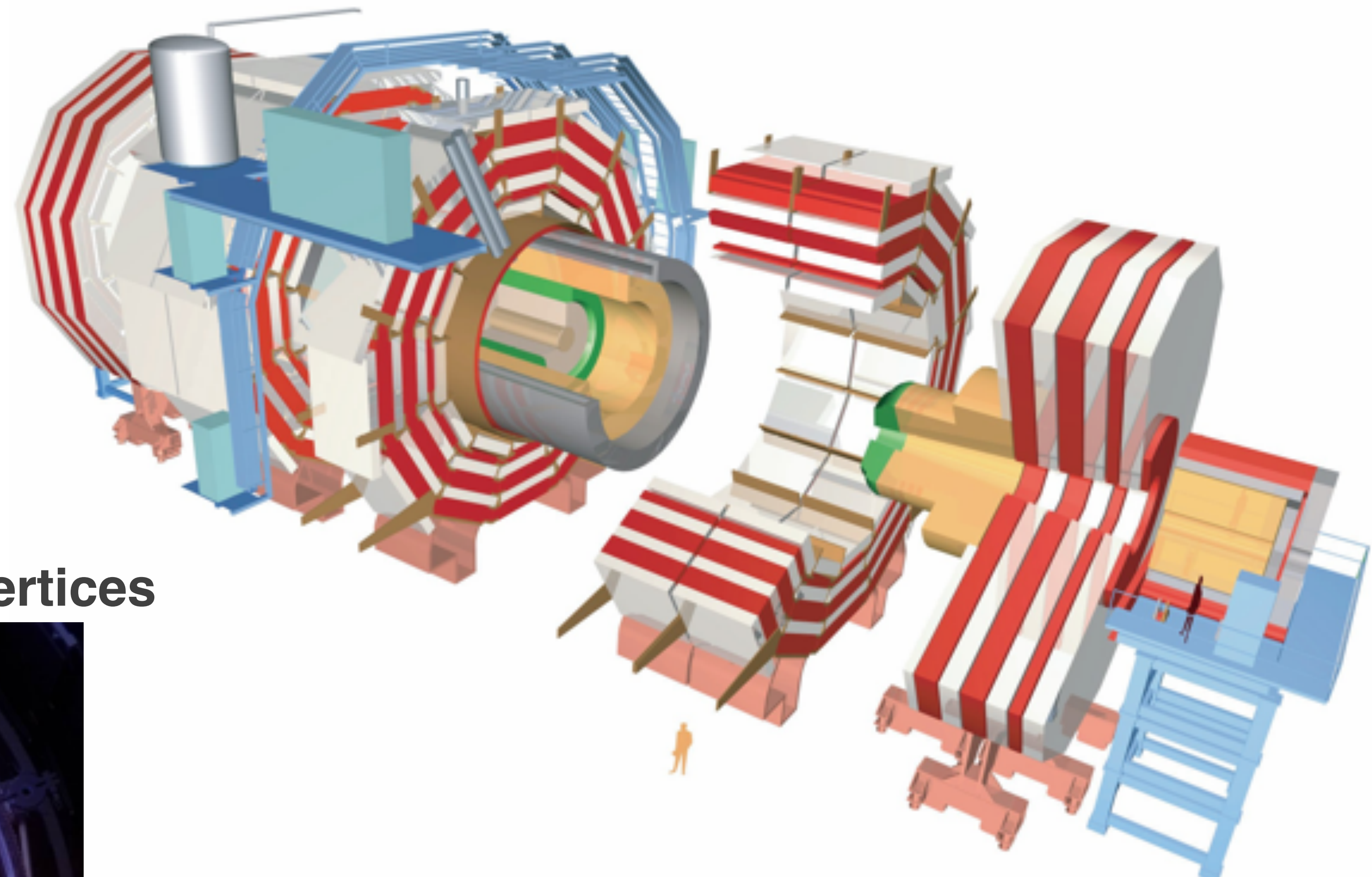
# The Standard Model and LHC

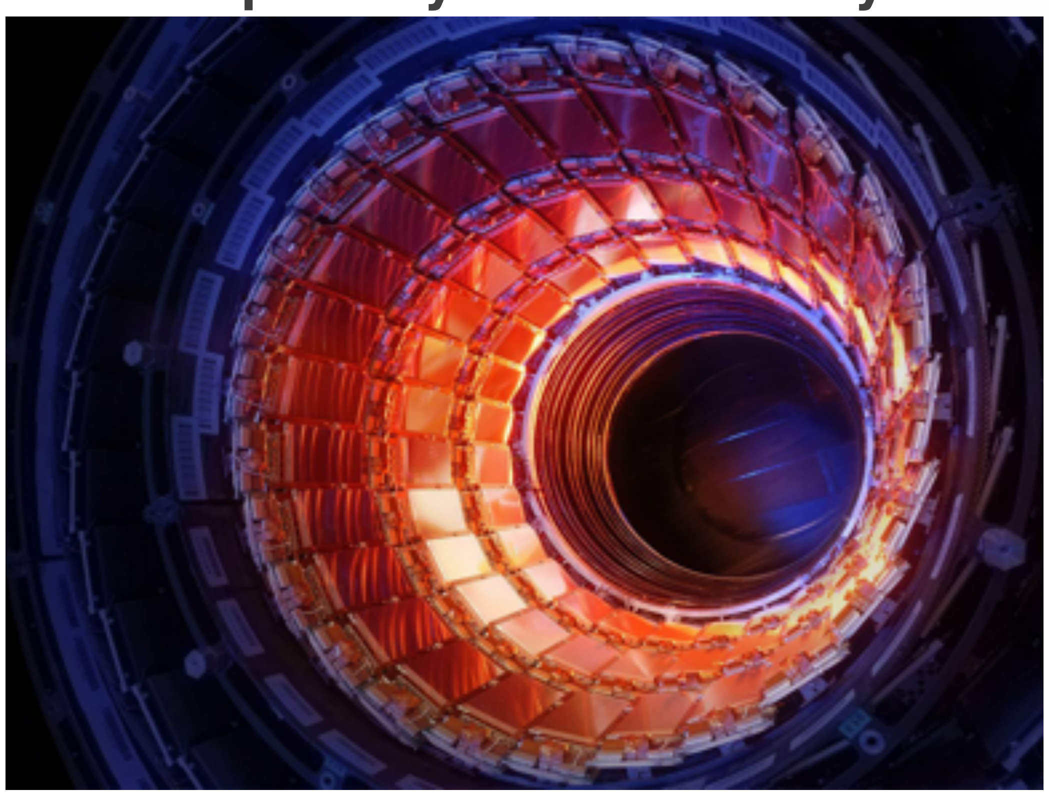
- Foremost model in particle physics
  - Describes:
    - Visible matter in our world
    - 3 of 4 fundamental interactions
    - How particles acquire mass
- Open questions remain
  - What is dark matter?
  - How do neutrinos acquire mass?
  - etc…
- Large Hadron Collider (LHC)
  - Delivered ~20$fb^{-1}$ so far at 13 TeV
  - Successful discovery of Higgs boson in 2012
- High Luminosity LHC (HL-LHC)
  - Will deliver up to 3000$fb^{-1}$ by 2035 at 14TeV.




# Compact Muon Solenoid (CMS)

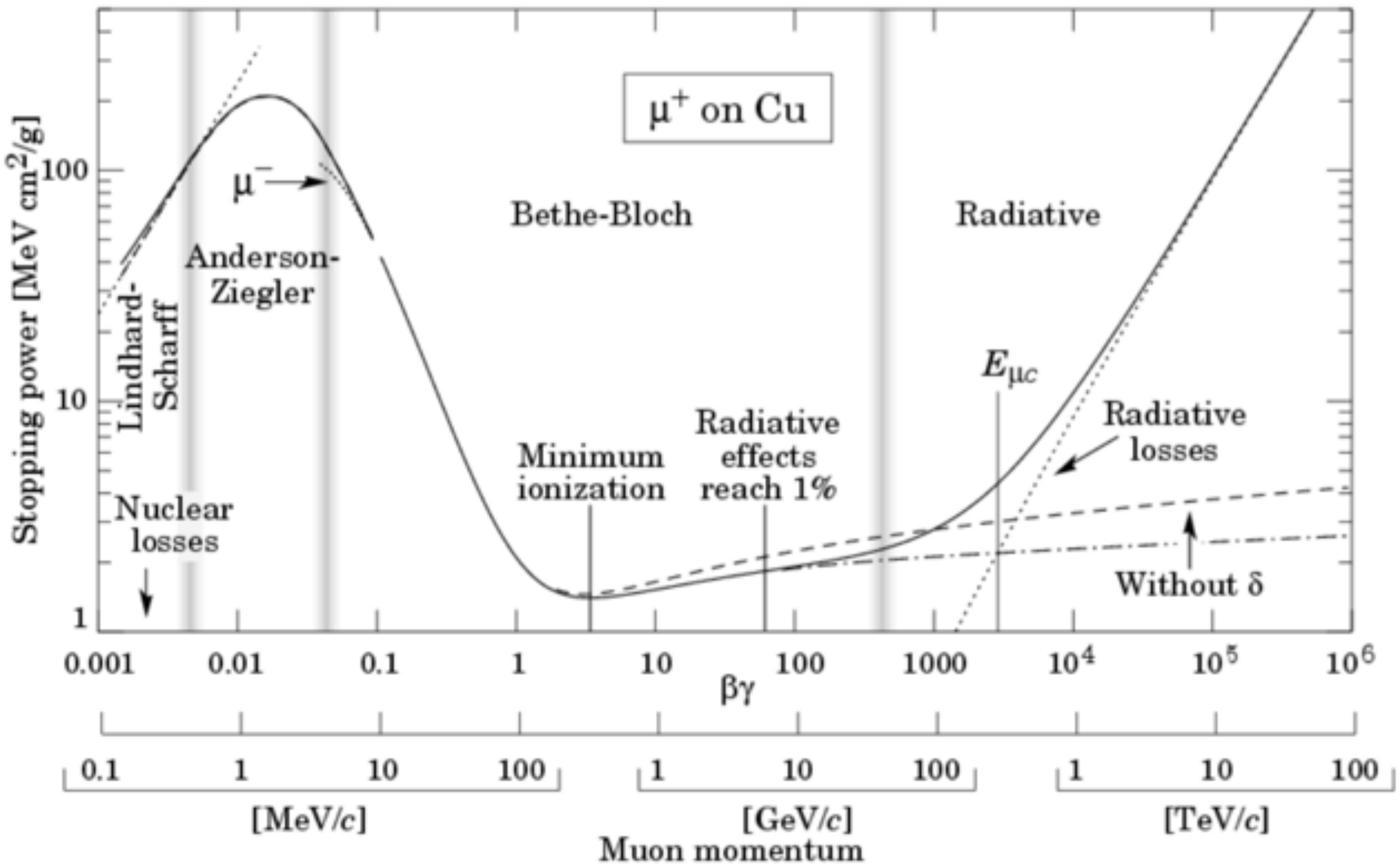
- CMS
  - Muon Detector
  - Solenoid
  - Hadron Calorimeter (HCAL)
  - Electromagnetic Calorimeter (ECAL)
  - **Tracking Detector**
    - **Tracks particle trajectory**
    - **Measures particle charge and $p_T$**
    - **Localizes primary and secondary vertices**

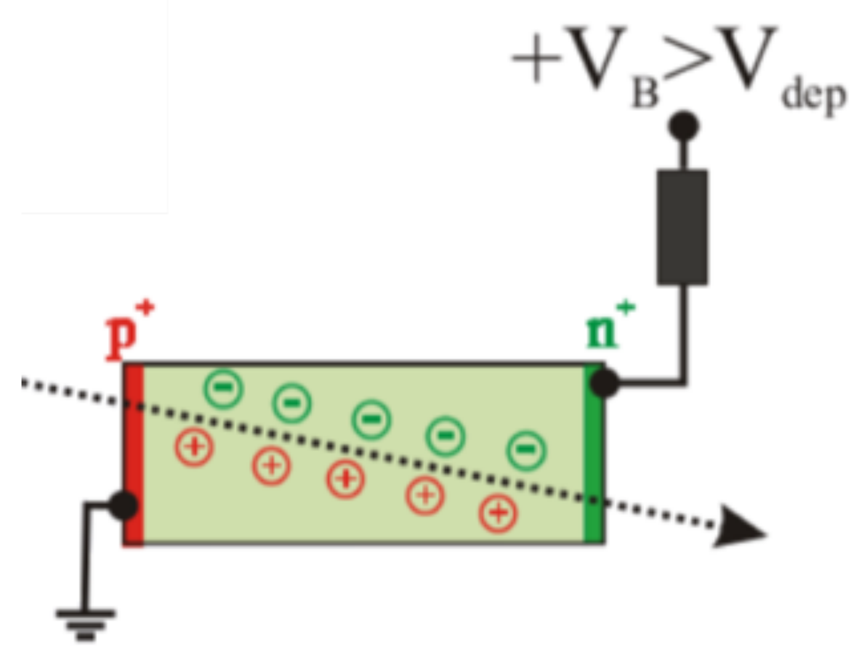




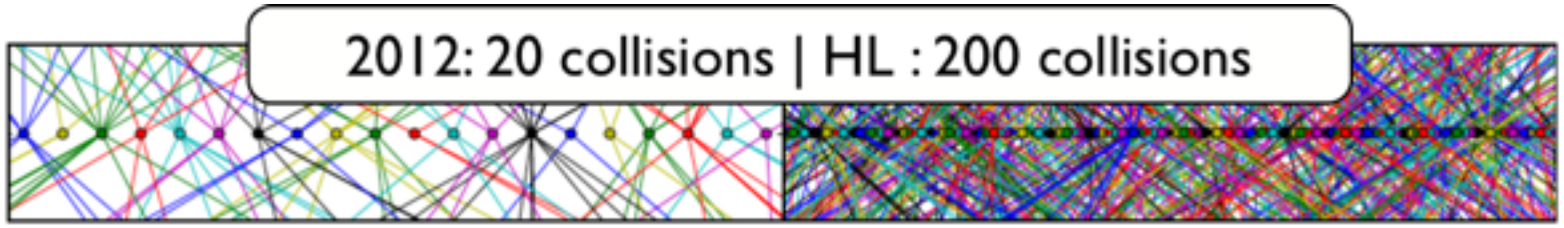
# Silicon Sensors

- Can be modeled simply by a reverse-biased diode
  - Minimum ionizing particles (MIPs) traverse the silicon, generating an electron-hole pairs (EHP) as they deposit energy
  - Charge carriers drift toward their respective electrodes, creating a signal pulse
  - In 300µm silicon, a typical MIP generates 20,000-25,000 EHPs, or a signal of ~4fC

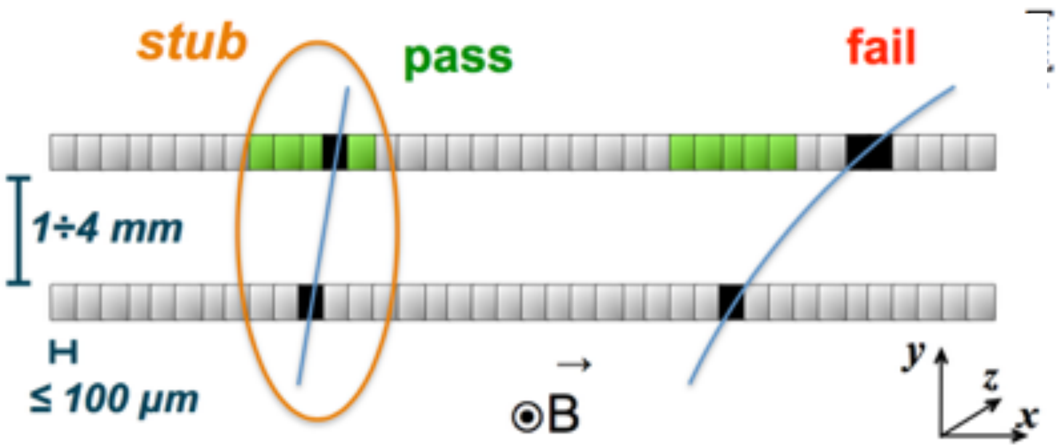


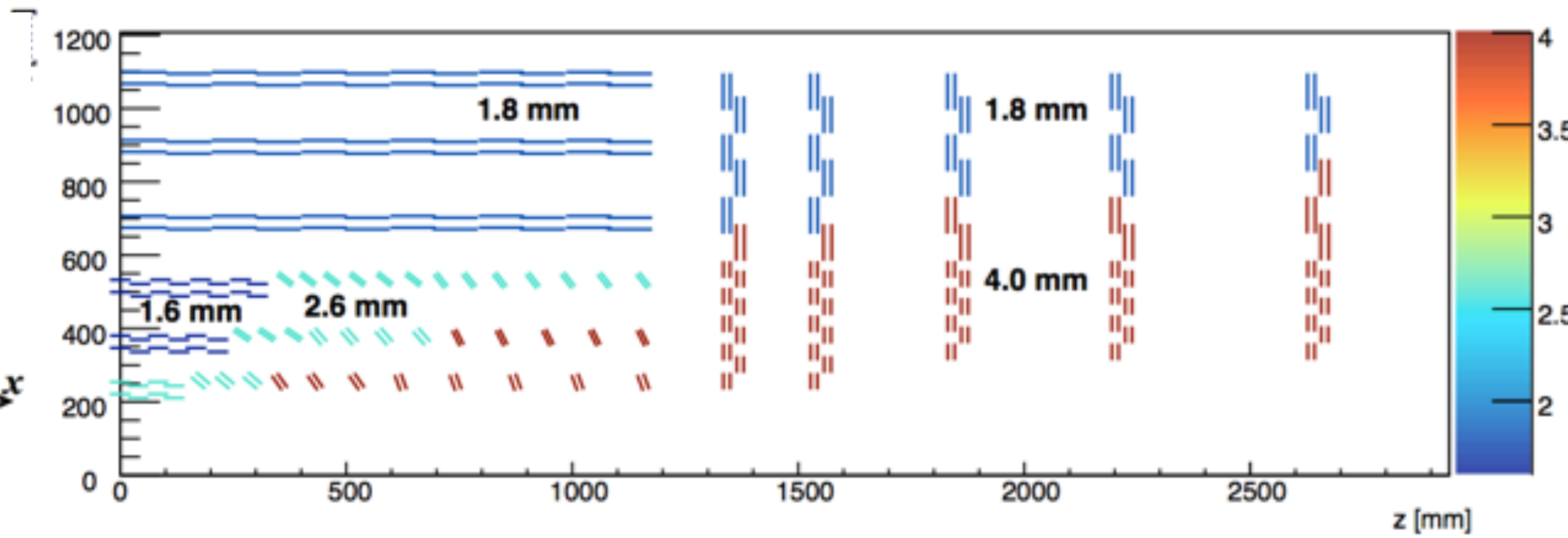



# Tracking in HL-LHC




- HL-LHC Environment
  - Increased instantaneous luminosity: $1.2 \cdot 10^{-34} cm^{-2}s^{1}$ –> $5\text{-}7 \cdot 10^{-34} cm^{-2}s^{1}$
  - interactions per-bunch crossing (pileup) ~23 –> 140-200
  - Up to $3000 fb^{-1}$
- High luminosity poses new challenges for detection
  - Radiation Hardness
  - Tracking information in L1 triggering
    - $p_T$ modules: Back-to-back silicon sensors separated by a few mm
    - Modules create high $p_T$ candidates called stubs –> sent as input to the L1 trigger at each bunch crossing (40MHz)





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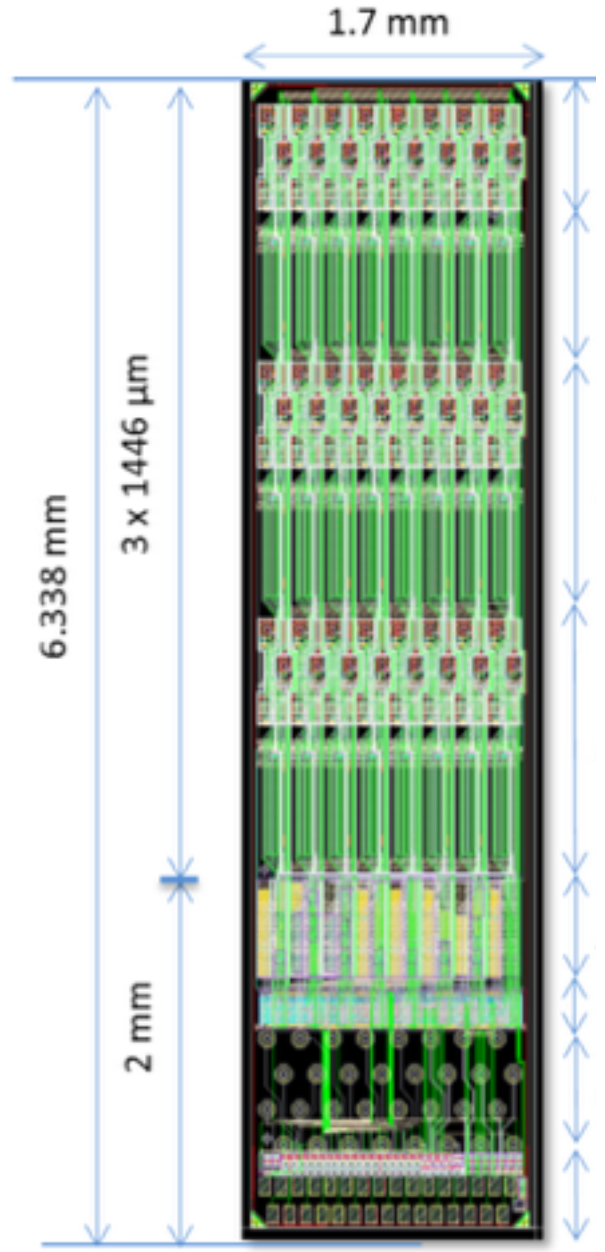
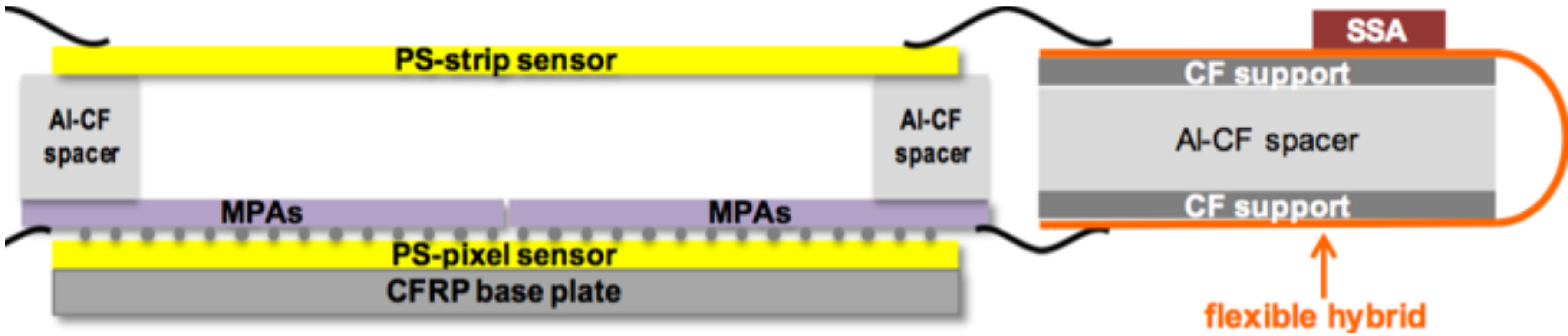
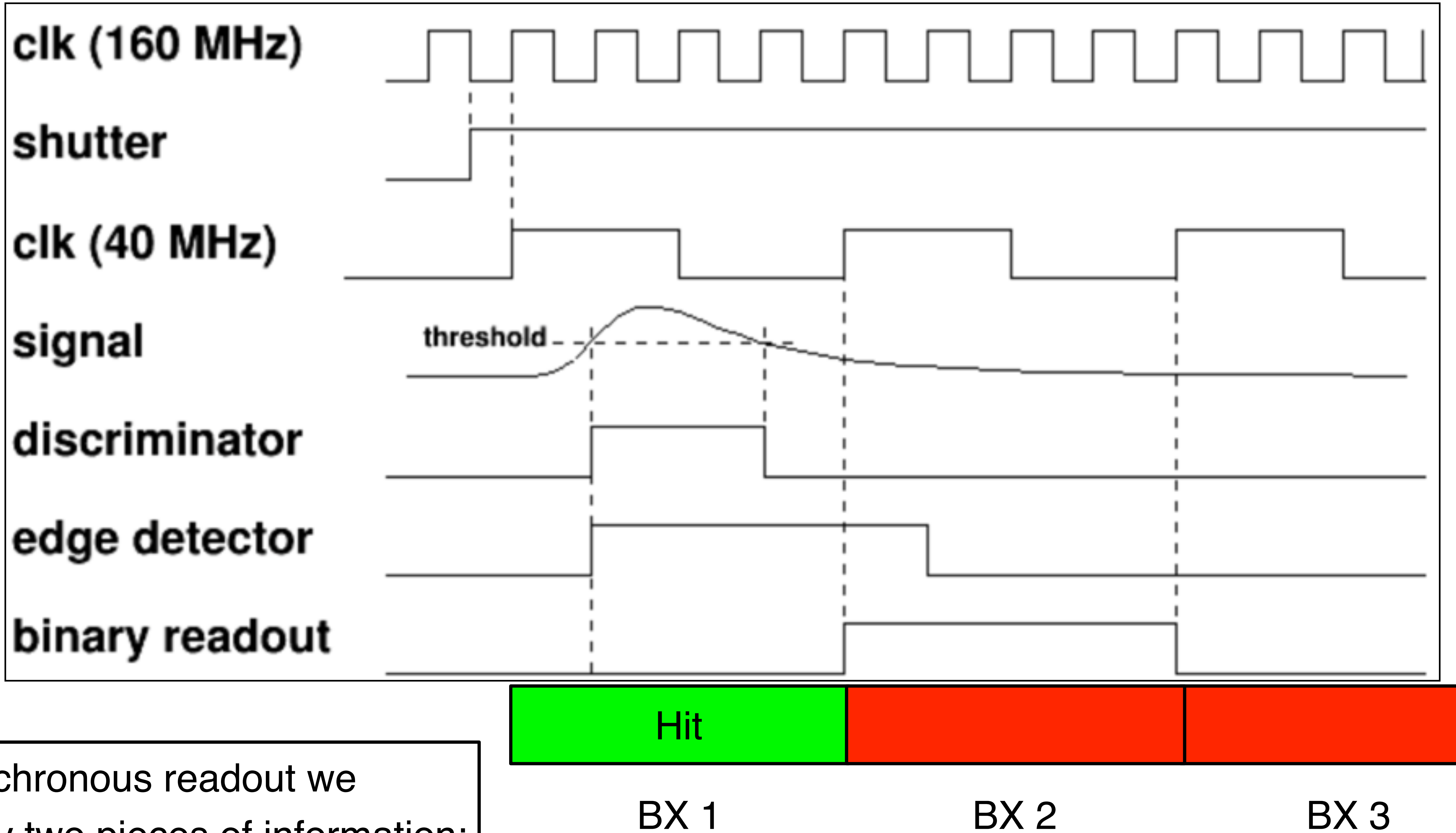
# Prototype of the Outer Tracker Modules

- The Macro Pixel ASIC (MPA)
  - IC bonded to an array of pixels in the pixel sensor
  - Stores both pixel and strip hit information for readout
- MPA-Light
  - The earliest prototype of the MPA
  - If satisfactory, MPA-Light electronics will be used in the MPA
- MaPSA
  - Module of 6 MPA-Lights bump bonded to $n^+$-on-p pixel sensors
  - Operates in two general modes:
    - Asynchronous readout
    - **Synchronous readout**



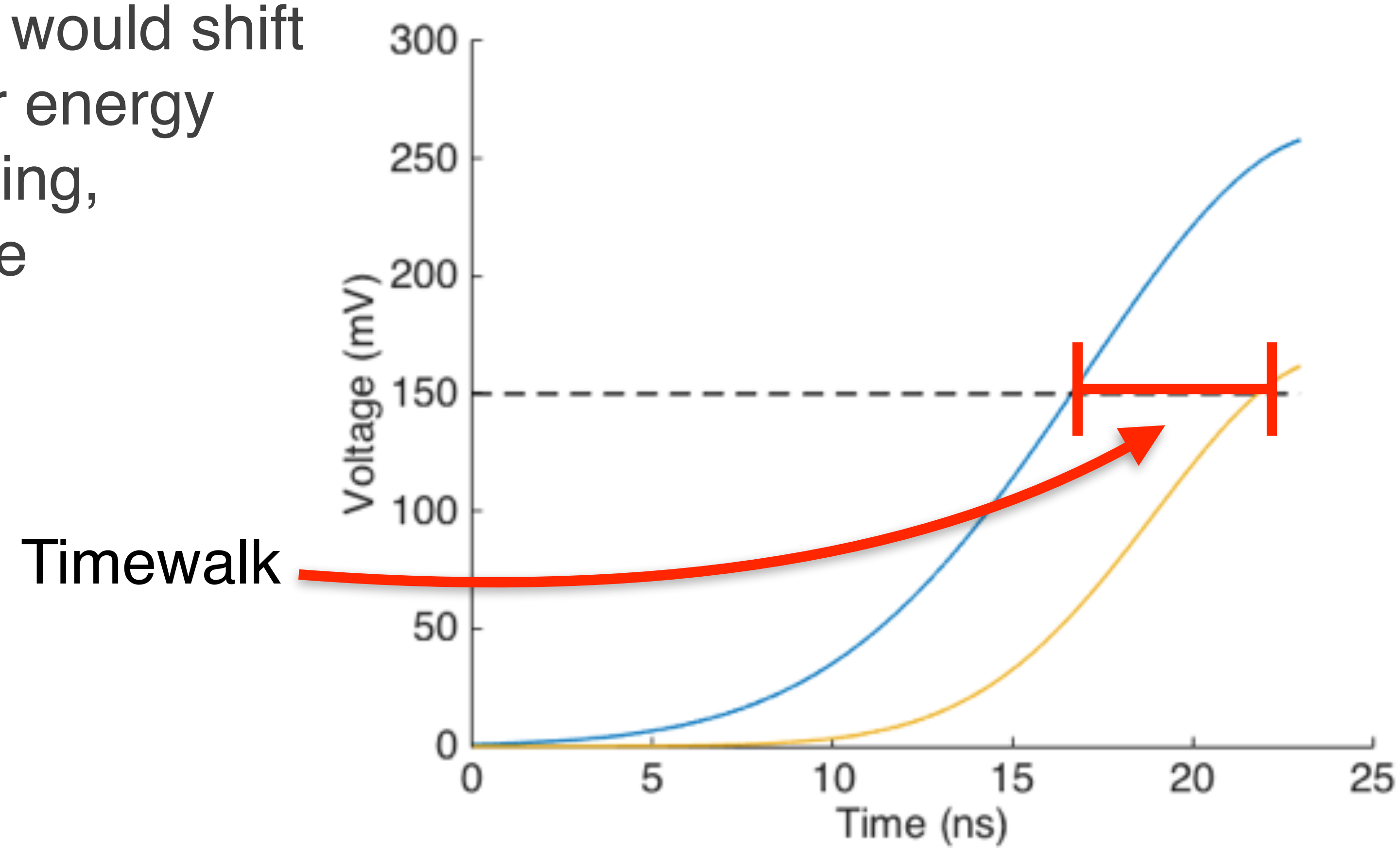
# MPA-Light and MaPSA



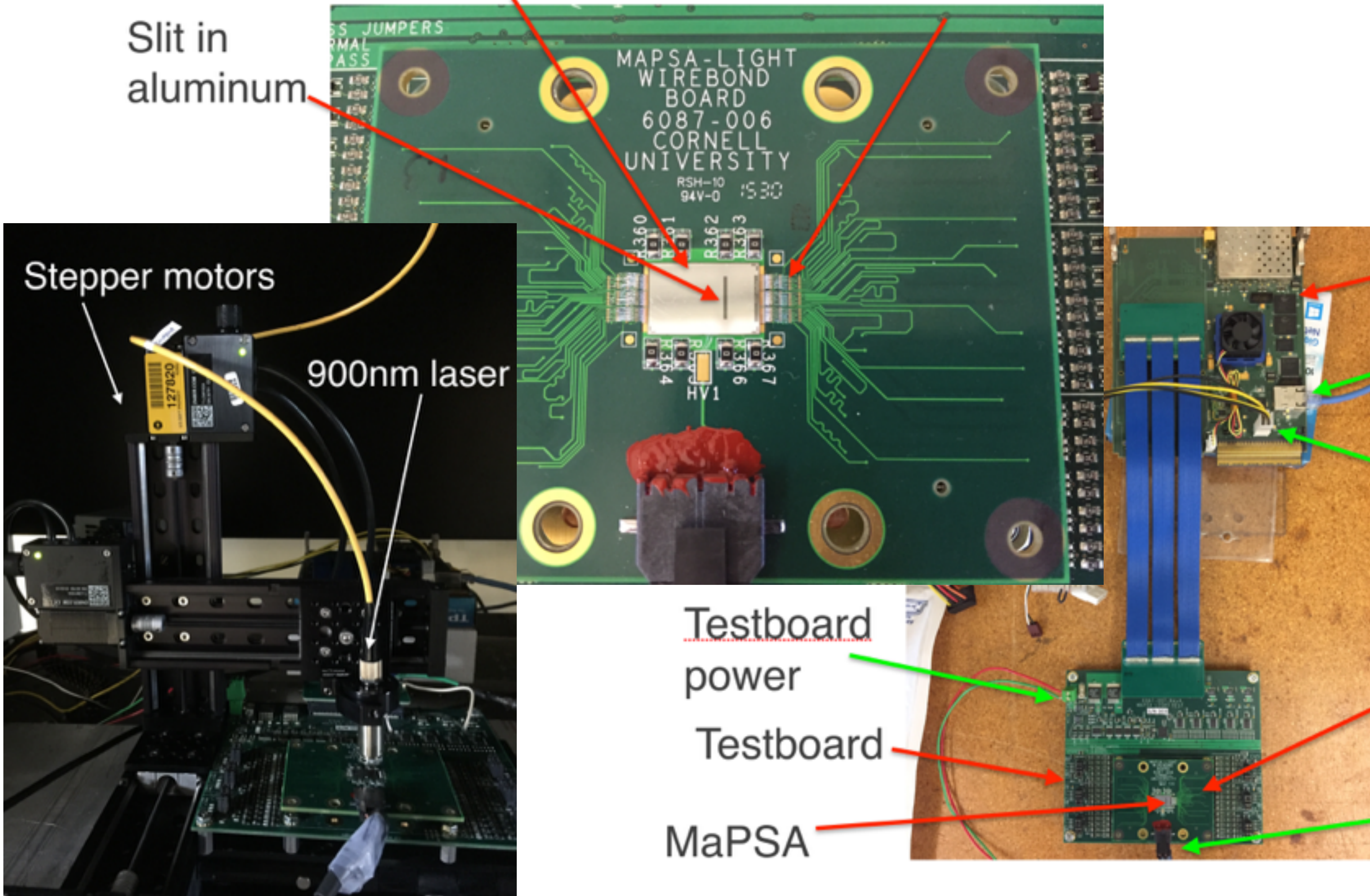

During synchronous readout we receive only two pieces of information: Which pixel was hit, and in which bunch crossing the hit occurred.

# Characterization of the MaPSA

- Efficiency
  - The number of hits observed divided by the number of signals sent
- Peaking time:
  - The duration necessary for a signal to reach its maximum value
- Timewalk:
  - An apparent difference in the arrival of two signals, caused when signals of different amplitudes cross a threshold
  - In the LHC, too large a timewalk would shift low amplitude signals from lower energy particles into a later bunch crossing, making track reconstruction more challenging

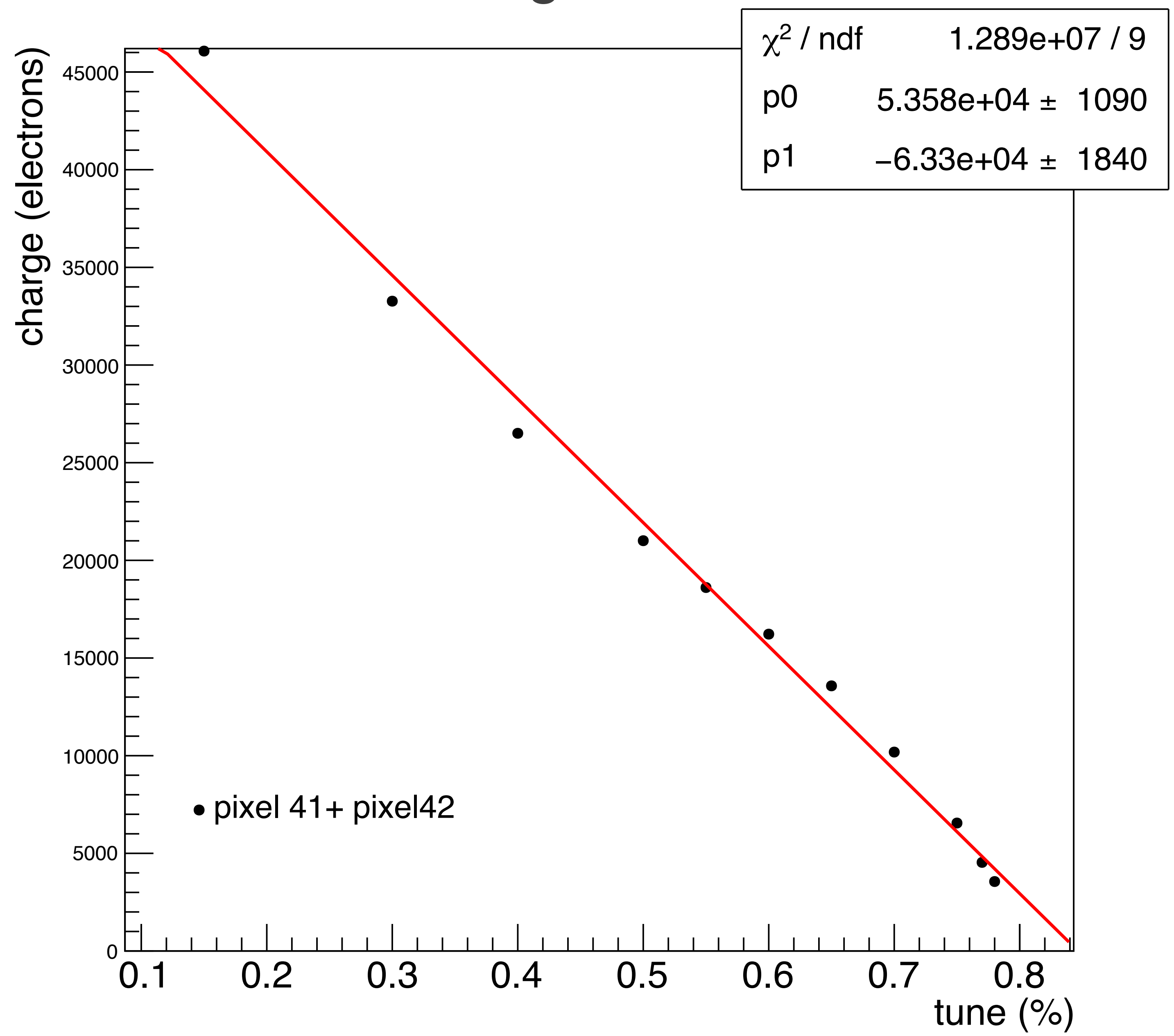


# Experimental Setup



# Laser Calibration

- Using a Phase 2 pixel, our laser was calibrated to provide a signal equivalent to a MIP (20,000 EHPs) in 300μm silicon at a tune of 50%
- At this time, the relation between laser tune and charge was measured for other tunes as well
- A line fit to this data to provides a rough conversion between laser tune and signal charge for our measurements.



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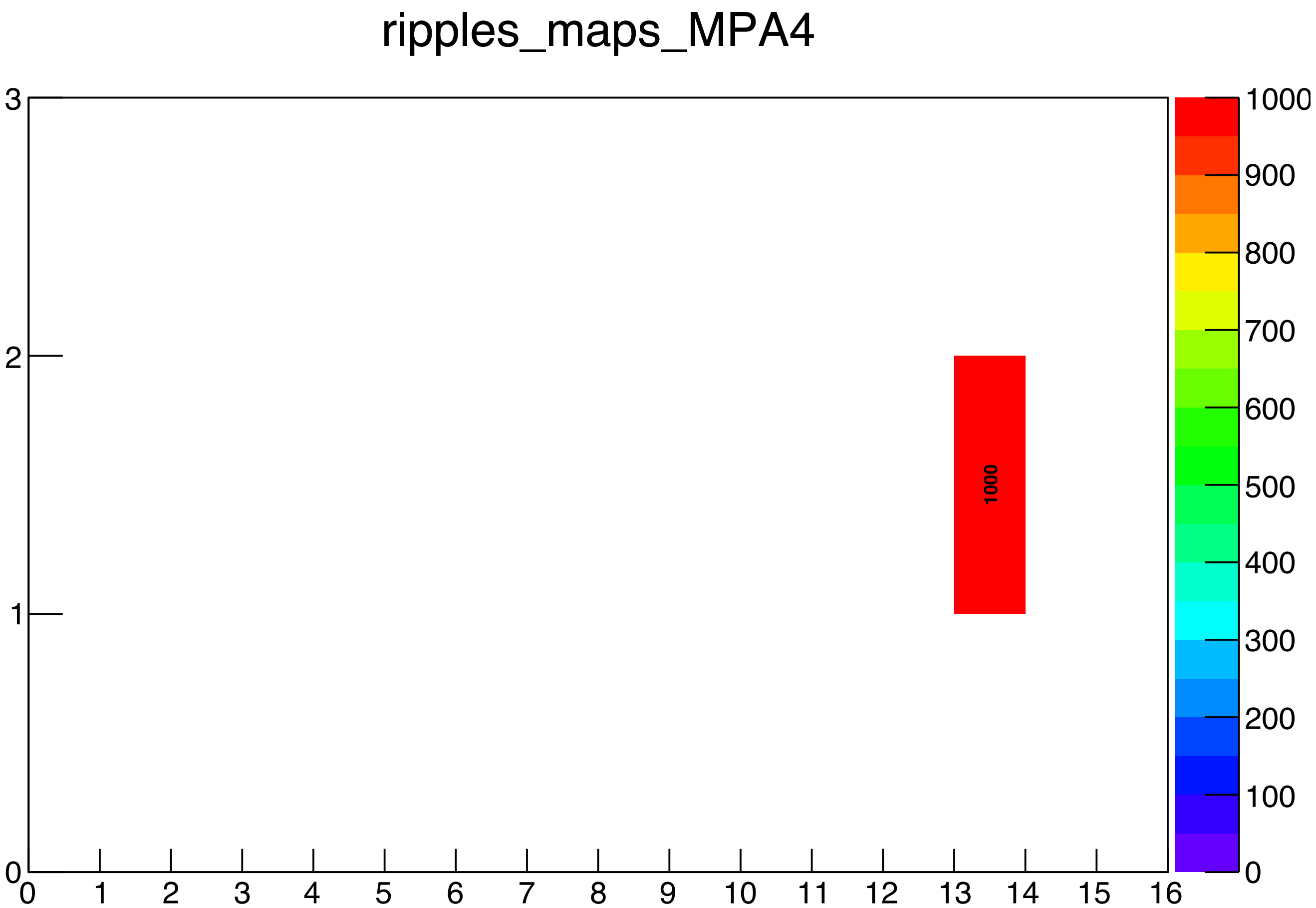
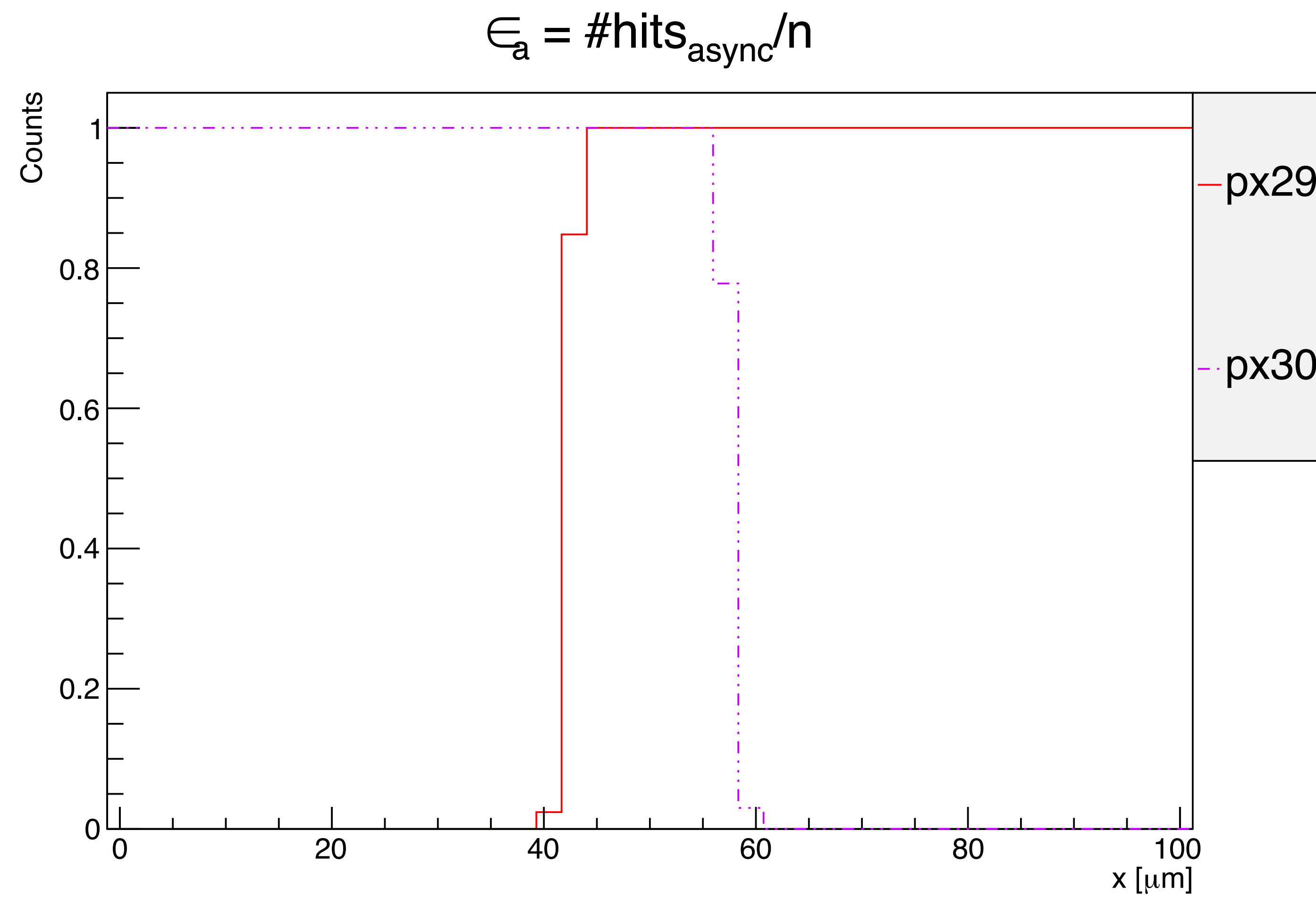
# Efficiency

- The MPA-Light observes pulses corresponding to MIPs with 100% efficiency
  - Even in the region between pixels, where charge is shared, at least one pixel always records 100% of the laser pulses delivered




100% efficiency is observed when the laser shines over a single pixel

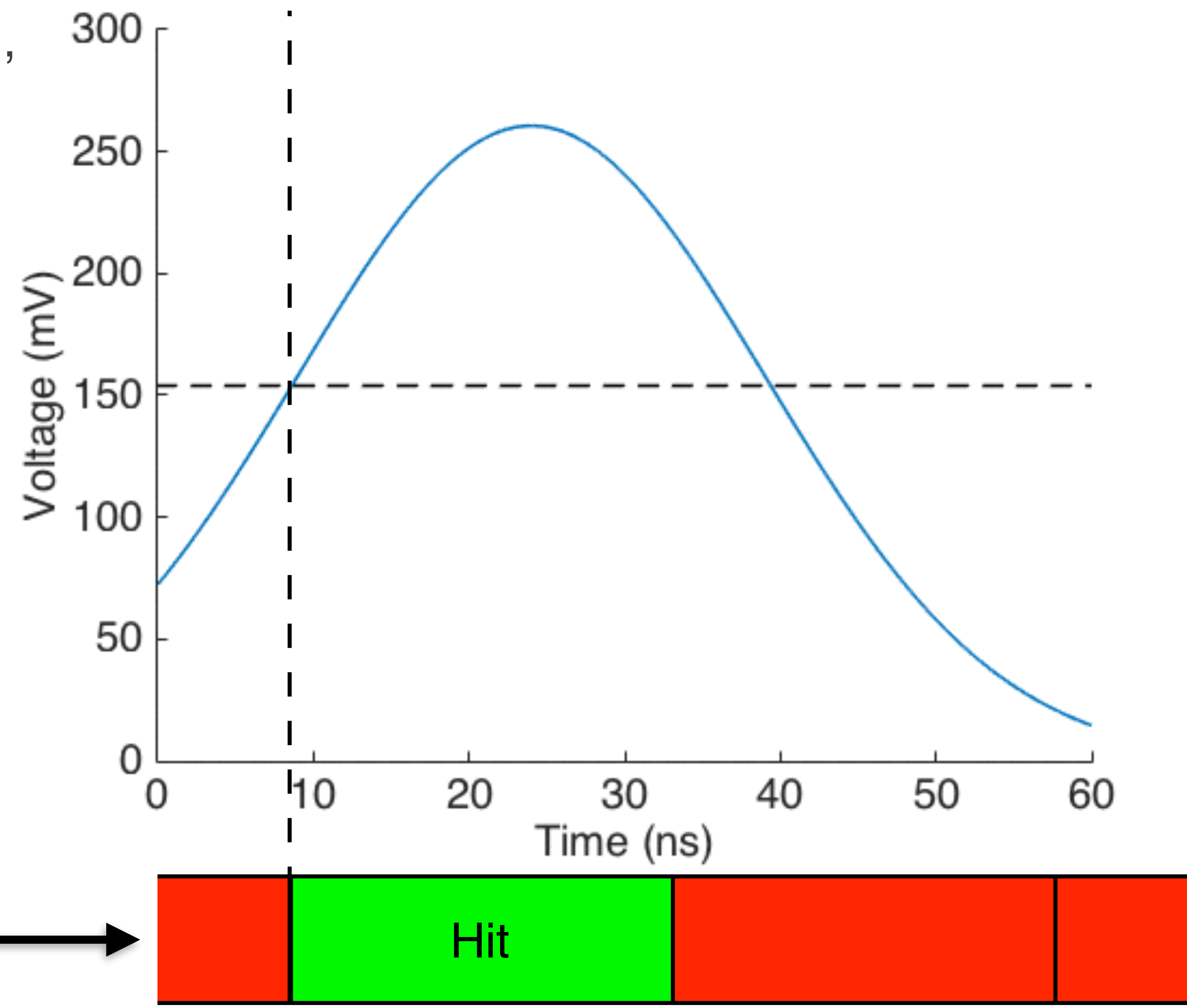



100% efficiency is preserved as we scan across two pixels

# Taking the Measurements

- All measurements rely on a single piece of data and two parameters
  - Bunch crossing: For the purposes of this setup, just the clock cycle during which the signal arrives
  - Threshold: The voltage level which, if crossed by the signal, generates a hit in the MPA-Light
  - Time delay: A delay in the arrival of the laser pulse, produced with the timeout trigger of an oscilloscope

Threshold just above 150mV: Hit arrives in later bunch crossing



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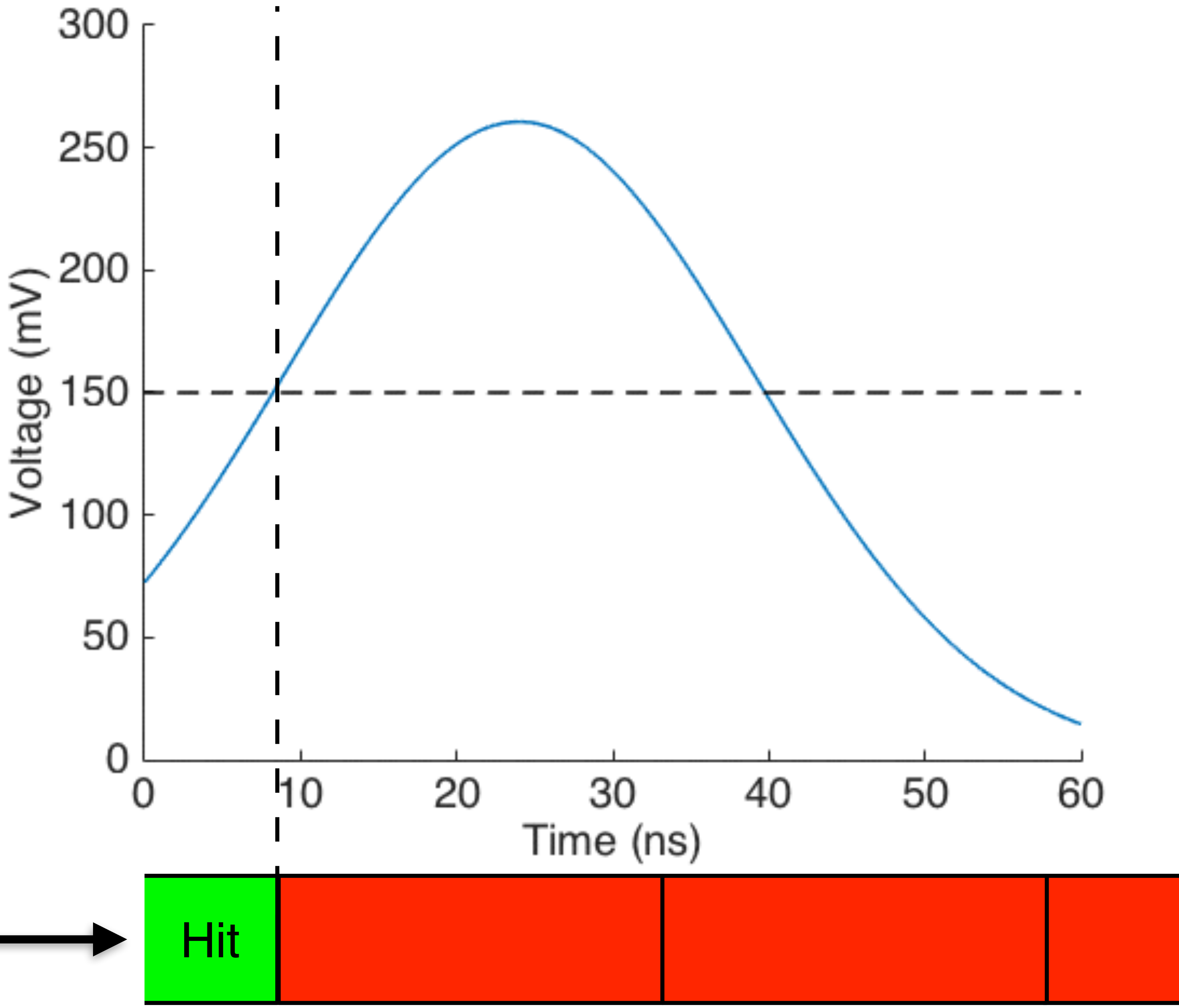
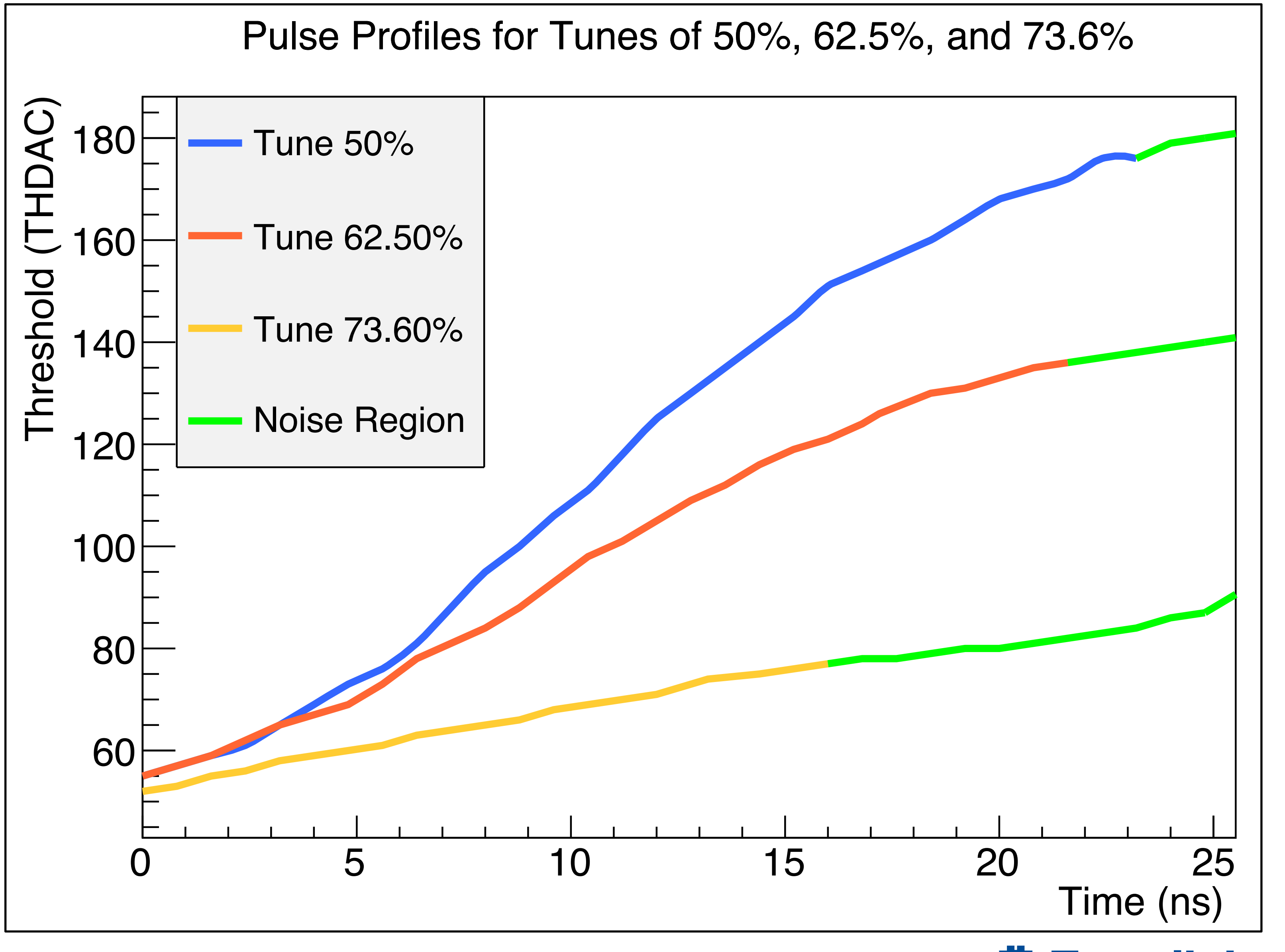



Threshold of 150mV: Hit crosses into earlier bunch crossing –> point localized

# Peaking Time Measurement

- The MPA-Light peaking time specification is 24ns
- Profiled rising edges of 3.51fC, 2.25fC, and 1.12fC signals, starting at the peak and descending until the signal was enveloped in noise
  - The green lines show noise –> less than 100% efficiency in these regions

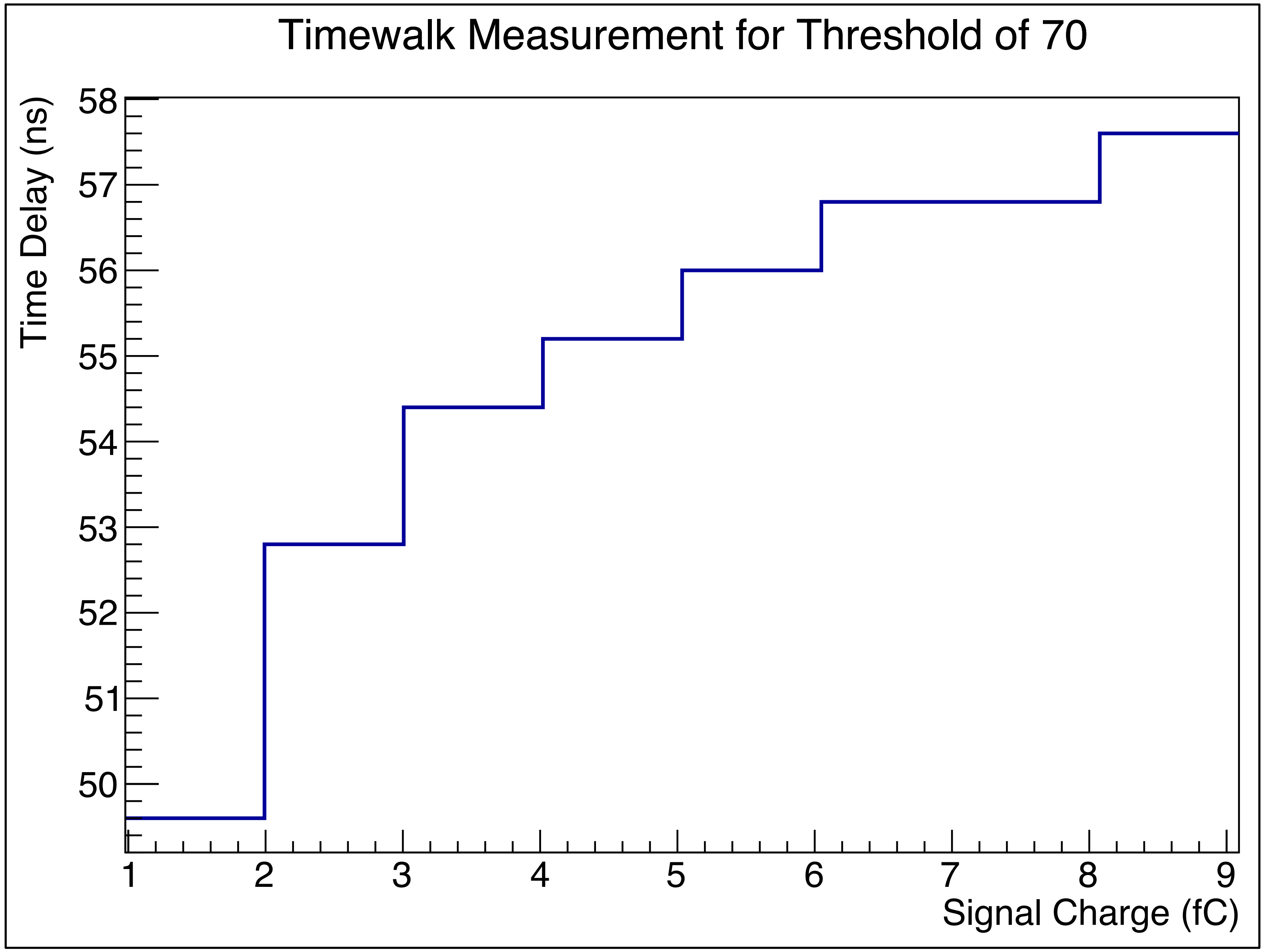
| *Laser Tune* | *Signal Charge* | *Peaking Time* |
|---|---|---|
| *50%* | *~3.5fC* | *~23.2ns* |
| *62.5%* | *~2.3fC* | *~21.6ns* |
| *73.6%* | *~1.1fC* | *~16ns* |




**All three pulses have peaking times <24ns, consistent with specification**

# Time Walk Measurements

- From simulations, the MPA-Light timewalk specification is <14ns (signals between 0.75fC and 12fC with threshold of 0.5fC)
- Developer of MPA-Light shows timewalk of 15±1.6ns using thresholds of 0.5fC and 1fC with signals between 0.5fC and 9fC
  - Maximum achievable signal with our setup is <9fC

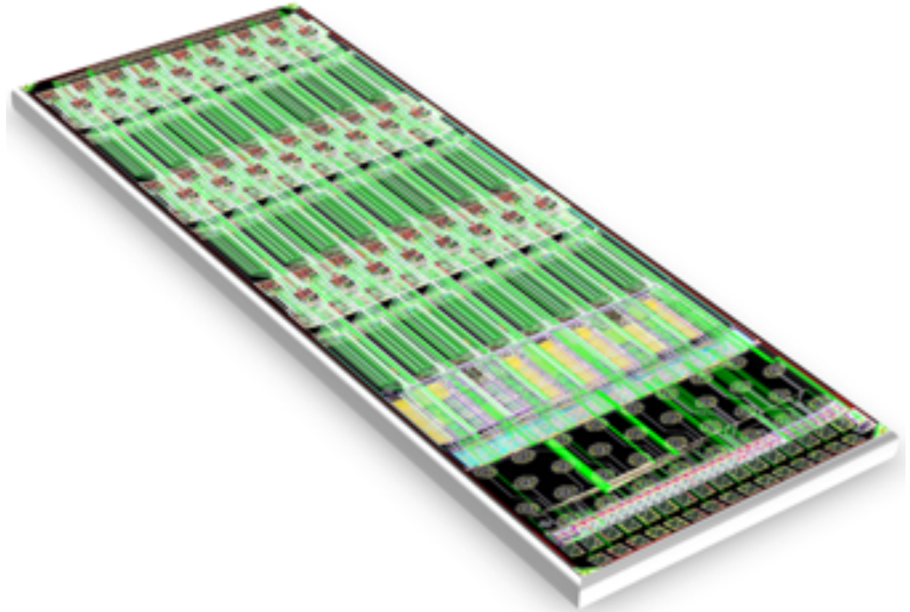



**With a threshold of ~0.9fC and signals between ~1.5fC and ~8.6fC, the timewalk is ~8ns, well within the specification**

# Summary and Conclusions

- The Phase 2 CMS upgrade will improve the tracking detector to handle the luminosity and pileup challenges posed by the HL-LHC
- In addition to being radiation harder, the tracker will include $p_T$ modules, capable of producing input to the L1 trigger
- The MPA-Light, a prototype of PS module electronics, has been tested to determine their readiness for the final modules
  - Peaking Time: For the different signals considered, the peaking time appears to be fairly uniform and consistent with the specification
  - Timewalk: Well within the range of 1 MIP (1.5fC-8.6fC), the timewalk of the MPA-Light is only ~8ns for a threshold of ~0.9fC. This is well within the specification.

**With regard to timewalk and peaking time, the MPA-Light electronics appear ready for implementation in the CMS Phase 2 upgrade**



# Acknowledgements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- To other members of CMS for their assistance and contributions to this project:
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