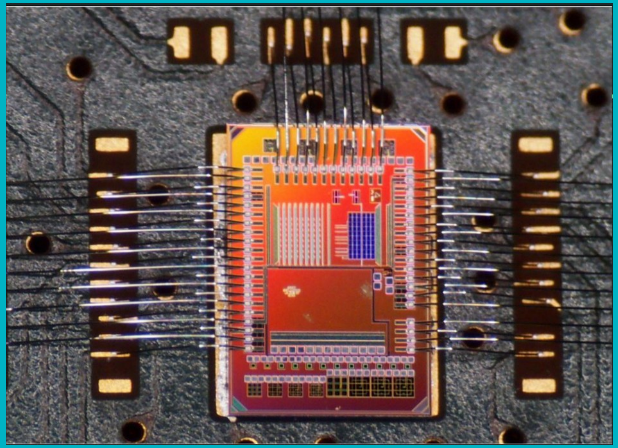
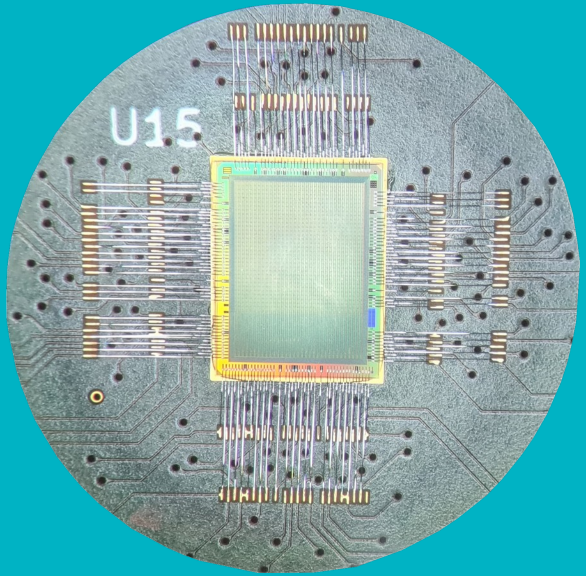
Nikhef





Time is of the essence: Depleted Monolithic Silicon Sensors

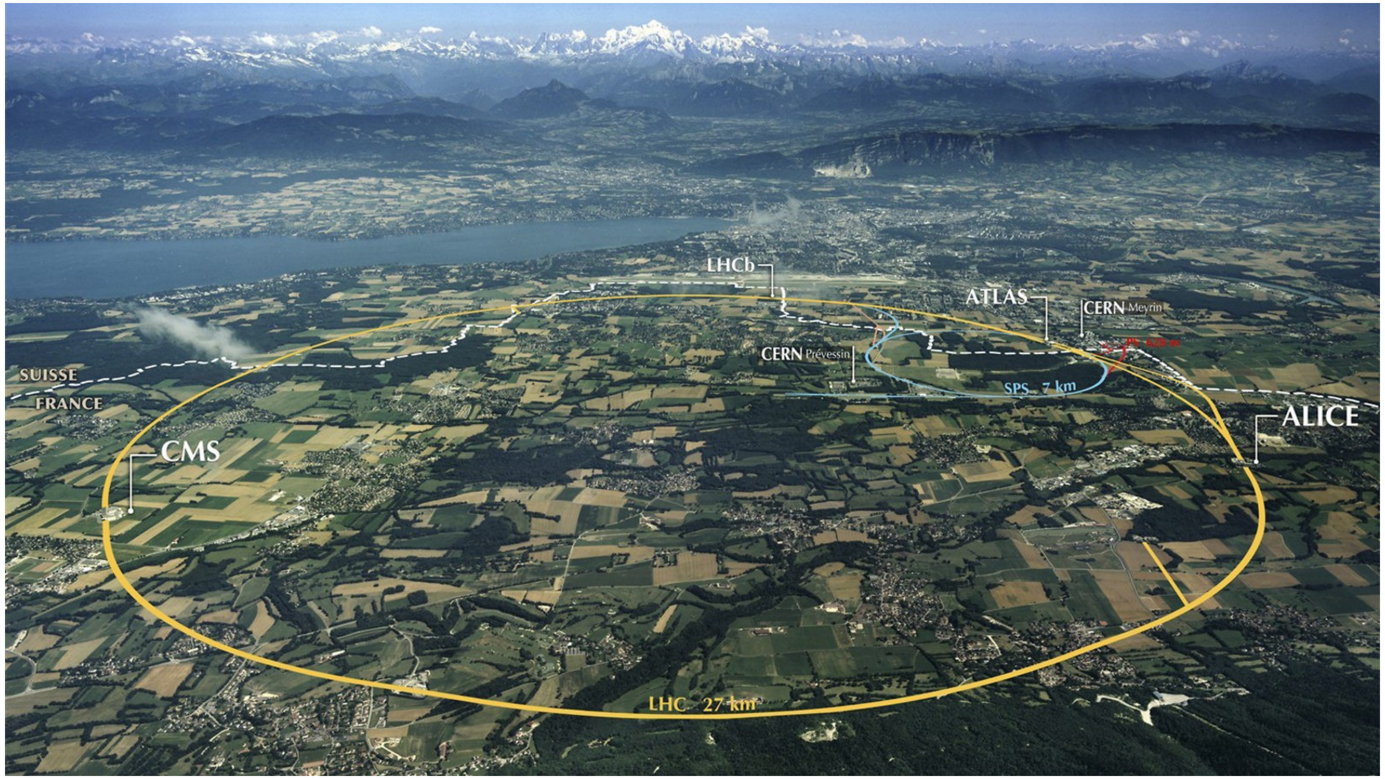
NNV Annual Meeting 2022

Uwe Kraemer

04 Nov. 2022

Particle Colliders

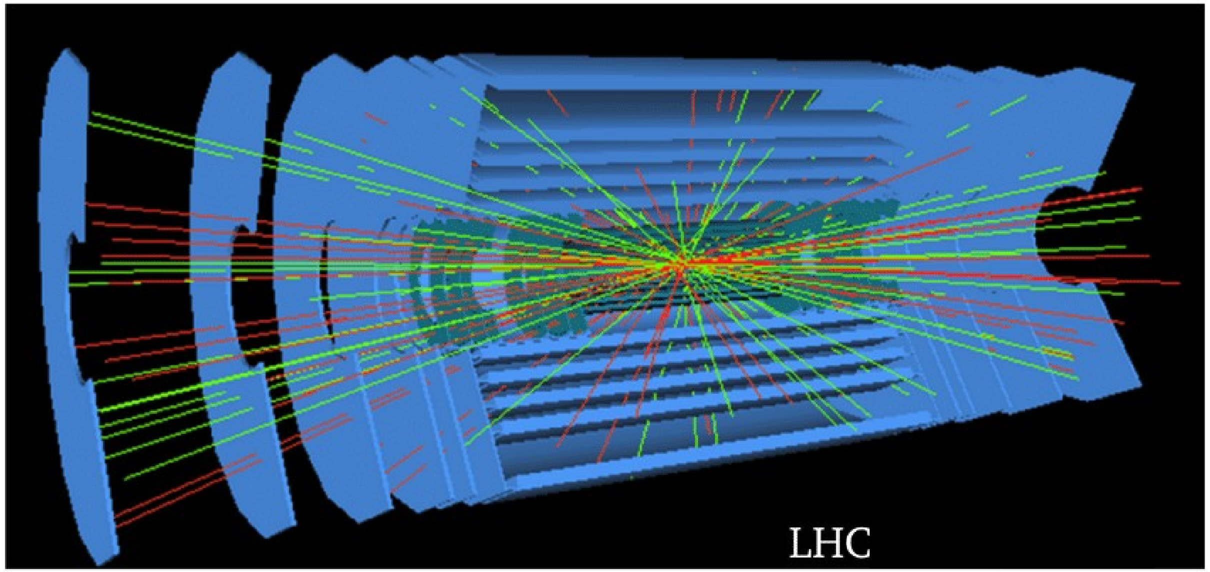
- The most prominent particle collider currently running is the Large Hadron Collider (LHC) at CERN
- An upgrade for the collider to the High Luminosity Large Hadron Collider (HL-LHC) is planned
  - Significant increase in collisions after upgrade
- Proton clouds collide every 25 ns at each of the experiments

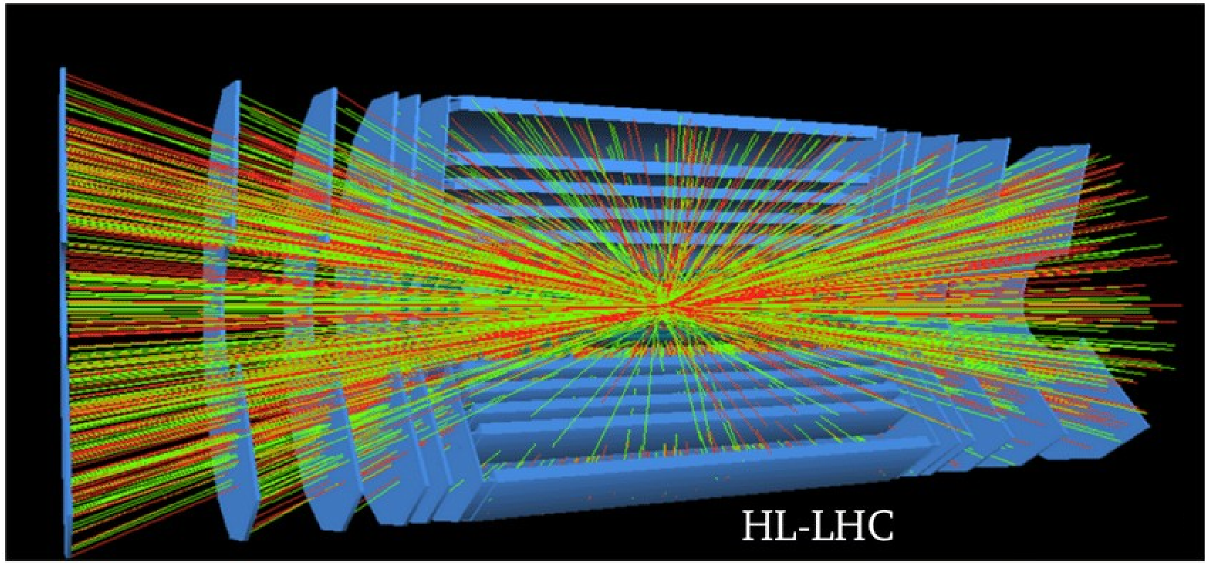


Detector Development in High Energy Particle Physics

- New colliders set new requirements for the detectors
- Detectors were not designed to handle the new scenario and it would not even have been possible at the time
- What worked for the LHC will not be sufficient for the HL-LHC
- What works for HL-LHC will not be enough for whatever the next collider experiment will be

  → Rat race between detectors and colliders





Tracking Detector Development

- Goal: Best possible track resolution
  - Improve spatial resolution

- Lowering material within particle trajectory

Fig.: Aluminium Sheets

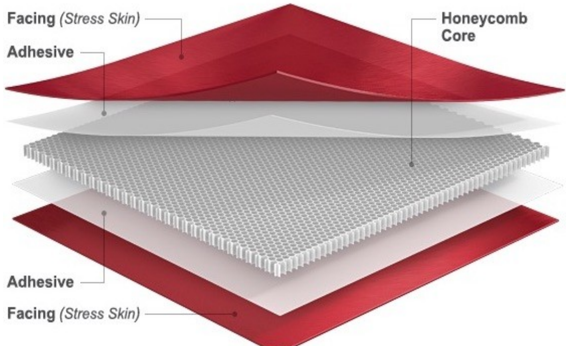


Fig.:Honeycomb material

- Improve time resolution

Fig.:Sundial

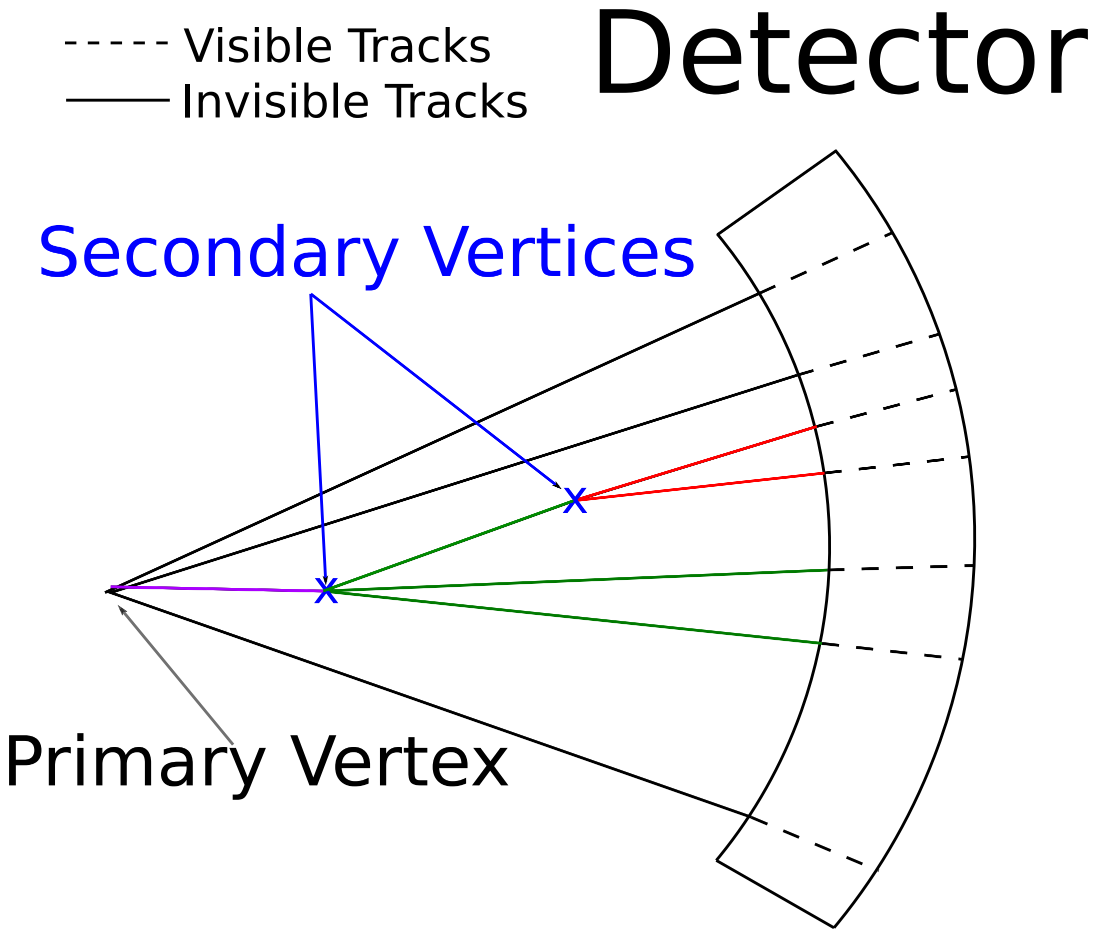
Fig.: Stopwatch

Spatial Resolution

- Search for new particles requires precise knowledge of particles produced in the collision.
- Particle lifetimes < 10^{-15} s

  → Impossible to detect directly
- Can reconstruct particles from decay products.
- Requires precise knowledge of momentum and vertex position

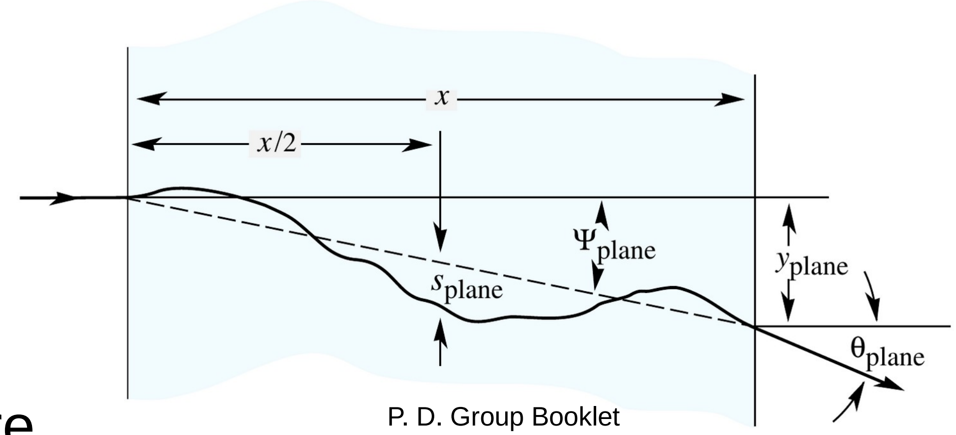
  → Increase pixel density as much as possible



Material Budget

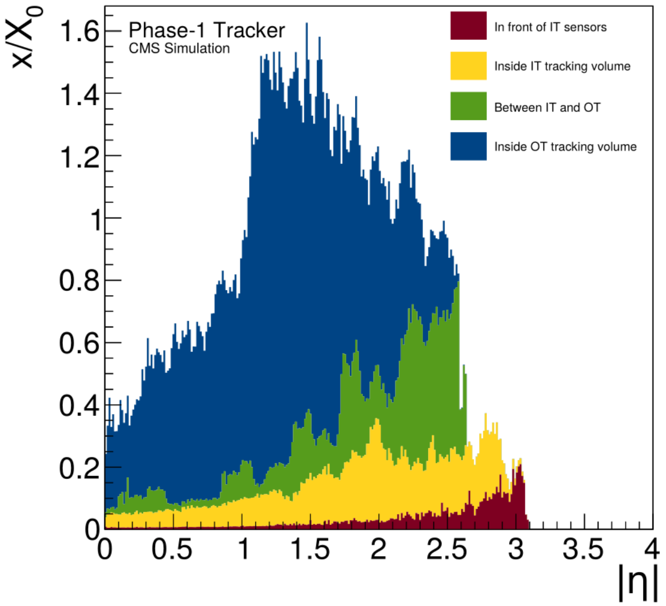
- Material within the particles path induces coulomb scattering
  - Deviates the particle trajectory
  - Worsens track resolution

→ Thinner, lighter sensors and reduce support structure



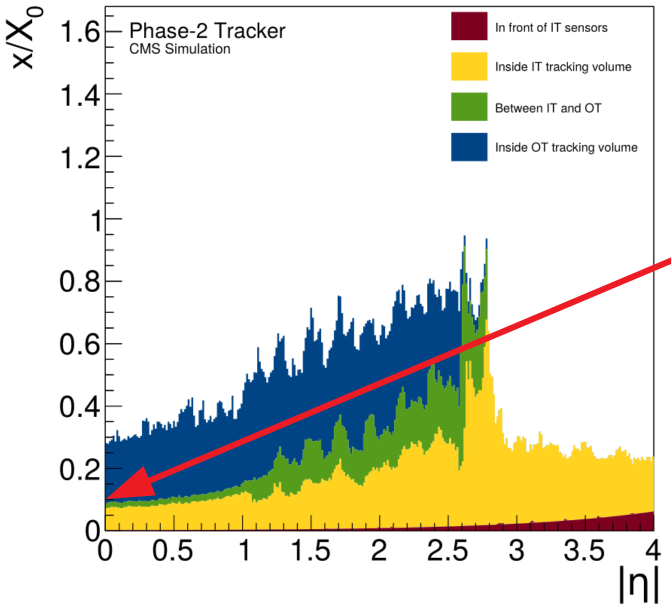
P. D. Group Booklet

Today



https://cds.cern.ch/record/2272264

Near future – Being built



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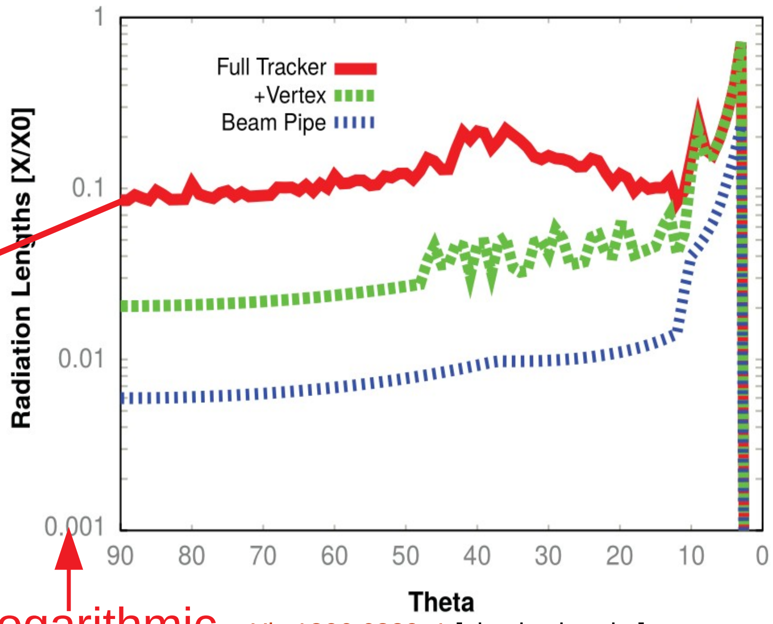
Goal for ultimate precision at e+e-



Logarithmic arXiv:1306.6329v1 [physics.ins-det]

Time Resolution

- Only recently garnered greater attention
- Adding time as another component significantly reduces tracking complexity
  → Faster charge collection
  → Faster digitization and charge sampling

- Allows Time-of-Flight based particle identification at O(10ps) time resolution

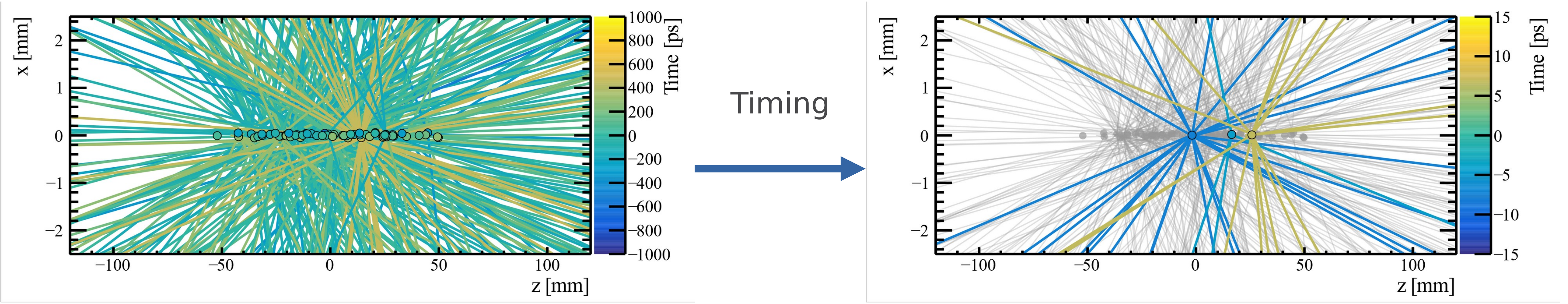


Fig.: Reconstructed primary vertices (left) with 2 ns time resolution (right) with 30 ps time resolution (© LHCb Collaboration)

Silicon Detector Concepts

Hybrid: Silicon Sensor and readout electronics are on dedicated pieces of silicon which are then interconnected

- ✓ Independent development of readout and sensor
- ✓ Well understood
- ✓ Radiation hard to high levels
- ✗ Thick total module O(300-800 um)
- ✗ Interconnection is expensive

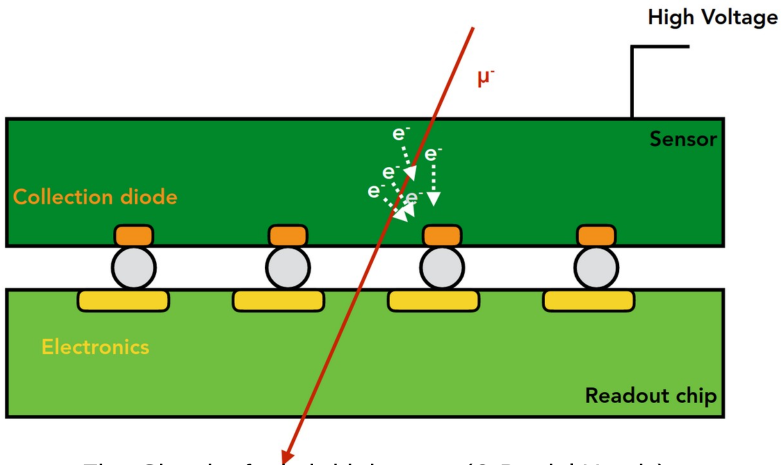


Fig.: Sketch of a hybrid detector (© Daniel Hynds)

Monolithic: Readout electronics embedded in the same silicon as the sensor

- ✗ Fairly new in particle physics
- ✗ Radiation hardness an ongoing research topic
- ✓ Thin(-nable) sensors O(~30 um)
- ✓ No interconnection required

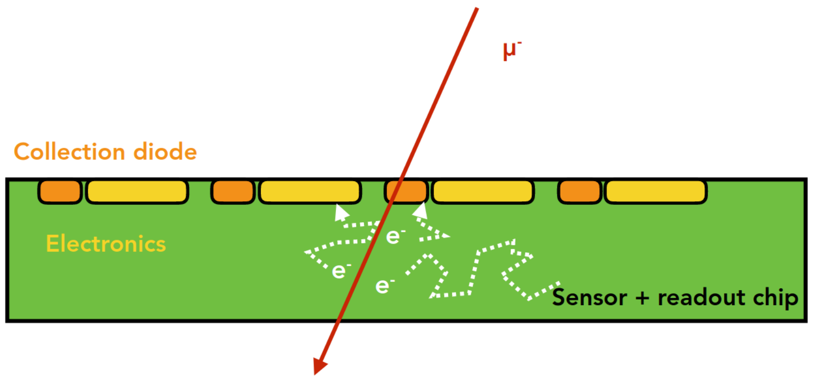


Fig.: Sketch of a monolithic detector (© Daniel Hynds)

(Depleted) Monolithic Active Pixel Sensors

- MAPS: Unshielded sensitive electronics in silicon subtrate
  - No large reverse bias can be applied
    - Mostly low charge zones
    - Slow diffusion based charge readout
      - → Prone to signal loss as a result of radiation damage
      - → Poor time resolution

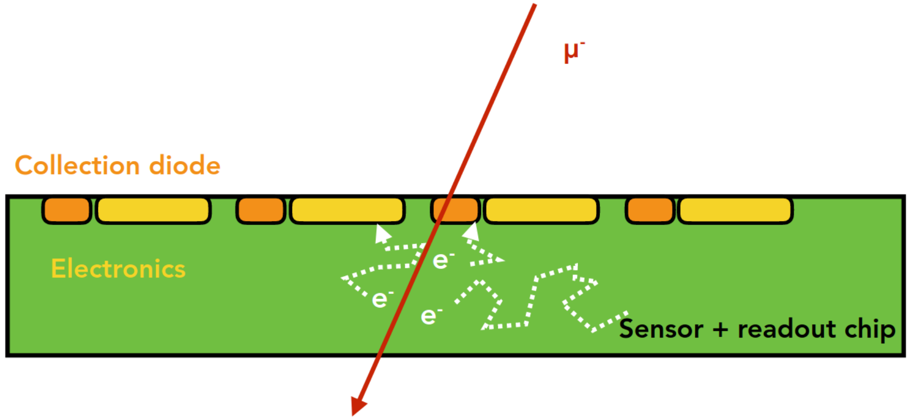


Fig.: Sketch of a MAPS (© Daniel Hynds)

- Depleted MAPS (DMAPS): Embed electronics in a deep N-doped well to shield from high voltage
  - Allows for application of ~O(100 V) reverse bias
    - Mainly high signal zones
    - Faster drift based charge collection
      - → Less sensitive to trapping
      - → Improved time resolution

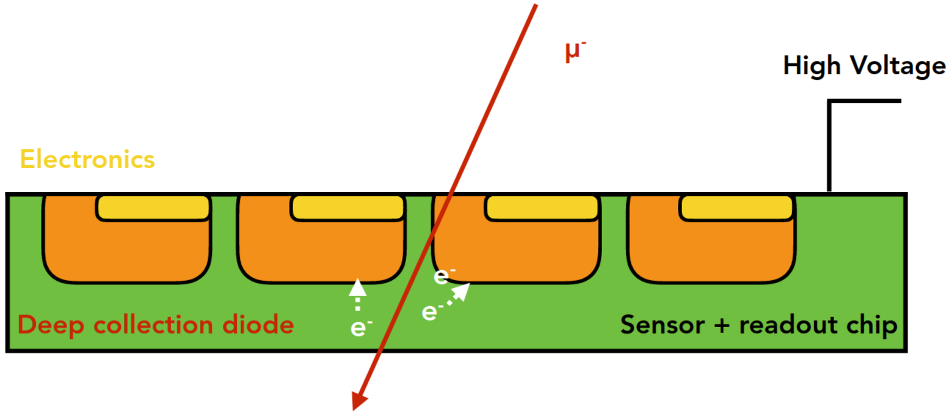
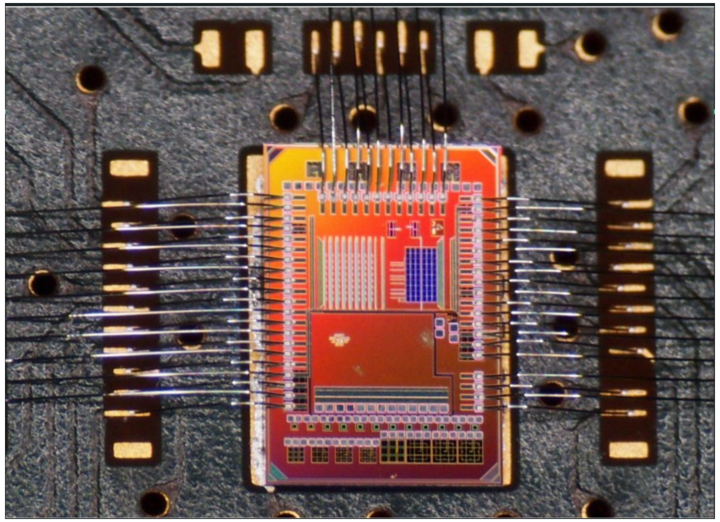


Fig.: Sketch of a DMAPS HV-CMOS (© Daniel Hynds)

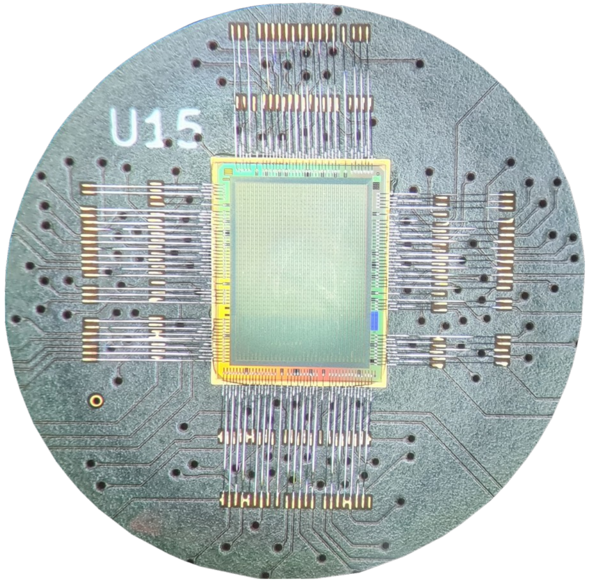
The RD50 DMAPS sensors

- The RD50-CMOS collaboration works on realizing radiation hard DMAPS sensors for future particle physics experiments

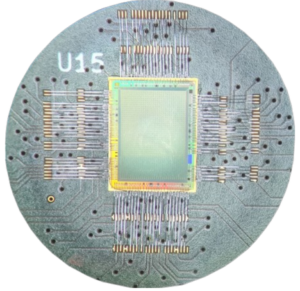
RD50-MPW2:
- 8x8 pixel matrix
- 60 µm pitch
- Only analog circuitry embedded within pixel



RD50-MPW3:
- 64x64 pixel matrix
- 62 µm pitch
- Analog and digital circuitry embedded within pixel



The RD50-MPW3



- Newest chip iteration with full analog and digital circuitry embedded in the pixel
- Received this August
- Manufactured at LFoundry manufacturer, 150 nm feature size
- Recently tested at the CERN SPS test beam facility
- Analysis of data and further tests ongoing

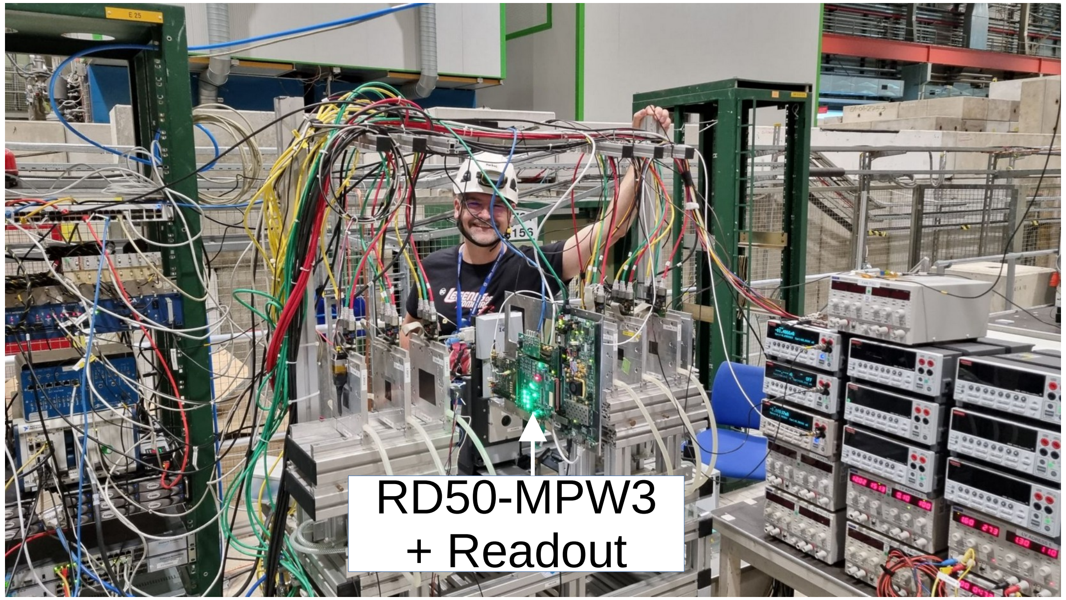


Fig.: Setup at the CERN SPS test beam line

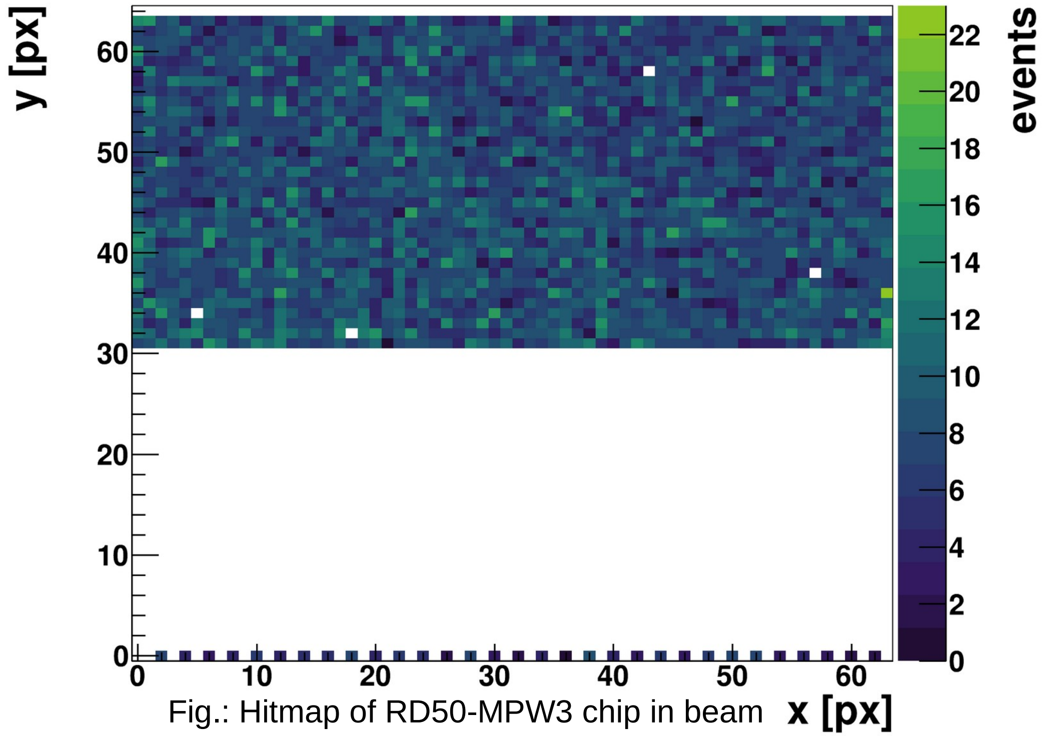
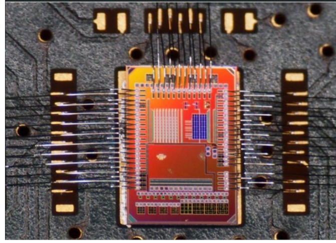


Fig.: Hitmap of RD50-MPW3 chip in beam

The RD50-MPW2



- Previous chip iteration with only analog circuitry embedded within the pixel
- Manufactured by LFoundry, 150 nm feature size
- Shown to work well even after irradiation high radiation doses

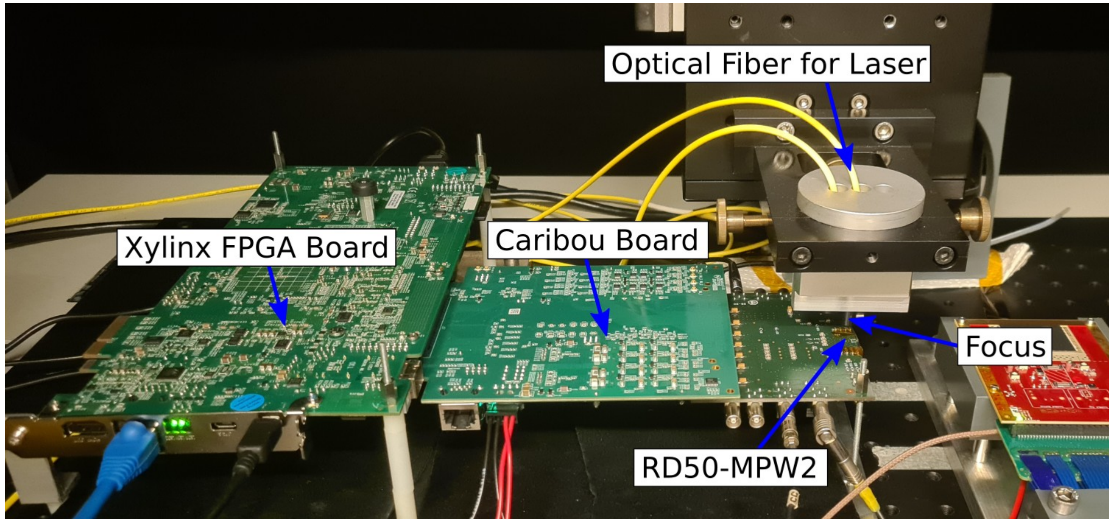


Fig.: Laser test setup at NIKHEF

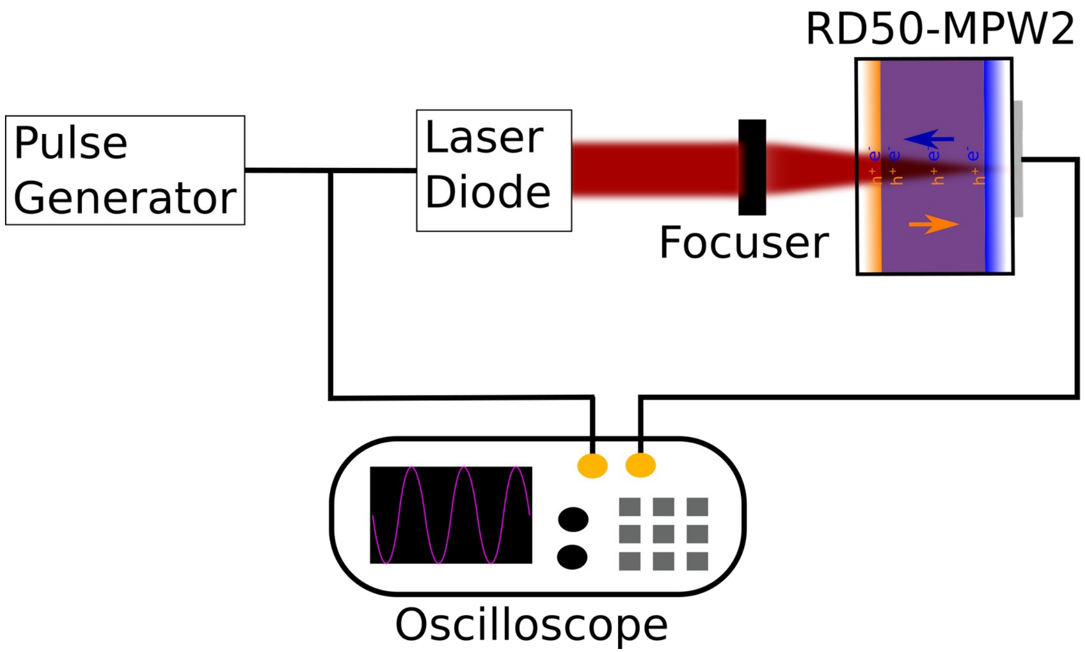


Fig.: Sketch of the laser test setup at NIKHEF

Look at the time

- Measurement of the time resolution requires reference point in time
- Time resolution = Variation of time between input and output Δt over many measurements
  - $\sigma_t = \sigma_{chip} \oplus \sigma_{osci} \oplus \sigma_{pulse} \oplus \sigma_{laser} \approx 424.7$ ps

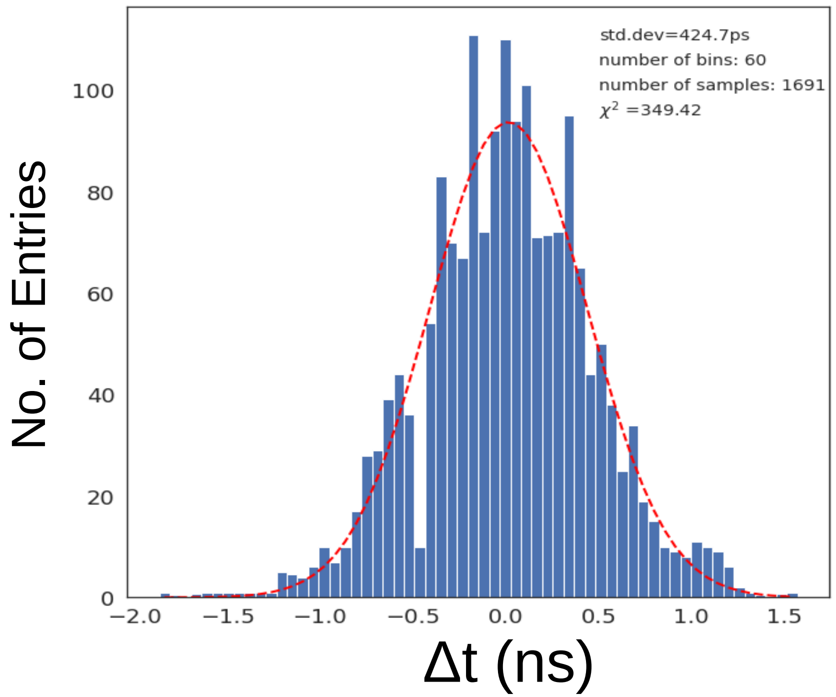


Fig.: Measured time difference

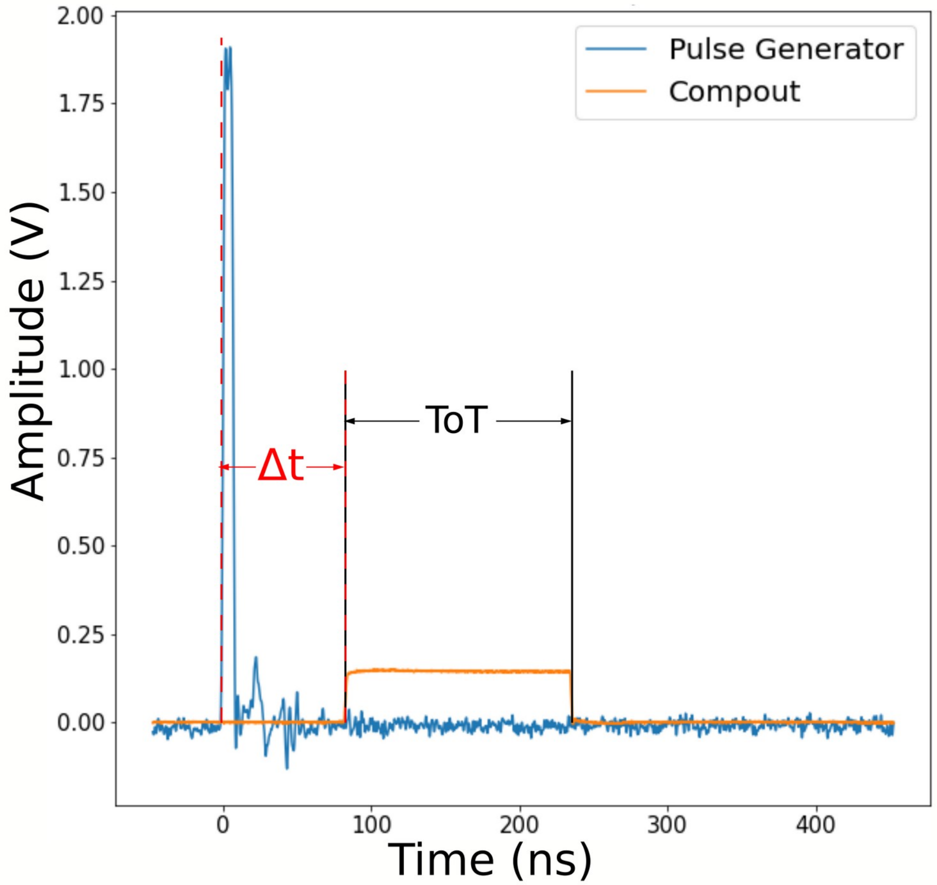
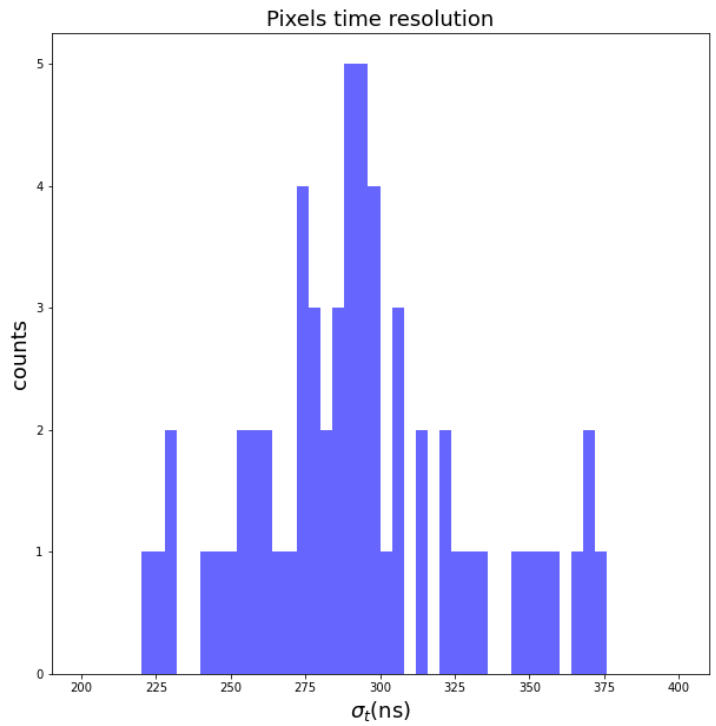


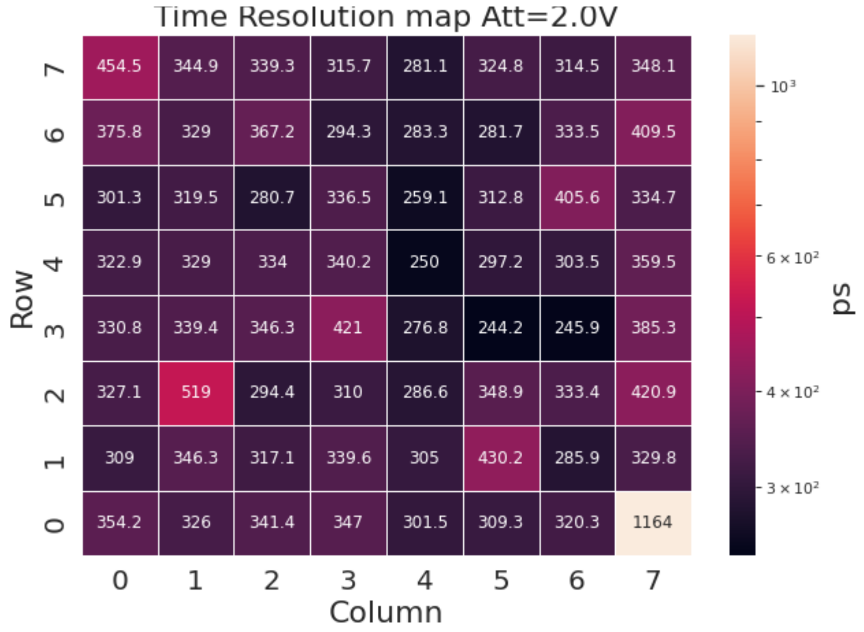
Fig.: Raw output on the oscilloscope

Look at the time

- Overall almost every pixel has a time resolution O(300 ps)
- Still a significant spread of values of 150 ps is present
- Single outliers with significantly worse time resolution are present
- No clear pattern that would indicate any systematic errors with respect to the pixel location

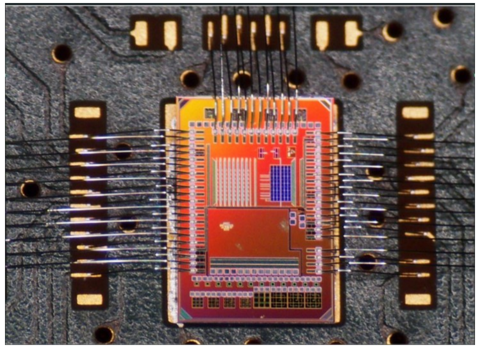
- Needs to be further investigated also with a second chip
- Chip is known not to be optimized for timing



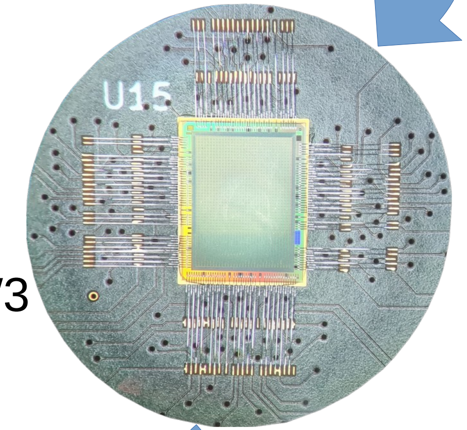


Summary and outlook

- Future experiments set ever more stringent requirements to the detectors
- DMAPS are a promising approach to reach ultimate tracking performance in silicon
- Recently received RD50-MPW3 chip and tested at test beam with analysis ongoing
- Results of the RD50-MPW2 time resolution are promising O(~300 ps)
- Need to try and replicate time resolution with RD50-MPW3
- What would be required of a potential RD50-MPW4?



RD50-MPW2



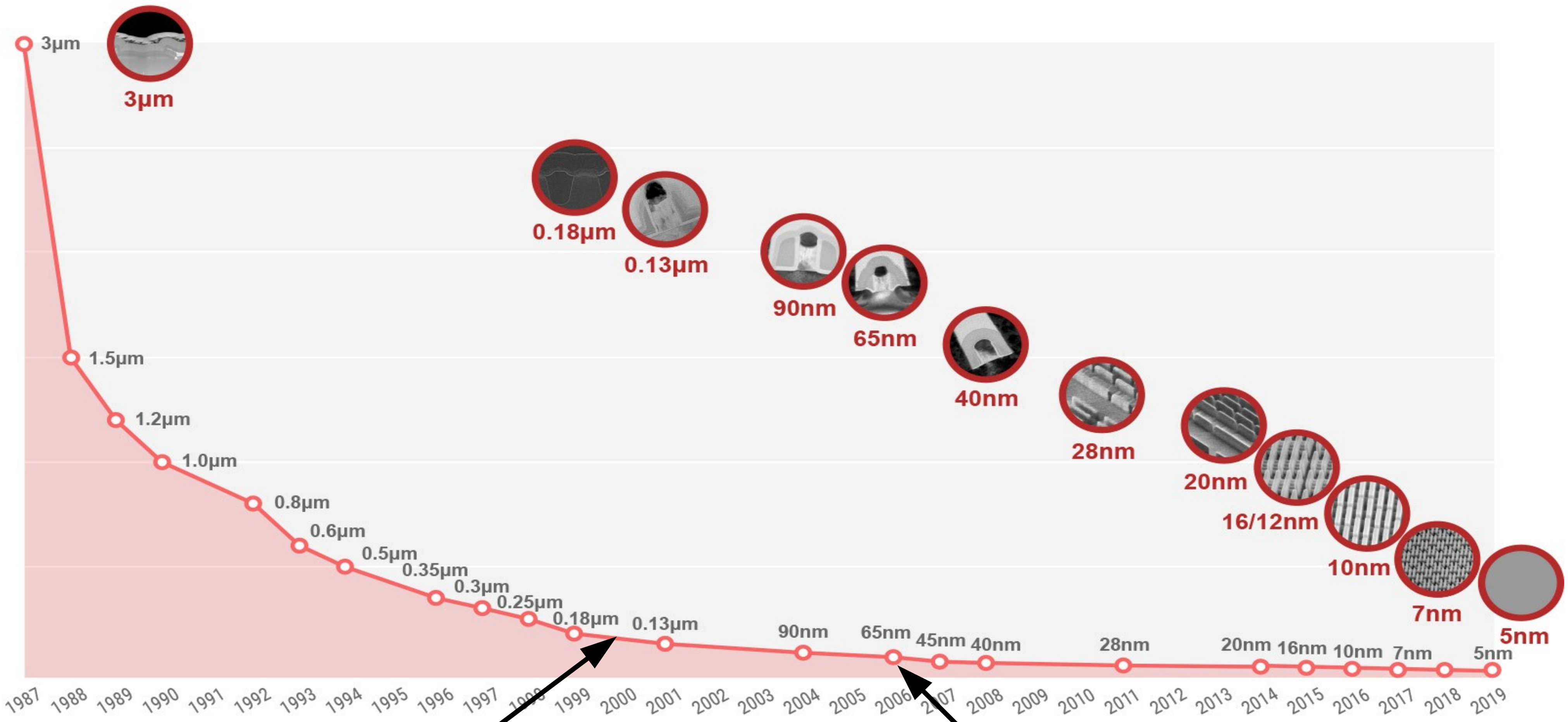
RD50-MPW3

?

RD50-MPW4?

Backup slides

New ASIC Generation



Current Feature Size

Cutting Edge feature size
(in particle physics)

Chip operation

- Laser is pulsed for a couple of nanoseconds to induce a short laser signal
- Signal induces charge within the silicon
- Charge is read out via the electronics embedded in the pixel
- While the charge is above a set threshold a constant output is set to one (Compout)
- The length of this output is proportional to the charge
- This comparator output is the last output of the analog pixel matrix