

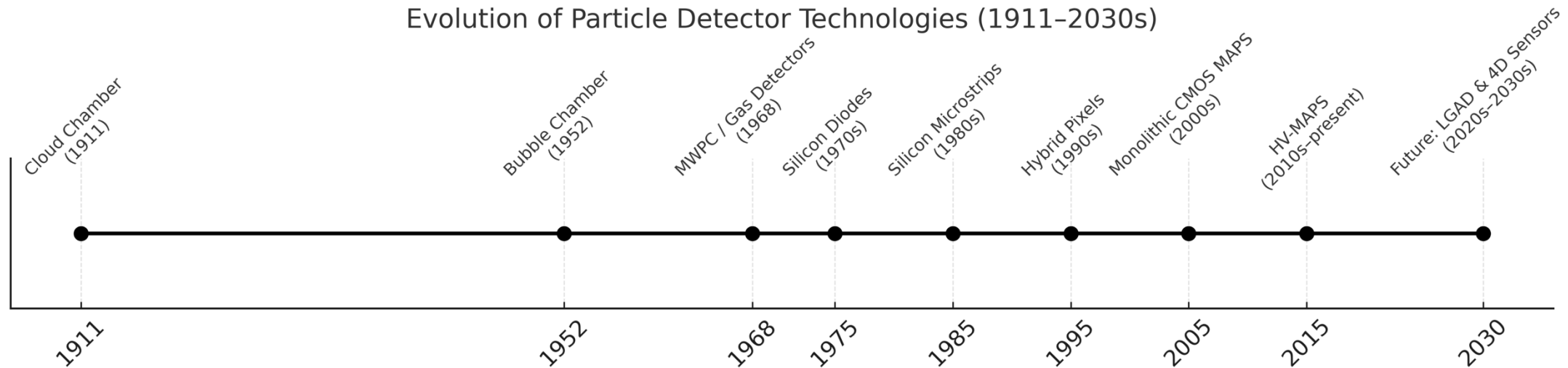
HV-MAPS Pixel Detectors for Particle Tracking and LiDAR: A Dual-Use Silicon R&D

Tianqi Gao

-
- Introduction to High Voltage Monolithic Active Pixel Sensor (HV-MAPS)
 - Our latest results from Mightypix/Telepix2
 - My early venture of HV MAPS application outside of HEP
 - HV-MAPS LiDAR
 - Astrophysics
 - Future pipelines after the Mightypix project is done and dusted

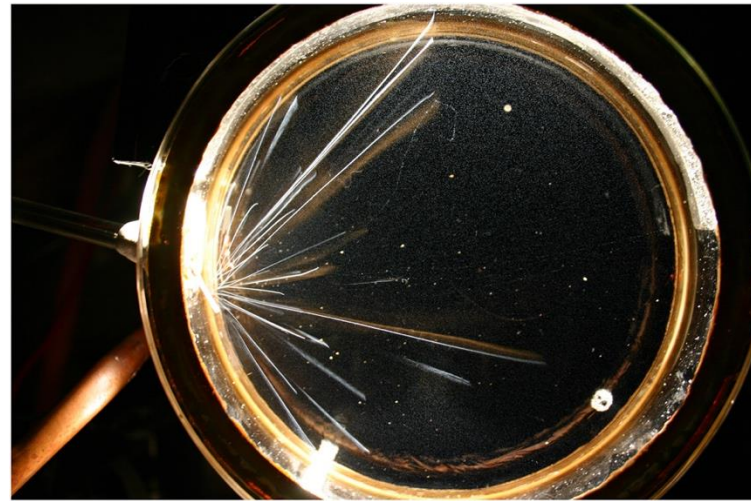
Section 1 - From Cloud Chambers to HV-MAPS

- Particle physics pushed from “see a single track” to “reconstruct 10^9 tracks per second” as accelerators got brighter and higher rate. This forced:
 - higher granularity,
 - faster readout,
 - better radiation tolerance.
- Early detectors were visual and offline (photographic); modern detectors are fully electronic, self-triggered, and radiation hard.
- All modern silicon tracking now aims for $\sim 10\text{ }\mu\text{m}$ spatial resolution with ns-scale timing in high-rate environments such as the HL-LHC.



Cloud Chamber (Wilson 1911)

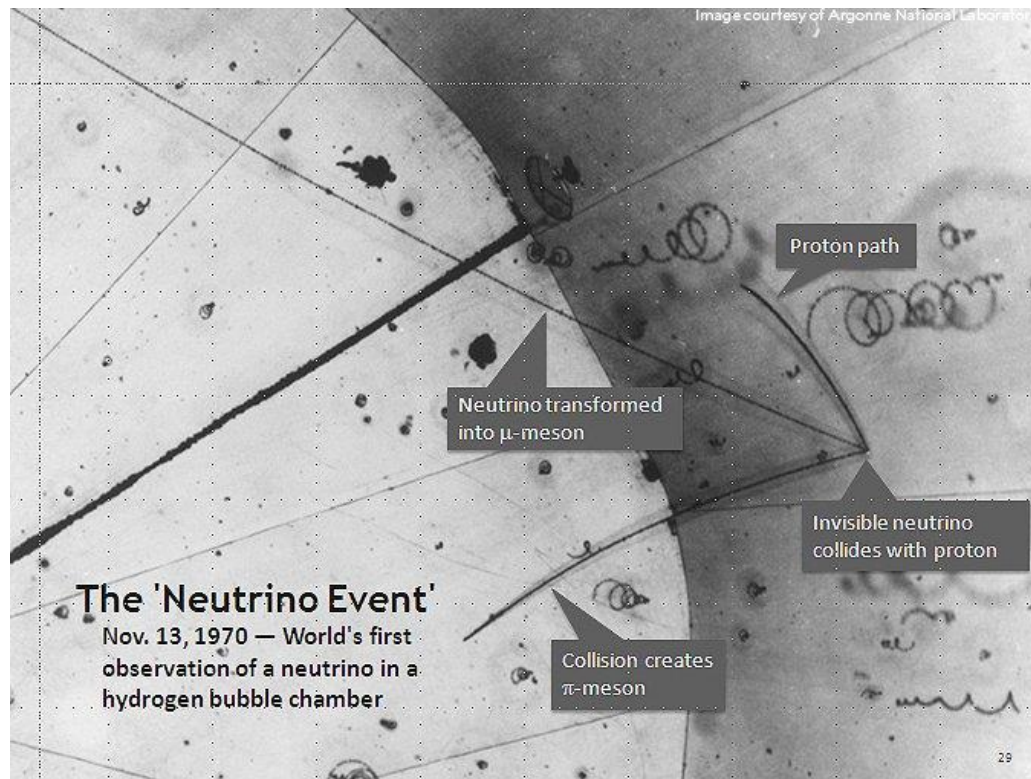
- Supersaturated vapour condenses along ionisation trails, making charged particle tracks directly visible as white lines.
- Used to observe and photograph cosmic rays and led to discoveries like the positron. (This is well documented historically in Cavendish and early cosmic-ray studies.)
- Purely passive and low-rate: every “event” is a single picture, not continuous data.



Tracks of beta particles from radium-226 obtained with a full-scale replica of Wilson's cloud chamber. Courtesy Wolfgang Engels.

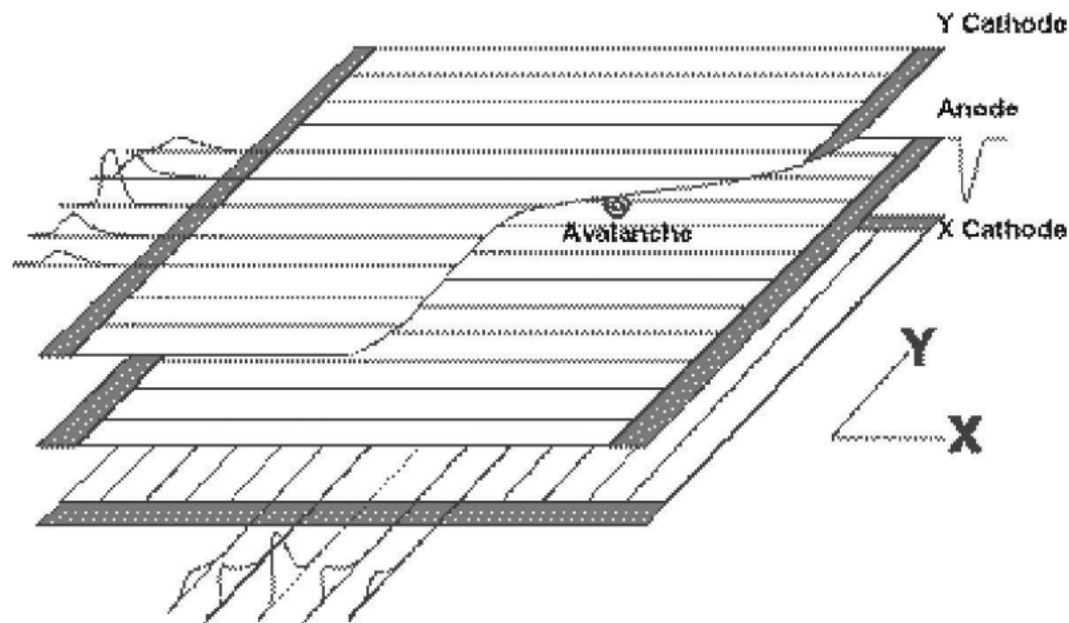
Bubble Chamber (Glaser 1952)

- Superheated liquid (often liquid hydrogen) forms strings of bubbles along charged tracks.
- Produced millions of high-quality bubble photographs and enabled resonance discoveries in the 1950s–1970s.
- Still photographic, not electronic: analysis required scanning film, not real-time trigger logic.



Gas Detectors and the Multiwire Proportional Chamber (Charpak 1968)

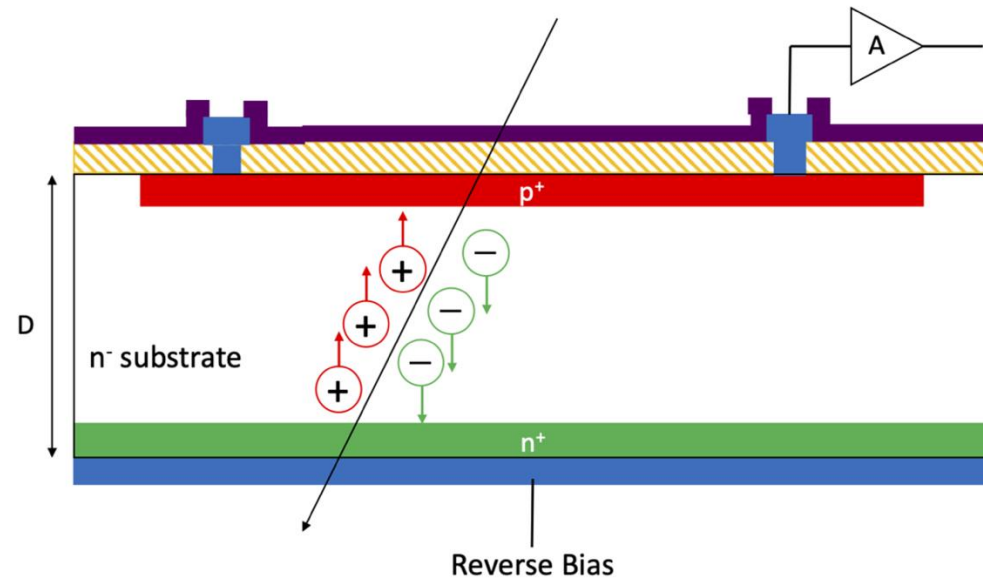
- Ionisation in gas is collected on many fine anode wires; signals are electronic, not photographic.
- The multiwire proportional chamber (MWPC) could localise hits in space, run at high rate, and be read out automatically.
- This step (Charpak, Nobel 1992) is widely viewed as the transition from photographic detectors to fully electronic tracking.



A 2D MWPC with segmented cathode planes. Signals induced on the two cathode planes are used to reconstruct the X-Y coordinates of the incident particle. S. Stapnes, Instrumentation for high-energy physics, (2006)

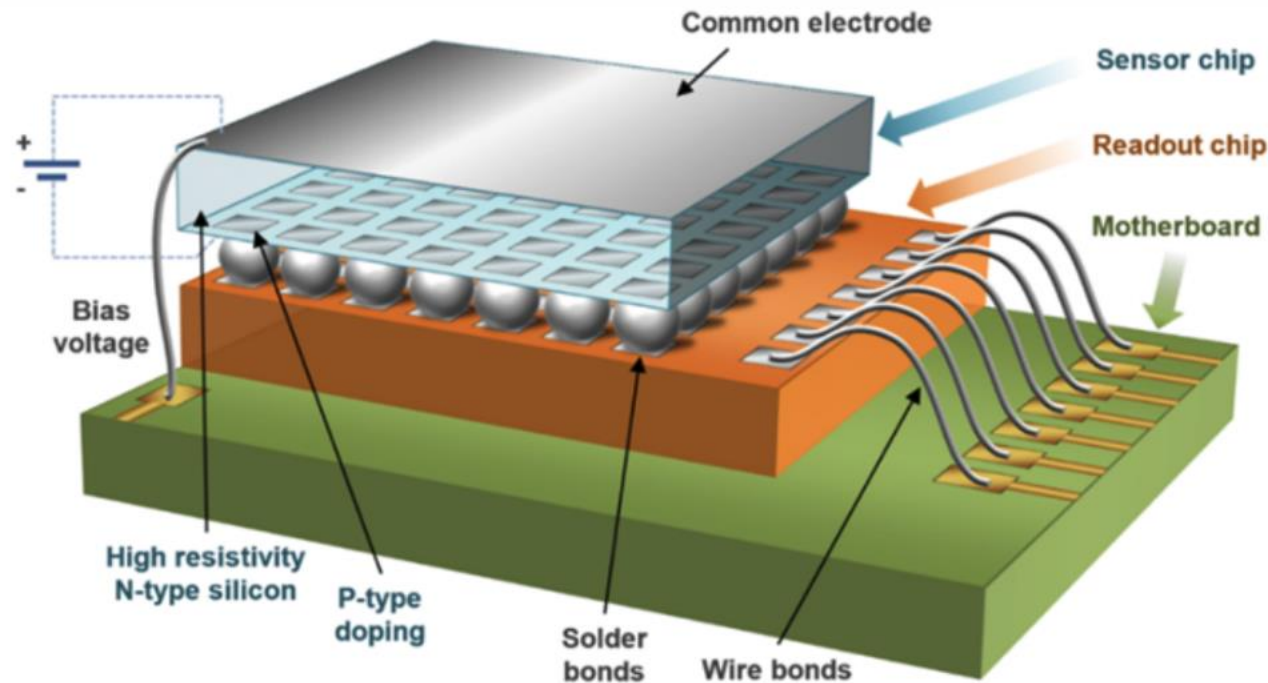
From Gas to Solid-State Silicon

- Silicon p–n junction detectors introduced in the 1970s gave much better spatial precision than gaseous trackers, and could be built very thin.
- Solid-state sensors enabled the first true precision vertex detectors at colliders by placing silicon very close to the interaction point.
- Silicon strip and pixel sensors became standard at LEP, Tevatron, and later the LHC.

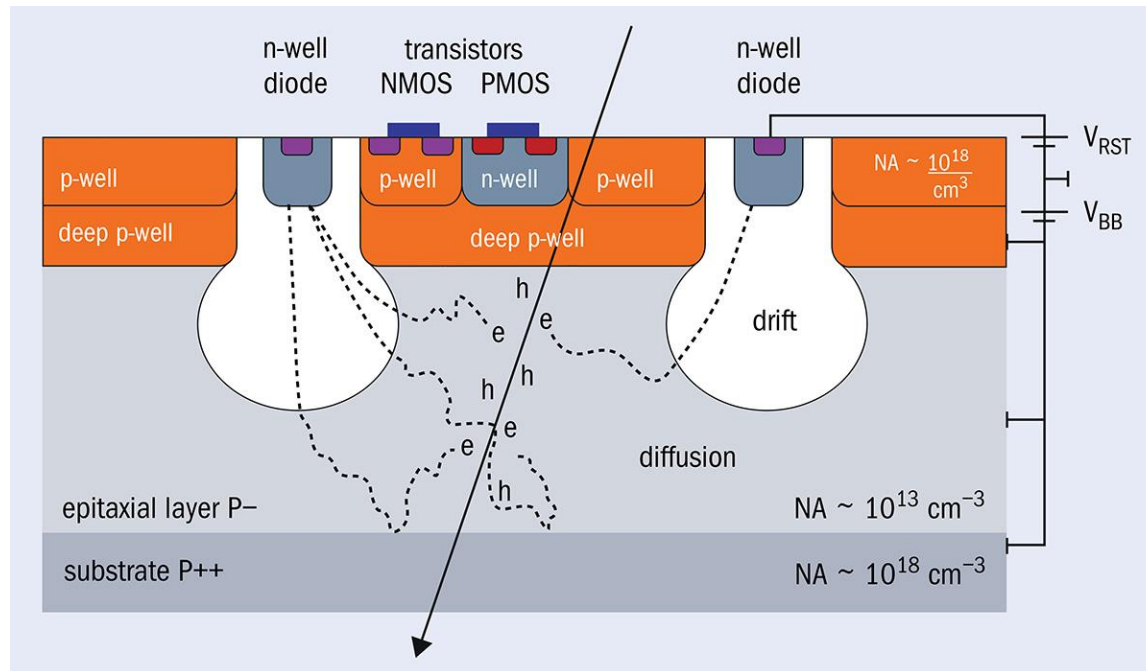


Silicon Microstrips → Hybrid Pixels

- Microstrip detectors give 1D position per layer; multiple layers reconstruct full 3D tracks with $\sim 10\text{--}30\text{ }\mu\text{m}$ precision at hadron colliders.
- Hybrid pixels bond a separate sensor to a separate readout ASIC via bump bonds. This is used in ATLAS/CMS and allowed operation in extremely harsh radiation at the LHC.
- Drawbacks: thick material from sensor+ASIC+bumps+cooling; expensive fine-pitch bump bonding at scale.

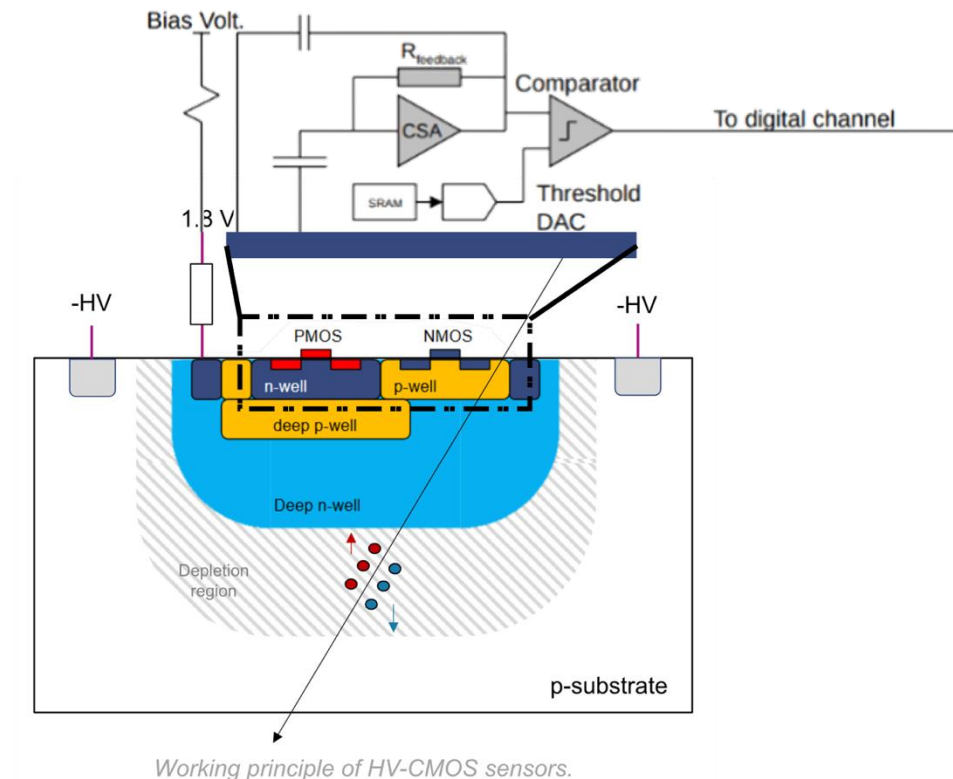


Monolithic CMOS MAPS



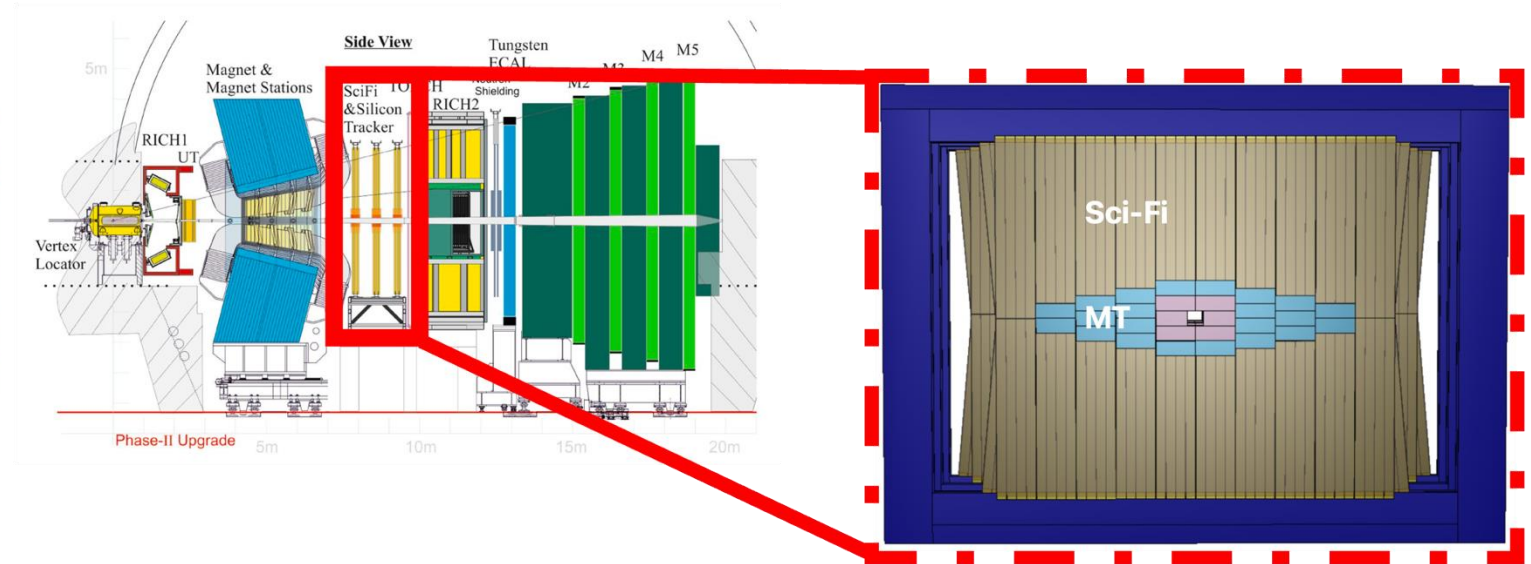
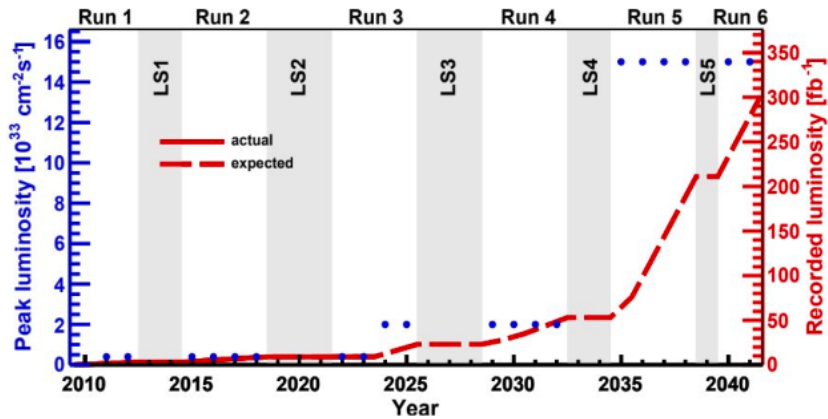
High-Voltage MAPS (HV-MAPS)

- HV-MAPS combine a depleted sensor with in-pixel amplification, discriminator, timing, and digital logic in a single CMOS die.
- HV-MAPS are a “depleted” variant of MAPS built in high-voltage CMOS: you bias the deep n-well at tens of volts so the sensitive volume is depleted, giving fast drift collection.
- Sensors can be thinned to $\sim 50\text{ }\mu\text{m}$, reaching per-layer material budgets down to around 0.1% X_0 , which is crucial for low-momentum tracking (Mu3e).



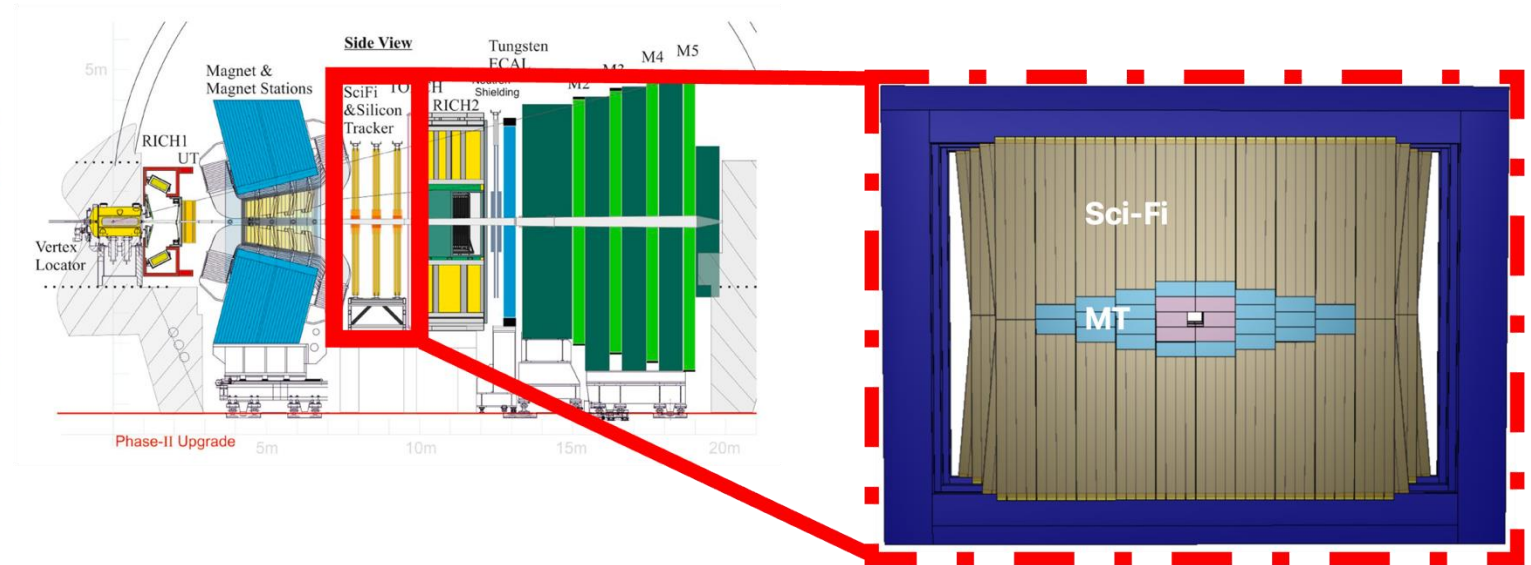
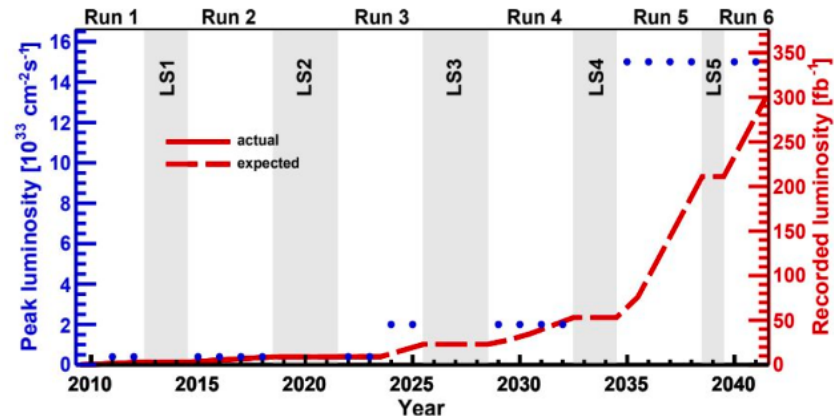
Section 2 - LHCb Upgrade II and MightyPix Motivation

- LHCb after LS4 aims for instantaneous luminosity around $1.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ ($\approx$ ten times higher than today), with corresponding high occupancies and radiation.
- The downstream tracking system (“Mighty Tracker”) will replace scintillating fibres in the central region with HV-MAPS pixel planes to survive that environment.
- MightyPix is the custom HV-MAPS line being developed to meet these conditions.



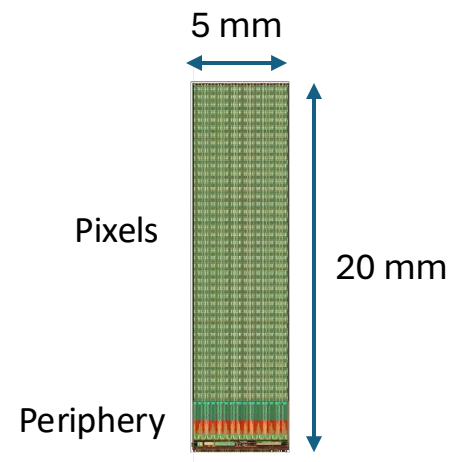
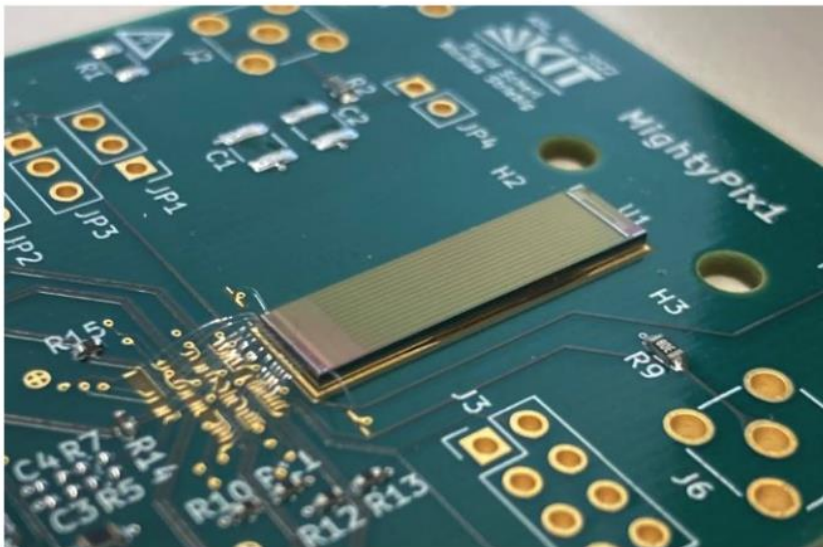
HV-MAPS in HEP: The LHCb MightyPix Project

- They can be thinned to $\sim 50\ \mu\text{m}$, reducing material to the order of (0.1 % X_0 per layer), which keeps multiple scattering under control in low-momentum tracking.
- They support continuous, triggerless readout at high hit rates - exactly what LHCb wants at high luminosity.
- Per-hit timestamps and ToT are used to correct timewalk and achieve $\leq 3\ \text{ns}$ timing.

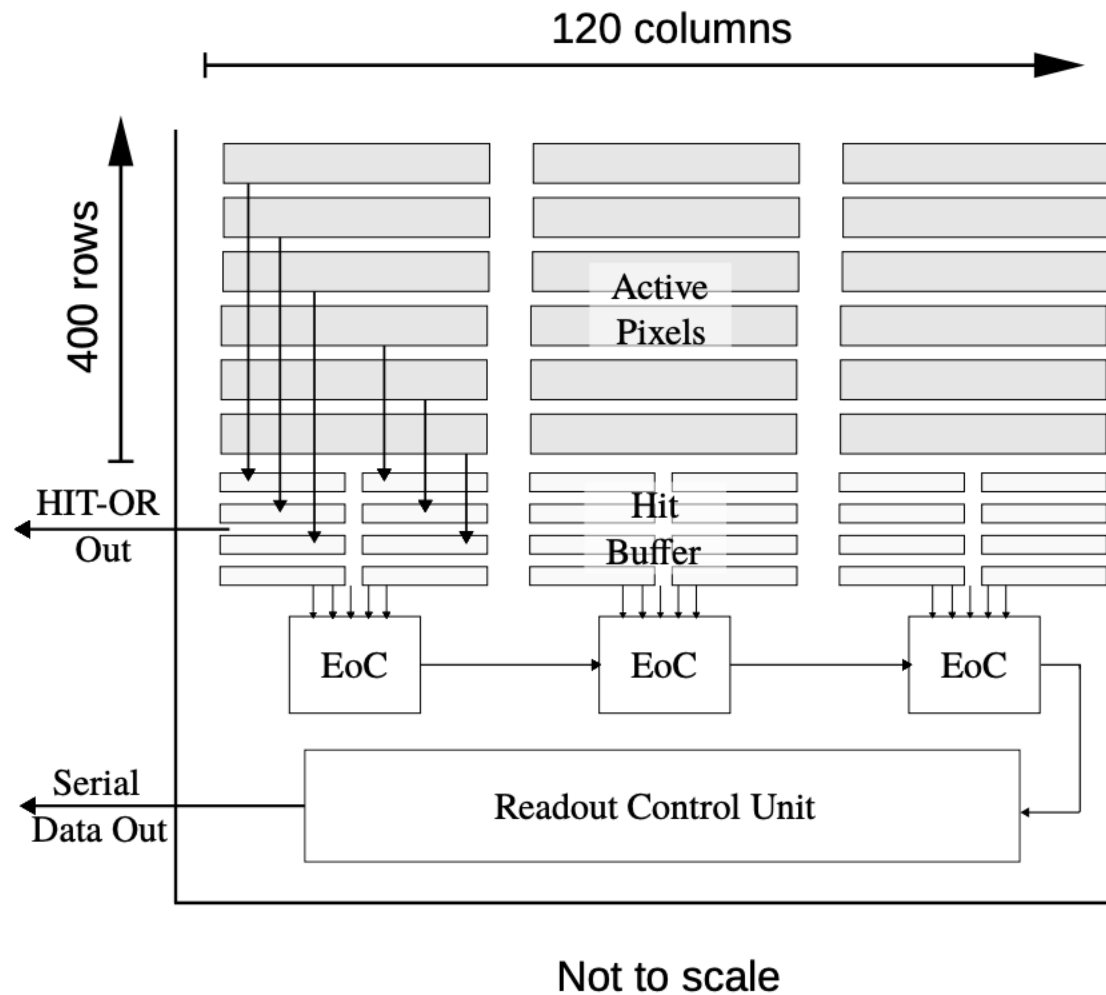


MightyPix Development Stages

- MightyPix1 (MP1): first full monolithic HV-MAPS prototype compatible with LHCb readout (IpGBT, etc.)
 - Config bit was connected to ground instead of DAC register in the design. 16 samples repaired by FIB
 - Two columns share the same digital output shielding, a digital signal from 1 pixel induces an analogue signal in its neighbour. Not repairable.
- MightyPix2 (MP2): adds timing refinements, radiation studies, portability across foundries (e.g. AMS vs LFoundry) as de-risking. Just submitted to AMS Foundry, due 2026
- MightyPix3 / production direction: aims at final sensor geometry and data format for installation in Run 5 / Upgrade II era. Planned submission late 2026, due 2027.

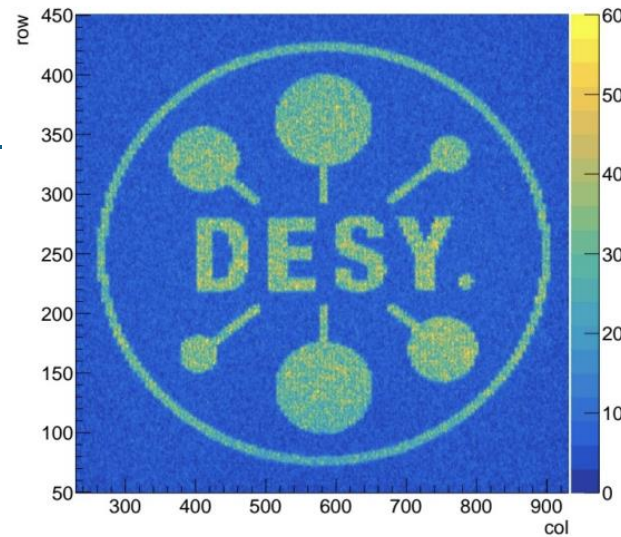


Readout Architecture



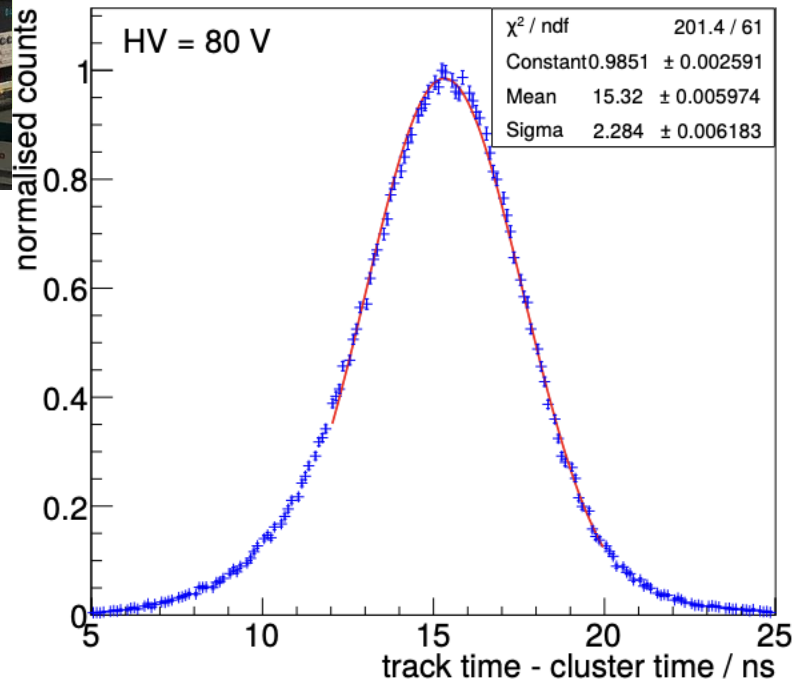
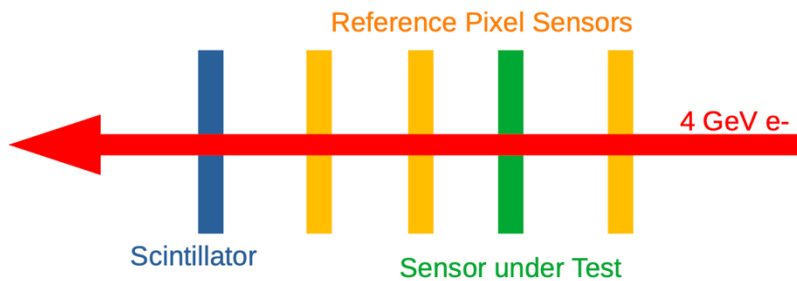
- 4 ns Time-of-Arrival sampling
- Address, timestamp, and time-over-threshold (ToT) info are buffered locally and moved via a column-drain / priority logic scheme for fast readout.
- Hit driven column drain readout at 1.25 Gbit/s
- Configurable trigger output (analogue Hit-OR)

Testbeam Characterisation



[arXiv:2503.08177]

- Validation of optimisation with multiple test beams at DESY
- 4 GeV electrons
- 6 layers Adenium (DESY) telescope
- 3 layers Mupix11 telescope
- Madaq and Eudaq readout system
- Analysis with Corryvreckan2
- $\sigma = 2.284 \text{ ns} \sim 3 \text{ ns}$ as designed

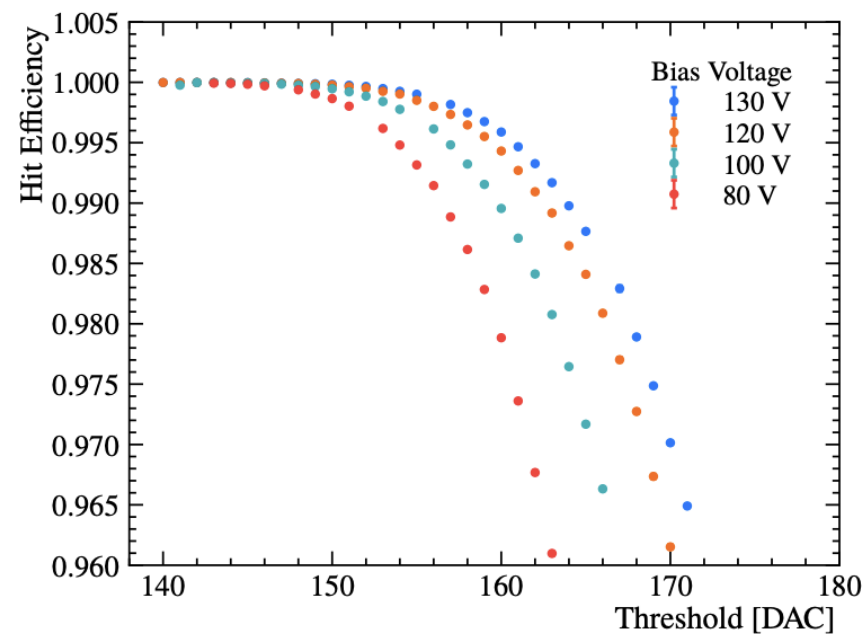
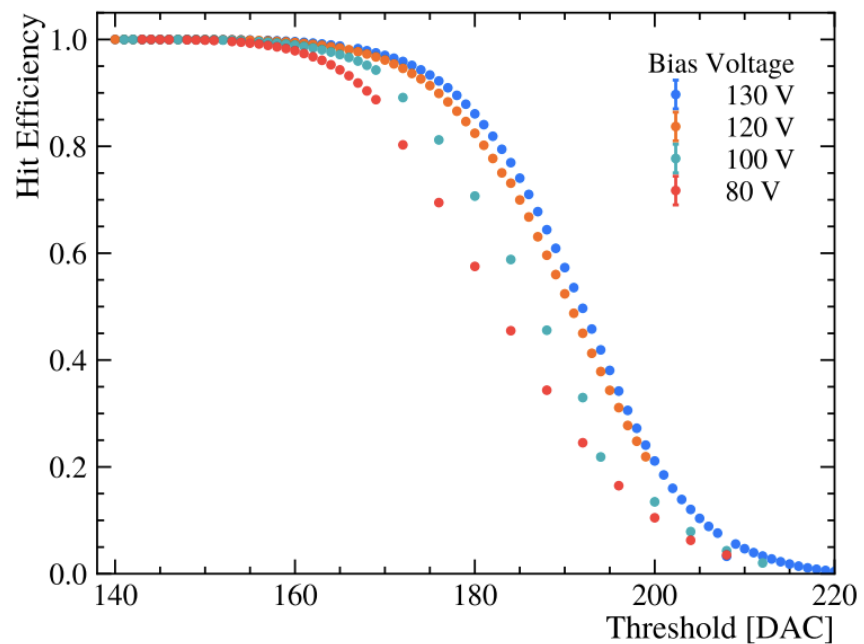


[arXiv:2503.08177]

All plots from Lucas Dittmann

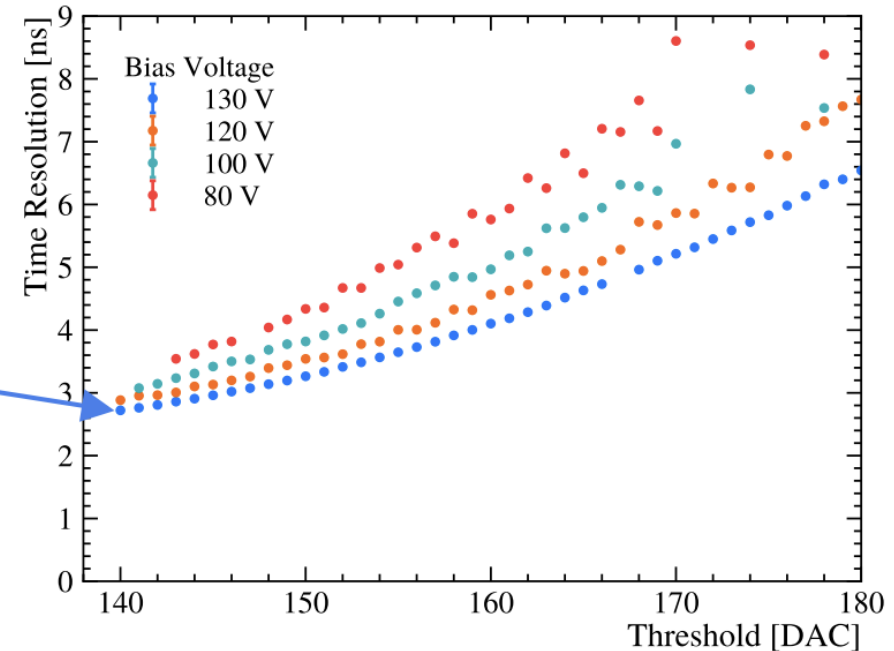
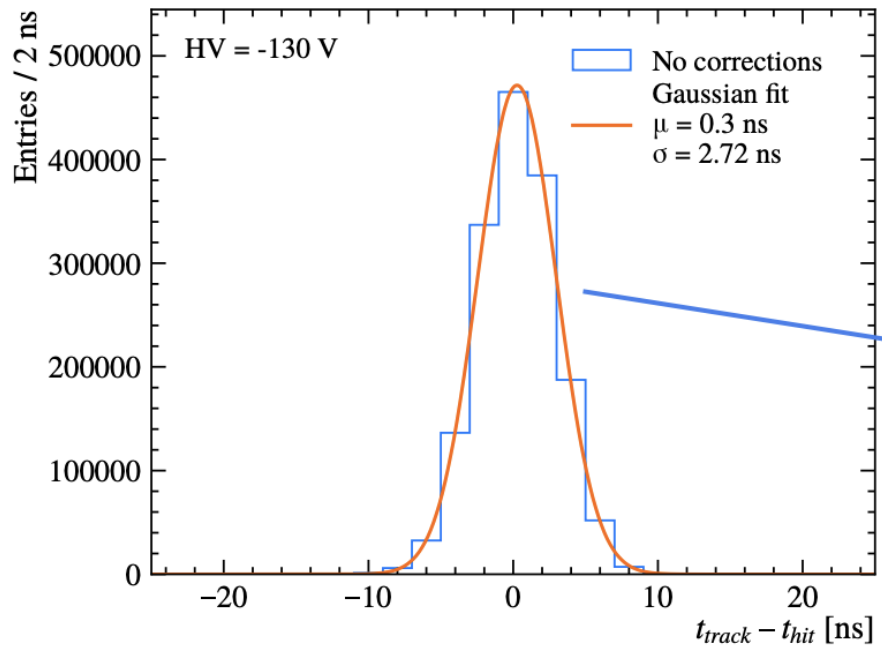
Testbeam Characterisation Cont.

- As expected, the hit efficiency is proportional to:
 - Bias
 - Threshold



Testbeam Characterisation Cont.

- Time resolution < 2.7 ns @ 130 V (Includes reference system)
- HV-bias has a significant effect on time resolution
- Timewalk is negligible at a low threshold



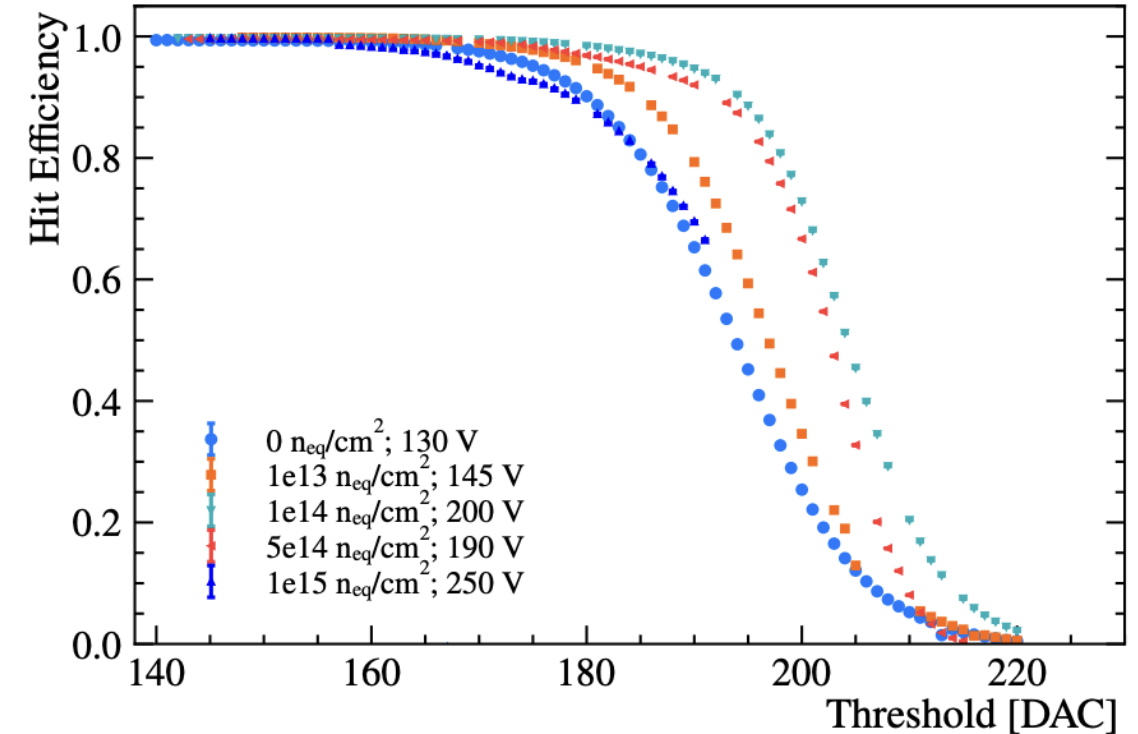
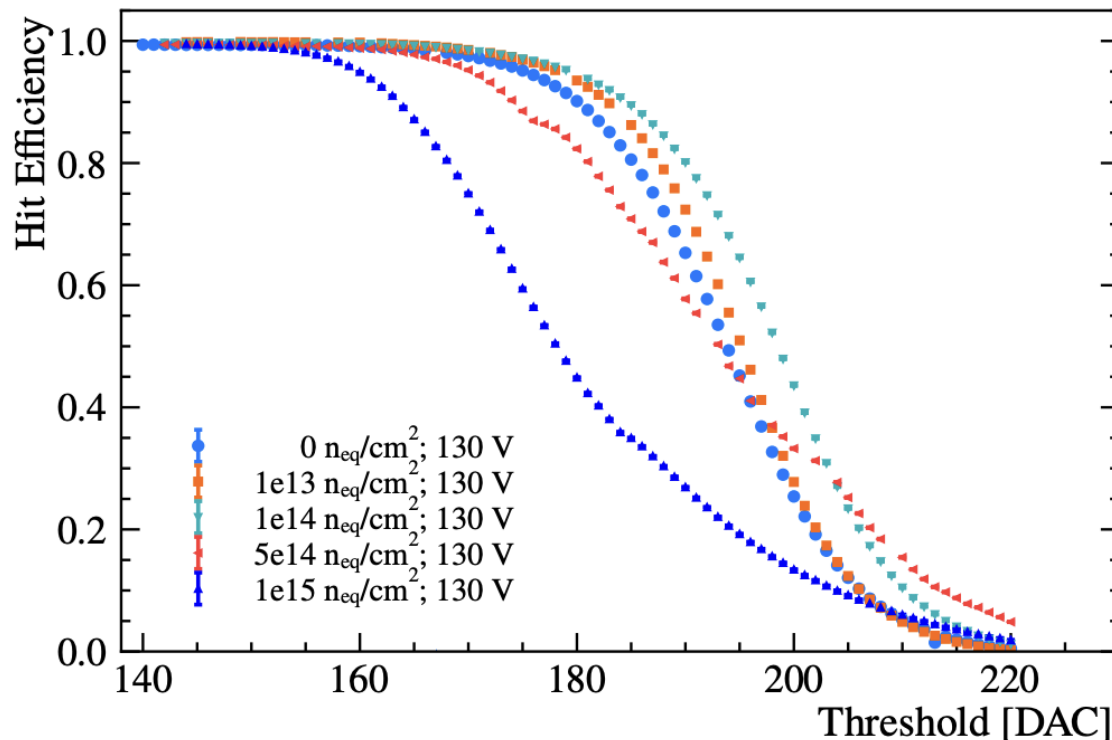
Radiation Hardness and Results

- ~~MightyPix~~ Telepix2 is designed to tolerate fluences of LHCb Run 5 downstream-tracker expectations.
- Requirements on HV-MAPS technology
 - 99 % hit efficiency within 25 ns (bunch crossing)
 - Radiation tolerance up to 3×10^{14} neq cm⁻²
 - Noise rate < 400 kHz/cm²
 - Now increased to around 3×10^{15} neq cm⁻² due to the possible UP tracker using it.

NIEL	Irradiation Facility	Sensor Thickness
0	-	200 μm
1e13 neq/cm ²	JSI Ljubljana	100 μm
1e14 neq/cm ²	JSI Ljubljana	100 μm
1e14 neq/cm ²	JGU Mainz	200 μm
5e14 neq/cm ²	JGU Mainz	200 μm
1e15 neq/cm ²	JSI Ljubljana	100 μm

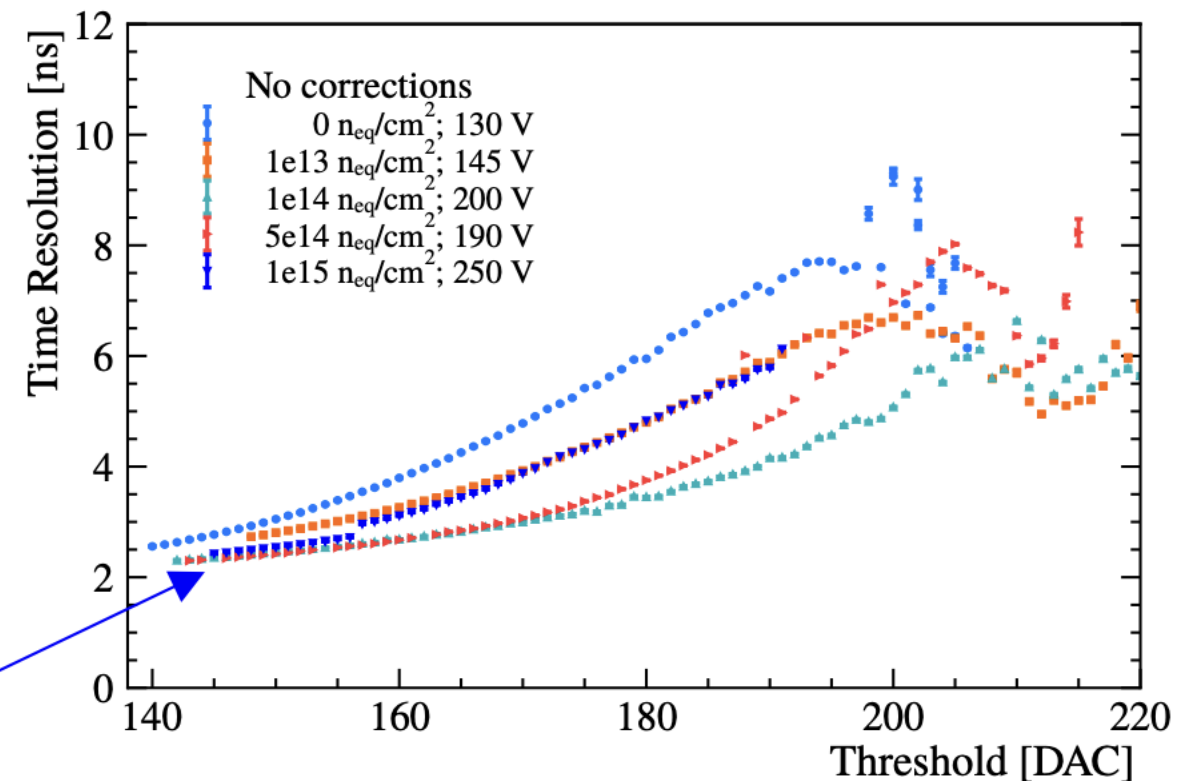
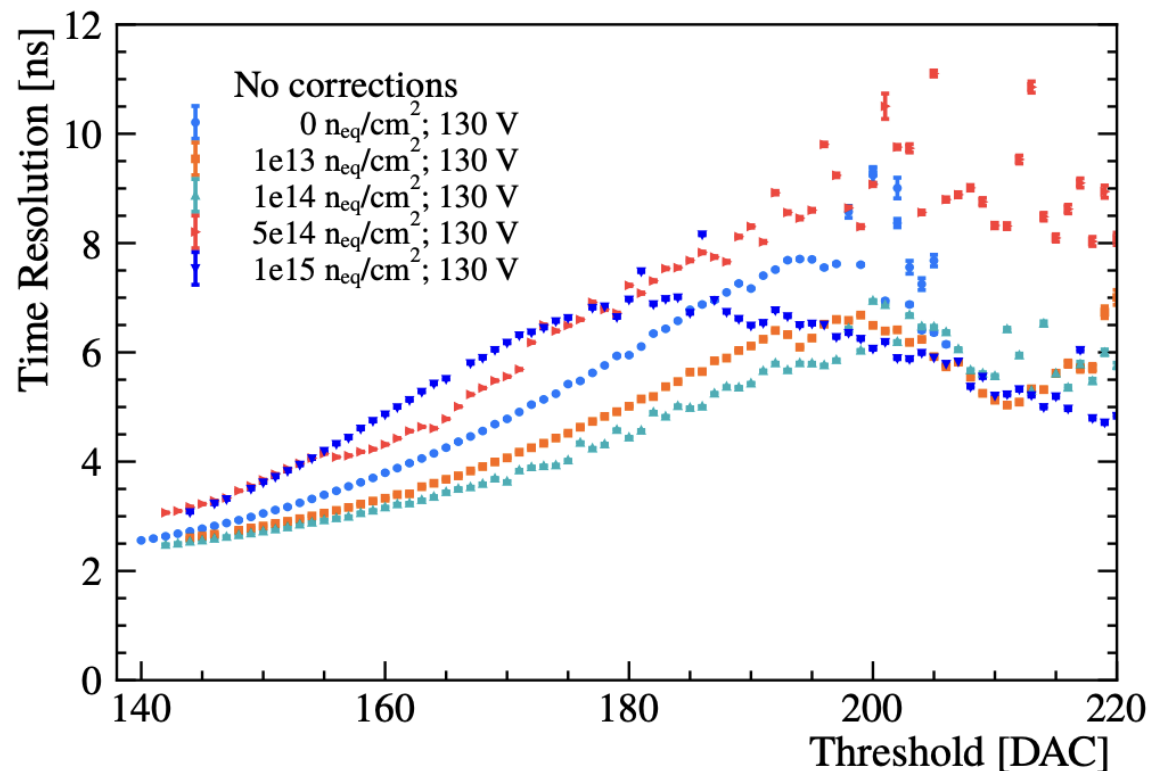
Radiation Hardness and Results Cont.

- Cooled between -10 to -30 °C
- After irradiation, HV-MAPS prototypes still show efficiencies > 99 % for minimum ionising particles and maintain multi-ns timing at suitable thresholds.
- After some light irradiation, up to 1×10^{14} neq cm⁻², the sensor can be pushed to a higher threshold.
- Efficiencies at higher bias allow us to push the Threshold if needed.
- Higher bias counteracts the radiation damage on detector performance.

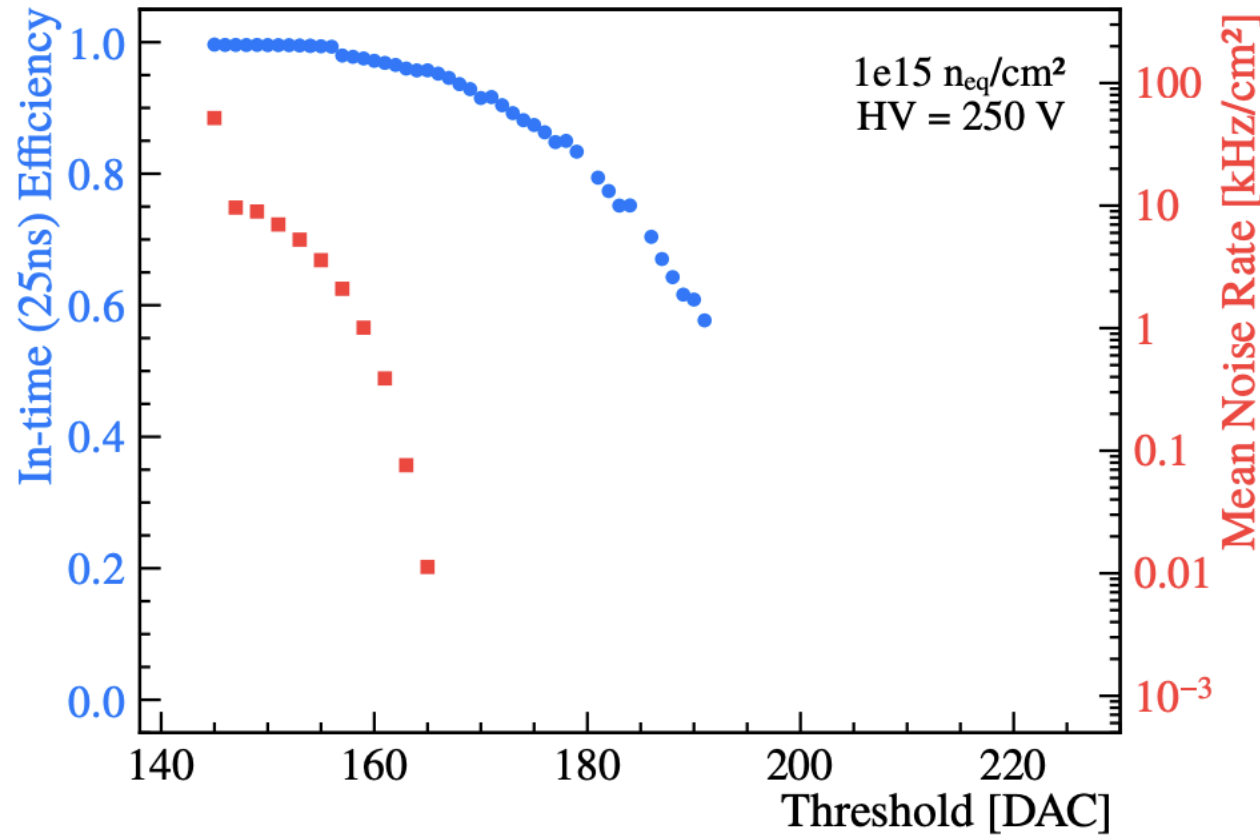


Radiation Hardness and Results Cont.

- Time resolution < 3 ns for all fluences (Includes reference system)
- The depth of the depletion zone has an impact on the collected charge and detector capacity
- Higher bias lowers time resolution



Radiation Hardness and Results Cont.



$$\text{In-time efficiency} = \frac{\text{Detected tracks within 25 ns}}{\text{All tracks}}$$

- In-time efficiency is the number of hits within a 25 ns time window
- After irradiation higher bias gives:
 - Better time resolution
 - Better efficiency
 - Lowers noise

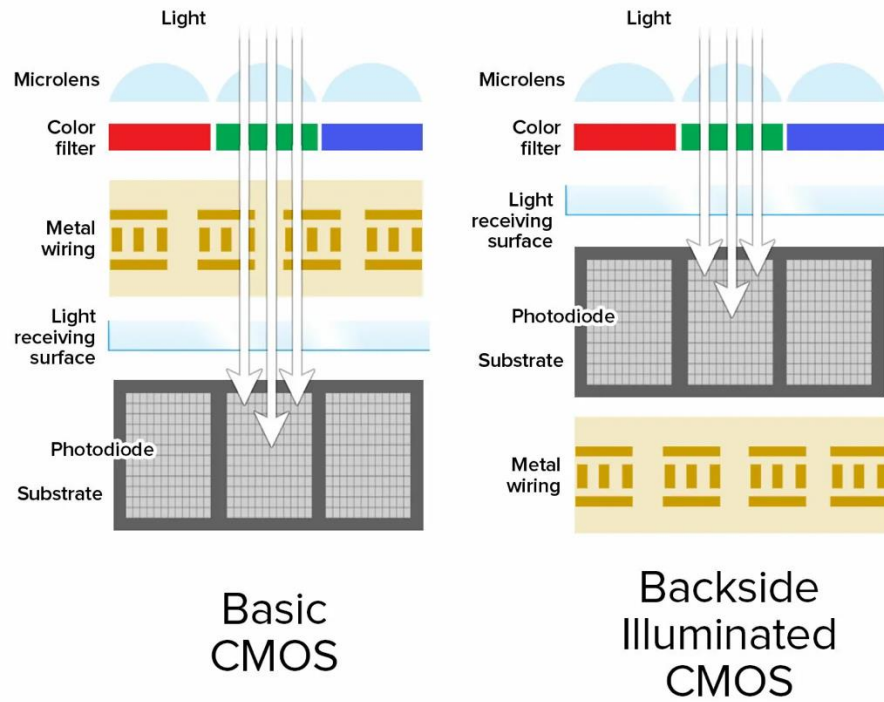
Beam Tests and Validation for LHCb Use

- Time resolution < 2.4 ns @ 80 V bias
- Time resolution of 2.7 ns @ 130 V bias
- Hit efficiency > 99 %
- TelePix2 is radiation-tolerant up to 1×10^{15} neq/cm², after irradiation,
 - In-time efficiency > 99.5 %
 - Time resolution < 3 ns
 - Efficiency > 99.9% with longer ranges of bias and threshold
 - Noise rate < 400 kHz/cm²
- HV-MAPS technology is sufficiently radiation-tolerant for use cases such as LHCb Upgrade 2

Challenges and Ongoing Improvements

- Need to test the radiation tolerance of Mightypix
- Power density and cooling: thin sensors + minimal material imply low-mass cooling concepts must be proven scalable.
- Higher radiation tolerance demand, needs to test
 - The bulk from AMS
 - The 180 nm CMOS circuits
- After both neutron and ionising irradiation

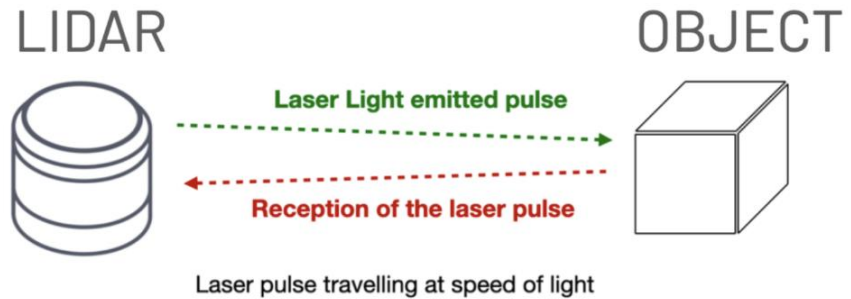
Section 3 – Adapting HV-MAPS for LiDAR



Camera CMOS sensors and HV MAPS are very similar

- Both are CMOS pixel arrays: each pixel senses charge, amplifies it, and sends digital data off-chip.
- Common building blocks: diode → amplifier → logic → readout, all in CMOS.
- HV-MAPS pixel: detects ionisation charge → records time (ToA) + integrates signal amplitude per event (ToT).
- Camera pixel: detects visible/IR photons → integrates intensity over exposure time (ToT).
- LiDAR pixel: Check for the photon arrival → records time (ToA).
- Time-stamping -> LiDAR
- Photon-integration -> Camera
- HV-MAPS is a compromised combination of both.

LiDAR 101



$$distance = \frac{c \times t}{2}$$



- Types of LiDAR
 - Scanning LiDAR
 - **Flash LiDAR (need lower time resolution, ~500 ps)**
 - **Structured light (favours spatial resolution, 1–6 μm)**
 - FMCW LiDAR (Frequency-Modulated Continuous Wave)
 - Indirect ToF (iToF) / Phase Measurement
- Flash LiDAR works like a “camera + stopwatch per pixel”: illuminate, wait for return, timestamp photons.
- Needs ns-scale timing and pixel-parallel readout - identical requirements to HEP pixels.
- HV-MAPS already have: fast amplifier, discriminator, timestamp, and serial output.
- Therefore adaptation is architectural, not conceptual. Two ways to go about it,
 - Optimise time resolution
 - Minimise pixel pitch

Why LiDAR for Robotic Perception

- LiDAR gives absolute depth directly; cameras capture only brightness/colour and must infer distance computationally.
- A camera-based robot must compute in real time all this via stereo correlation, optical flow, segmentation & AI inference — billions of operations per frame. :
 - Stereopsis / Disparity – match left/right views pixel-by-pixel.
 - Convergence & Accommodation – eye-angle + lens-focus sensing for near-field range.
 - Motion Parallax – track apparent motion with viewpoint change.
 - Perspective, Shading & Occlusion – learn geometry from context.
 - Aerial Perspective – use haze/colour shift with distance.
- LiDAR bypasses all that: one laser pulse → time-of-flight → direct 3D distance in hardware.

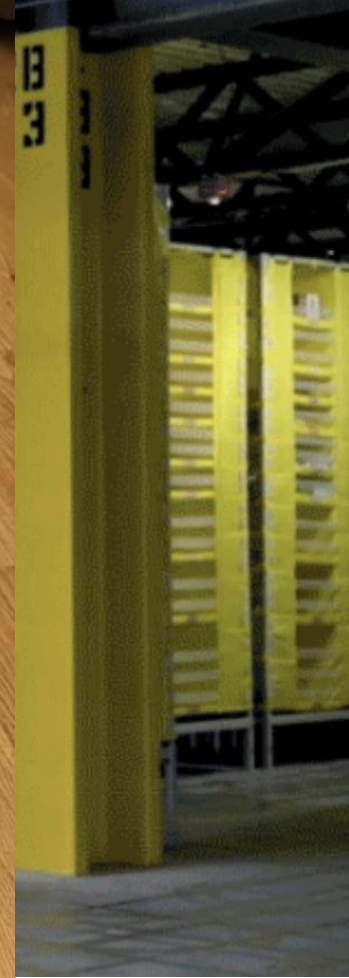
Why LiDAR for Robotic Perception

- LiDAR gives a more complete view of the environment than cameras, which are computationally expensive.
- A camera-based system requires complex computer vision algorithms for object detection & AI inference.
 - Stereo vision
 - Convolutional neural networks
 - Motion estimation
 - Perspective projection
 - Aerial imagery
- LiDAR bypasses the need for complex computer vision algorithms.



Why LiDAR for Robotic Perception

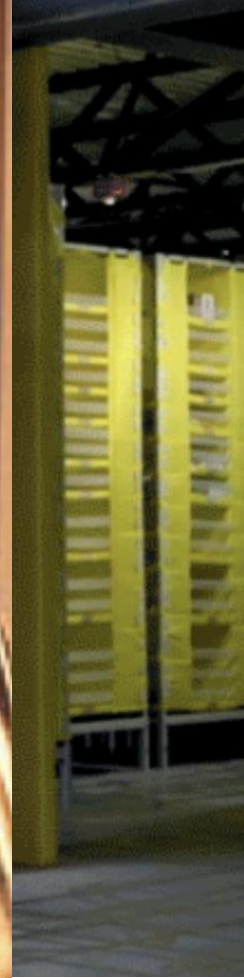
- LiDAR gives
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 - Persp
 - Aeria
- LiDAR byp



computationally.
tation & AI

Why LiDAR for Rob

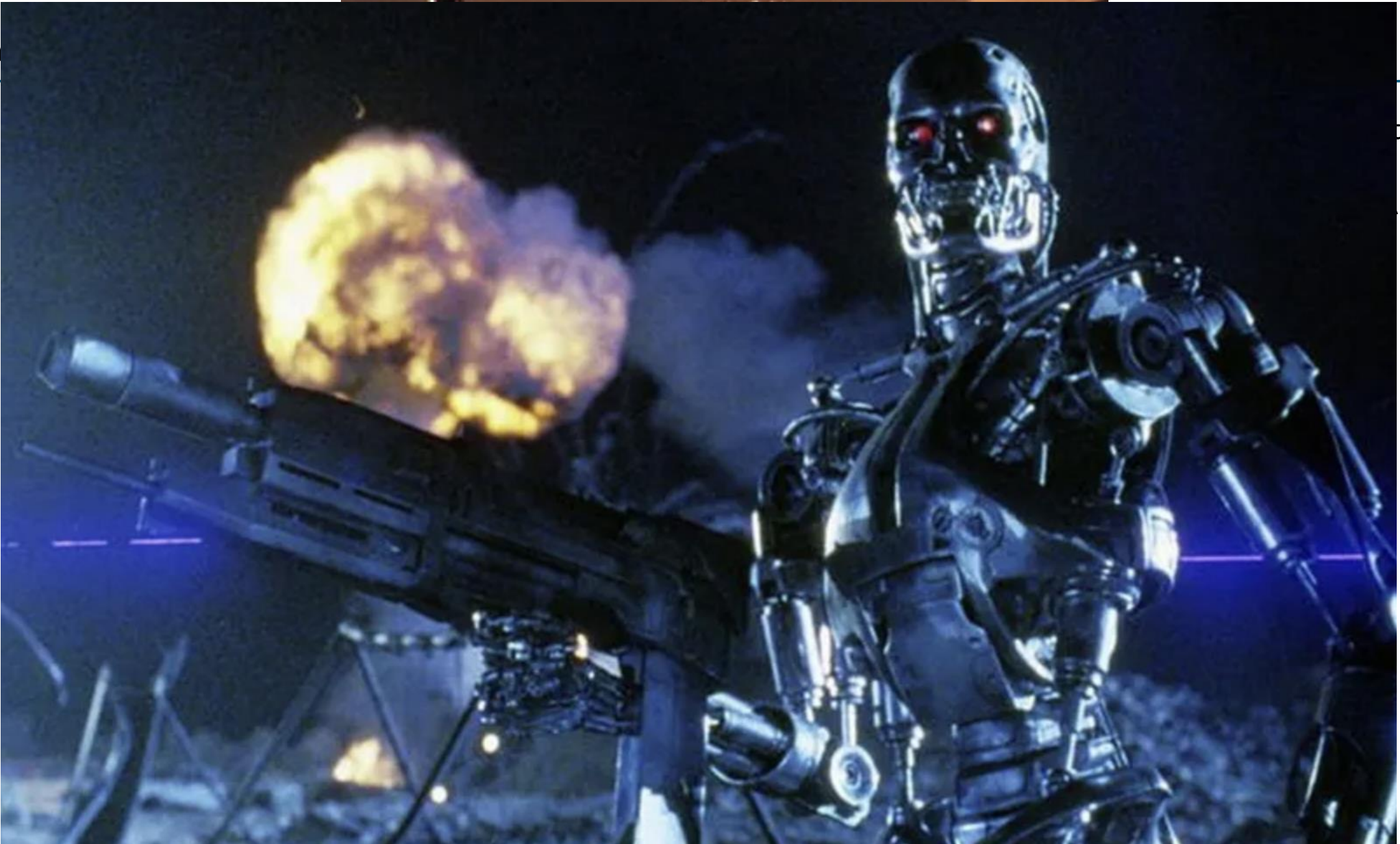
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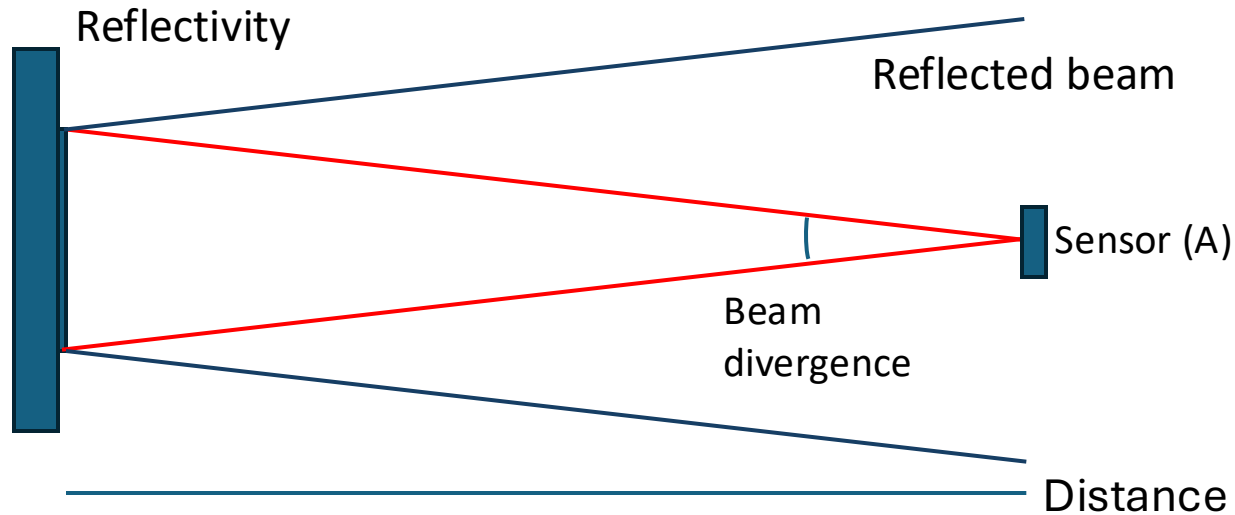
tionally.

Why Tesla Says “No LiDAR” – and Why HV-MAPS Change That



- Elon Musk: “Humans drive with vision, not LiDAR” → claims extra sensors add cost and fusion ambiguity.
- HV-MAPS dual-mode operation:
 - 3000 Hz ToF burst (5 ns pulses) for depth $\sim 15 \text{ us/s} \sim 1.5\text{e-}3\%$
 - Camera mode for visible range imaging/video fills up the second
- Dual-mode operation could solve both of his claims
 - Same pixels → same optics → no sensor fusion problem. true fusion in silicon.
 - A.I. + Robotics + cars → economy of scale → no added cost problem.

Flash LiDAR detection efficiency by HV-MAPS



Returned signal efficiency: $\eta = R \cdot [A / \pi \cdot (d \cdot \theta)^2]$

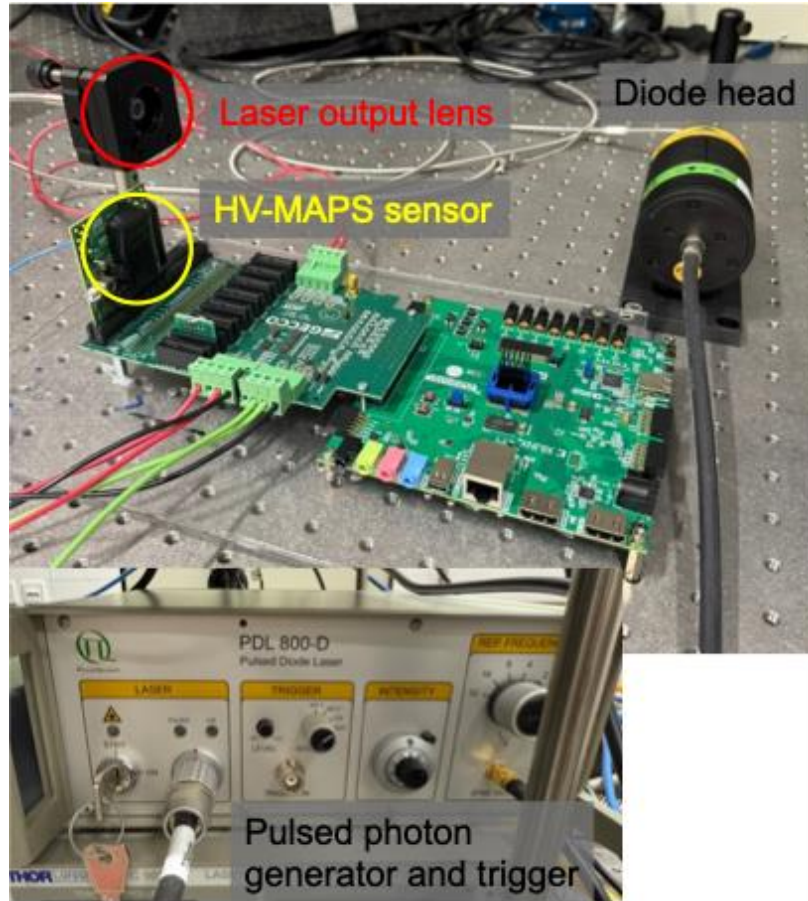
- R = Reflectivity (10%)
- A = Aperture area (7.07 cm²)
- d = Distance (20 m)
- θ = Beam divergence (0.26-0.52 rad)
- Pulse energy: 180 μ J
- Pulse width: 5 ns
- Maximum Permissible Exposure: 1.3 $\times 10^{-6}$ J cm⁻²
- Calculated efficiency is then η (6 $\times 10^{-6}\%$).
 - The silicon will absorb $\sim 2.5 \times 10^5$ keV
 - 50,000 times above the detection floor of ~ 5 keV per pixel

Timing Requirements for Automotive and Robotic LiDAR

System type	Timing jitter / binning	Typical range precision	Range capability
Mechanical / scanning	200–400 ps	2–5 cm	100–250 m
Flash / solid-state LiDAR	100–300 ps	1–3 cm	200–300 m
SPAD arrays	50–150 ps per-pixel	1–5 cm	10–100 m (scene-limited)
Indirect ToF	Equivalent of 100–500 ps	1–5 mm	< 10 m (short-range)

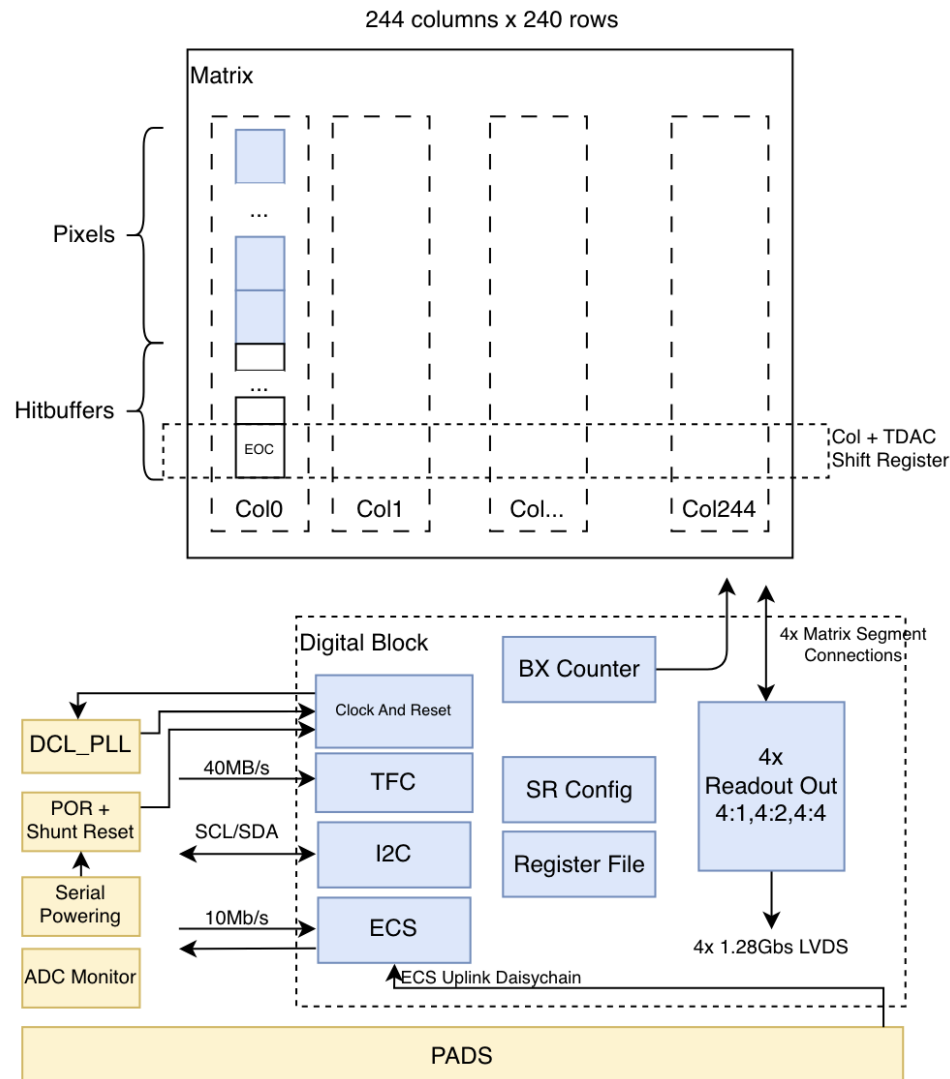
- Automotive and robotic LiDAR target 1–10 cm depth accuracy → 100–700 ps timing precision.
- Commercial SPAD and scanning systems already operate in this regime.
- HV-MAPS chips currently reach ~2 ns, and sub-ns timing is realistic with minor PLL/DLL upgrades.
- ⇒ HEP-grade timing already approaches LiDAR requirements.
 - ~2 ns to ~ 500 ps is absolutely doable.

Current Progress – HV-MAPS LiDAR Adaptation



- Setup:
 - PDL 800-D driver
 - $\sim$ ns pulse width
 - Single to 80 MHz repetition rate
 - < 100 ps trigger jitter
 - 905 nm pulsed laser head
 - HV-MAPS with GECCO readout
 - PDL 800-D triggered measurements
- Objective:
 - First ToF measurement using a HEP HV-MAPS chip.
 - Depth resolution/range precision.
 - Different materials.
 - Extract first timing S-curves and correlation histograms.
- Next:
 - Establish a stable experiment setup and analysis chain.
 - Try with a floodlight laser for flash LiDAR testing.

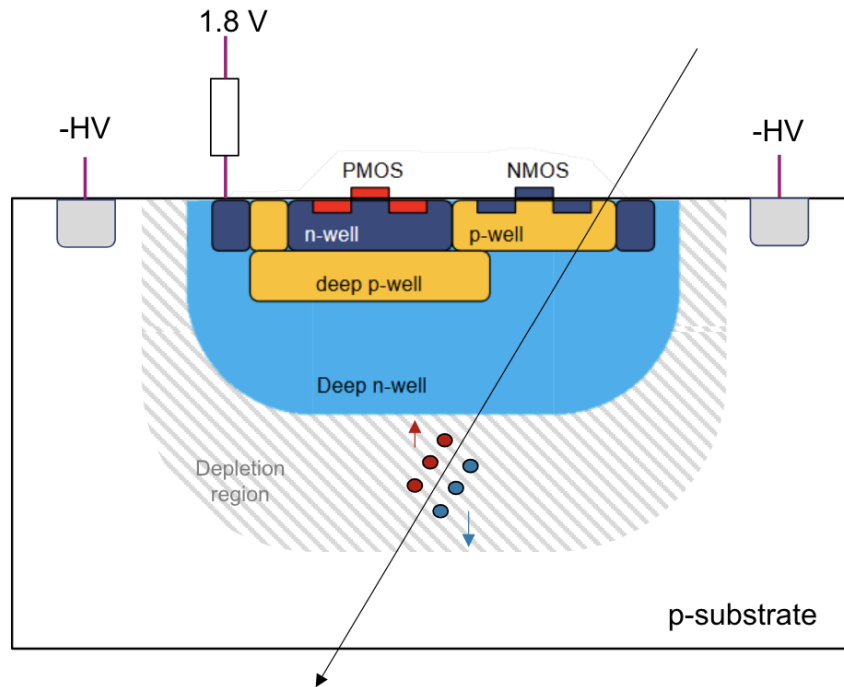
Architectural Adaptations Needed



Some basic examples of the modifications to achieve ~ 500 ps time resolution and better quantum efficiency.

- ASIC-level modifications:
 - Replace triggerless priority logic with frame-gated, direct ToF readout architecture.
 - Implement clean PLL and DLL clock structures to cut timing uncertainty from ns to ps scale.
 - Double-stack / 3D integration. $\rightarrow$ allows small pitch
 - Minimal-electronics HV-MAPS pixel: Strip timing logic, keep only diode + SF $\rightarrow$ smaller pitch
- Silicon-stack enhancements:
 - Introduce backside illumination with wafer thinning for higher photon collection efficiency.
 - Add surface passivation to minimise interface traps and dark noise.
 - Integrate a 905 nm band-pass filter to boost near-infrared quantum efficiency and suppress daylight background.

Architectural Adaptations Needed



Working principle of HV-CMOS sensors.

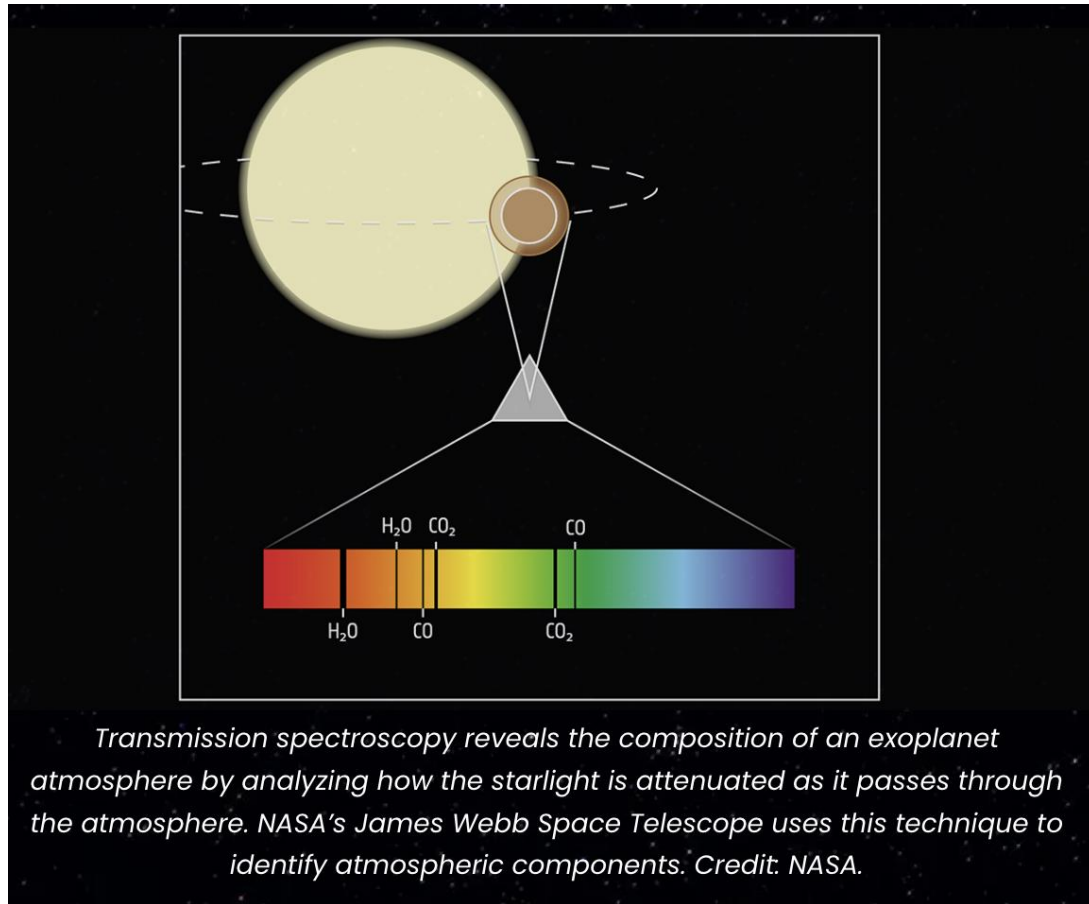
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Other Applications of ToF Detectors

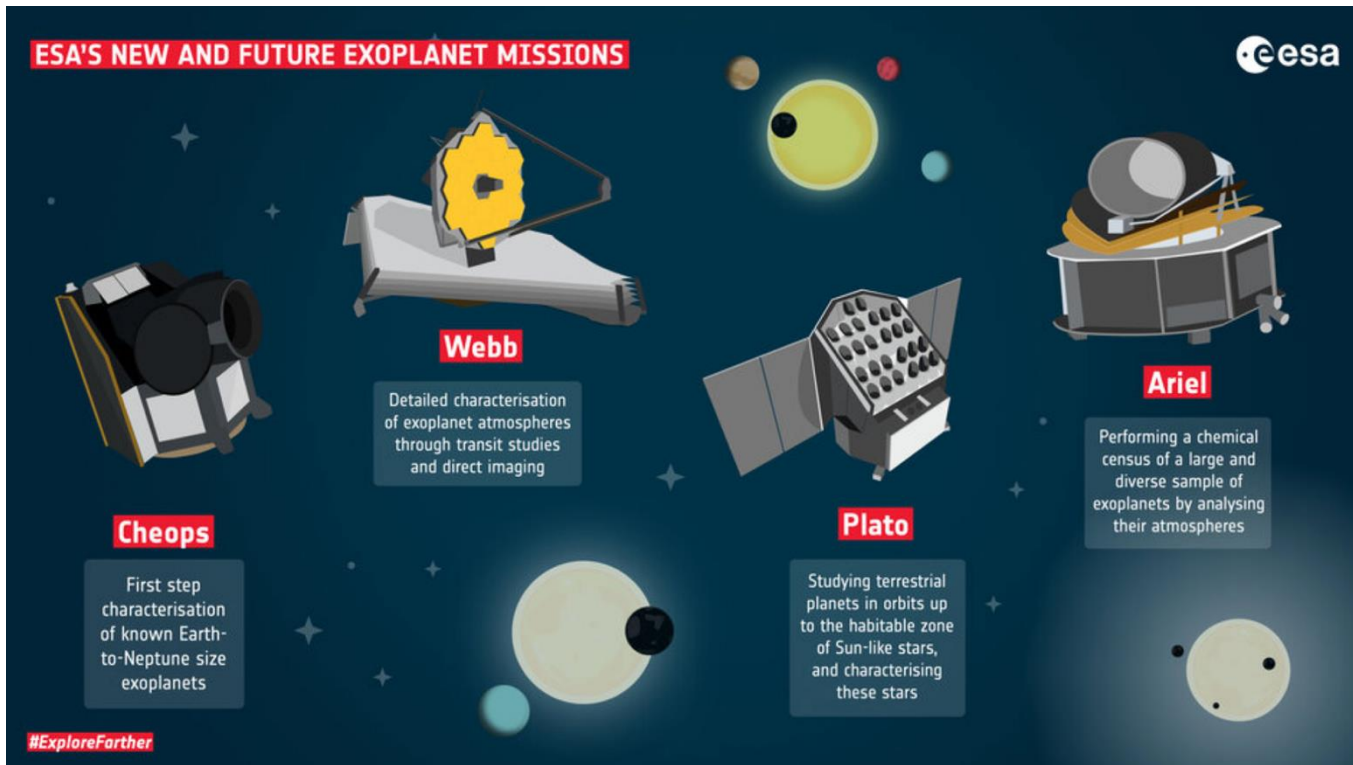
- Automotive ADAS: collision avoidance, lane keeping, blind-spot detection.
- Robotics: warehouse navigation, pick-and-place, human-safety zoning.
- Drones / UAVs: terrain following, obstacle avoidance.
- AR / VR: gesture and room mapping (Apple LiDAR, Kinect).
- Space LiDAR: surface and atmospheric profiling (ICESat-2, GEDI).

Section 4 – From HEP to Astrophysics - Ultra-Low-Light Imaging



- HV-MAPS concept: high-gain, low-noise, fast timing pixel arrays
- Exoplanet spectroscopy demands 10–100 ppm photometric stability and ultra-low noise over hours.
- Same strengths needed for faint-photon astronomy and quantum imaging
- HV-MAPS architectures can be repurposed for photon-timestamping and gain-stabilised detection at low flux.
- Core idea → reuse LiDAR and HEP-optimised sensor for ultra-low-signal photon detection

Scientific Motivation: Exoplanet Spectroscopy and Biosignatures



- Photon-starved domains: exoplanet transits, faint galaxies, transients. Require:
 - Sub-electron noise,
 - ns–ps timing for coincidence or drift correction,
 - ppm-level gain stability.
- Current detectors (sCMOS, HgCdTe) limited by drift, crosstalk, slow readout.
- MIRI and NIRSpec measured atmospheric features (H_2O , CO_2 , CH_4 ,) in transmission spectra down to ~ 50 ppm precision.
- Ariel at L2 explicitly target 10–100 ppm stability to detect atmospheric chemistry of warm exoplanets.

Key Sensor-Level Modifications for Astronomy

HV-MAPS Advantages

- Radiation tolerant.
- Fast timing
- Continuous calibration and drift correction
- Proven scalability.

Adaptations for Faint-Photon Detection

- e^- sensitivity.
- higher charge-collection efficiency.
- NIR-tuned backside layer (900–1700 nm).
- Correlated-double-sampling (CDS) to suppress $1/f$ noise.

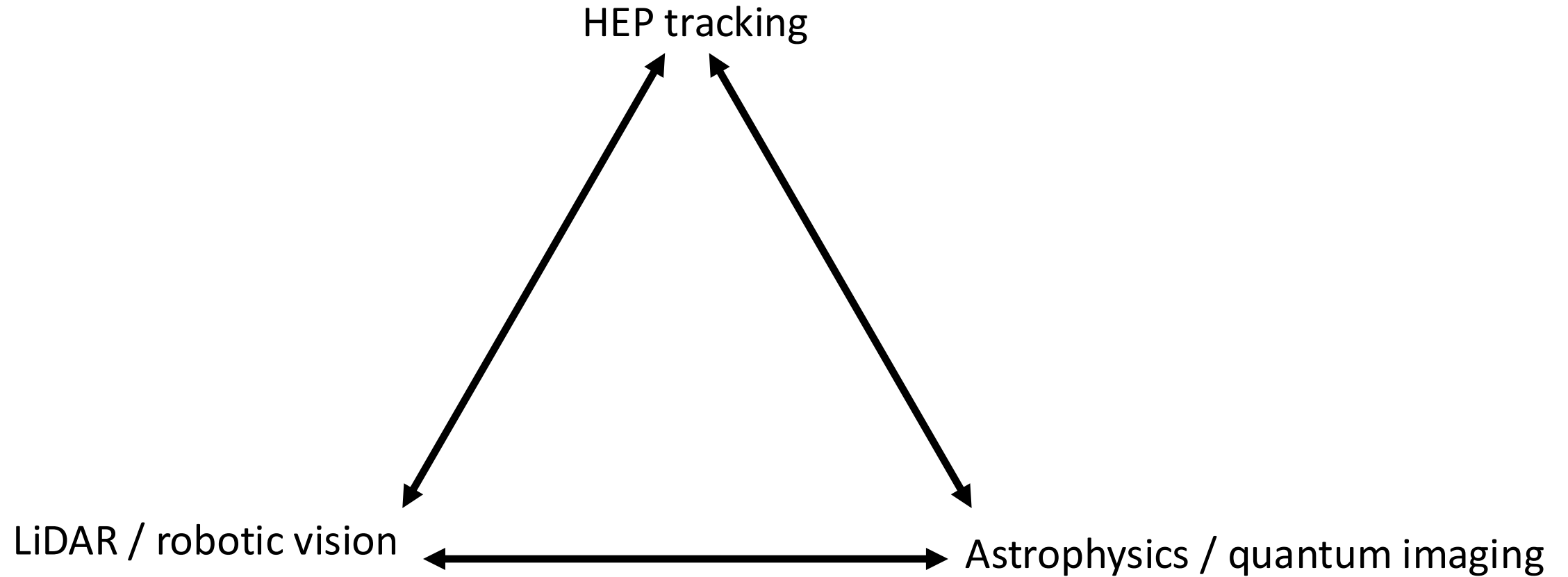
HgCdTe Mercury cadmium telluride avalanche photodiode (APD / e-APD) arrays:

- 60–70 % quantum efficiency from 0.9–4 μm .
- Near single-photon sensitivity, sub- e^- effective noise, and dark current $< 10^{-4} e^- / \text{pixel} / \text{s}$.
- Already deployed in space LiDAR and planetary / atmospheric sensors.
- Can adapt RCU to read out HgCdTe as a hybrid detector.

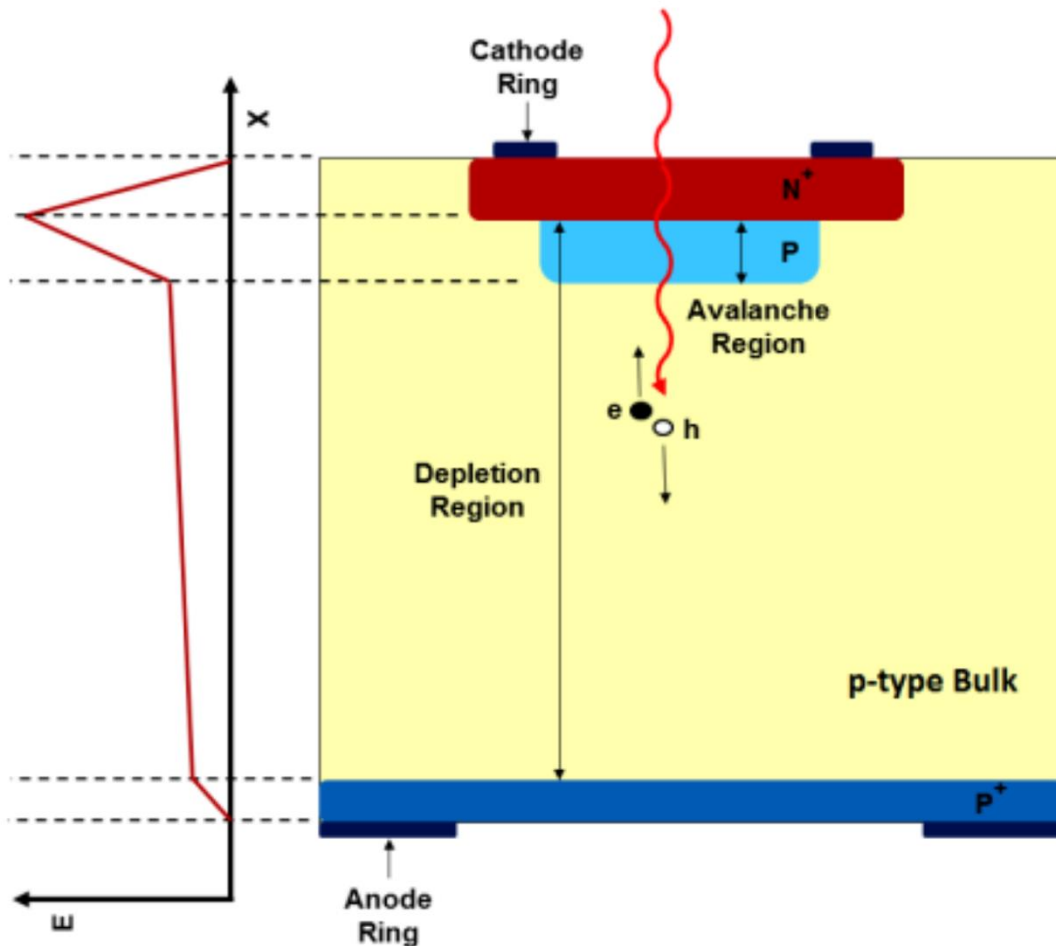
Cross-Disciplinary Applications for HV-MAPS

- Common R&D thread: HL-LHC → LiDAR + Astrophysics.
- Aligns with CERN DRD roadmap and non-accelerator instrumentation.
- One detector family, three frontiers:
 - HEP tracking
 - LiDAR / robotic vision
 - Astrophysics / quantum imaging
- Converging goals: ultra-fast timing, ultra-low noise, ppm-level stability, and intelligent on-sensor readout.

Cross-Disciplinary Applications for HV-MAPS

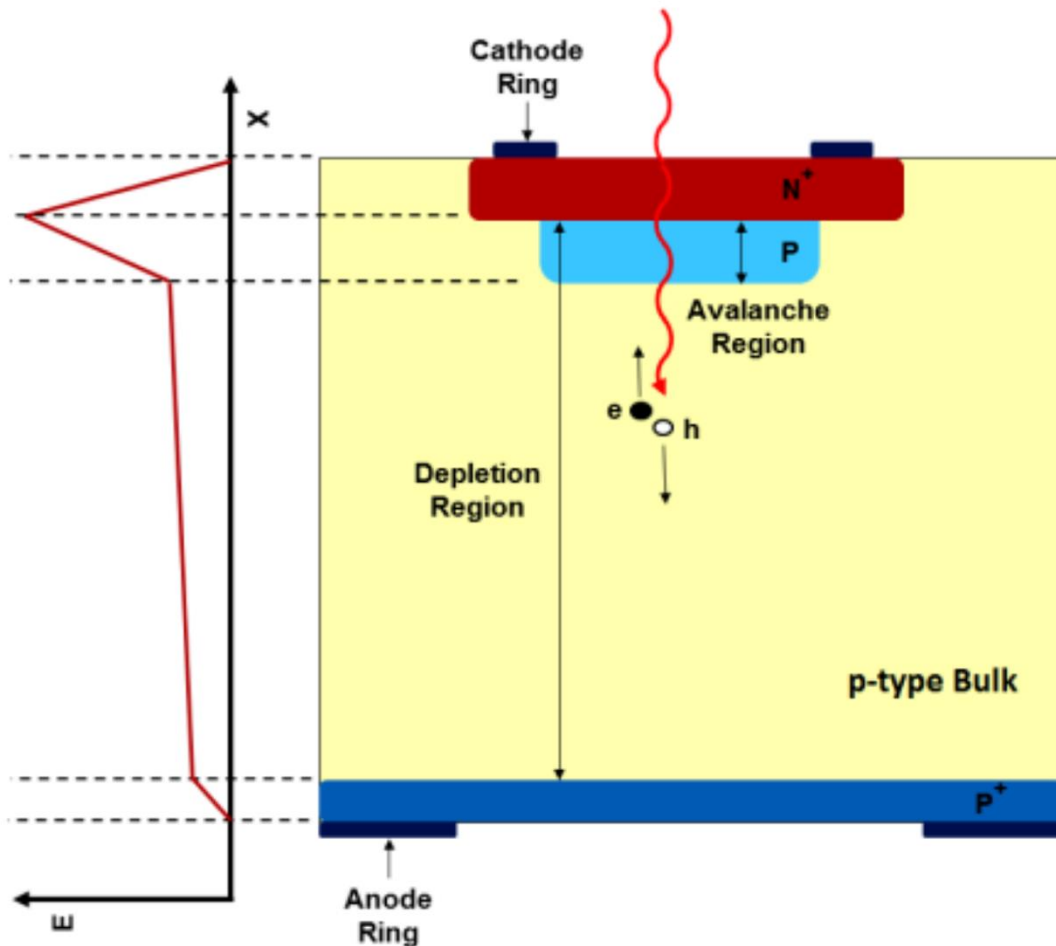


Section 5 – Future Pipelines: LGAD and Multi-Use Integration



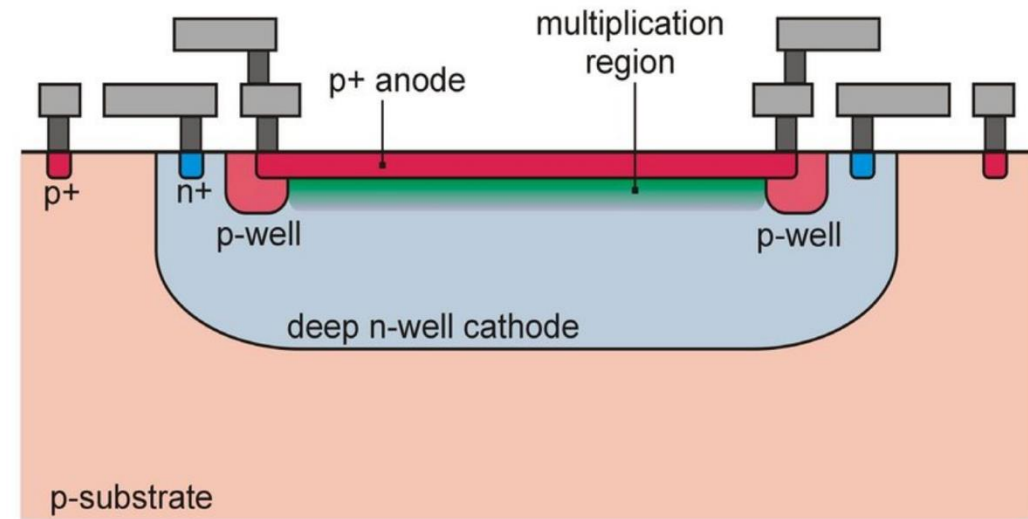
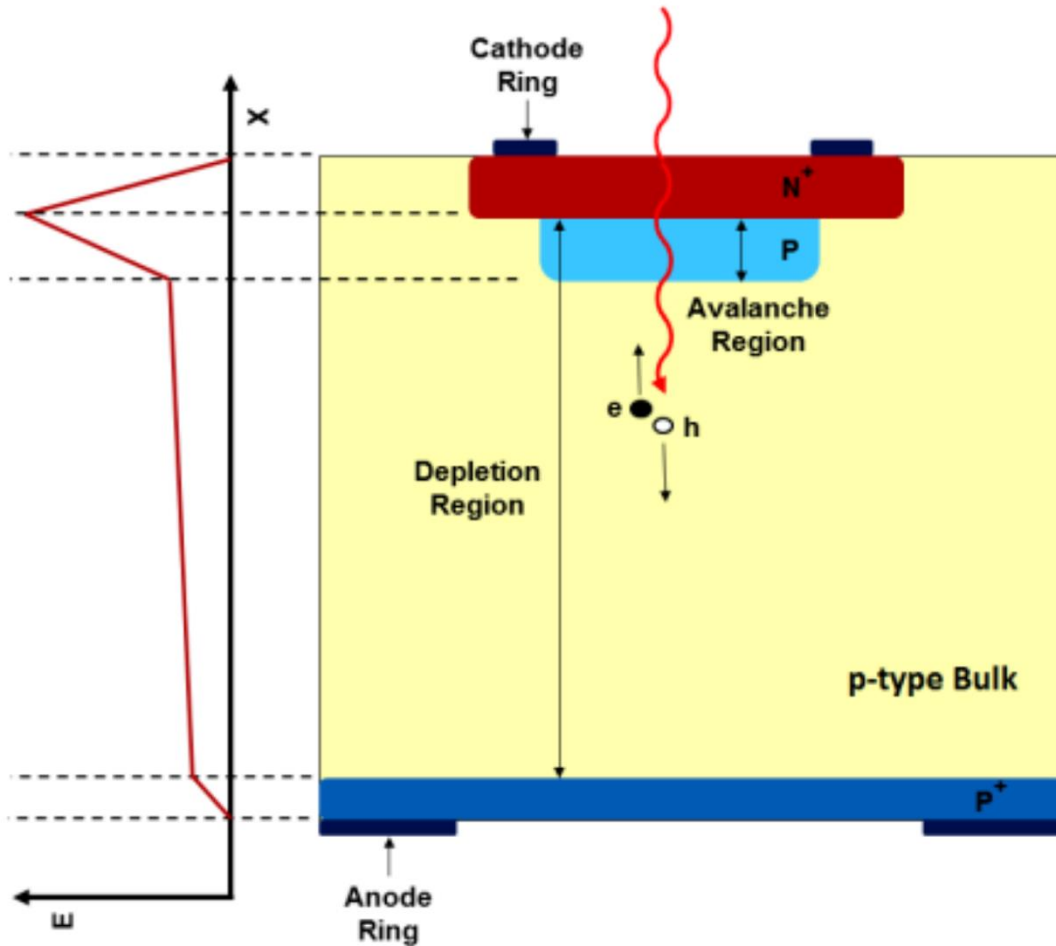
- HV-MAPS: monolithic CMOS $\rightarrow$ low cost, integration, moderate timing ($\sim$ ns).
- LGADs: segmented avalanche diodes $\rightarrow$ sub-50 ps timing, mature in HEP.
- Complementary technologies:
 - HV-MAPS $\rightarrow$ high granularity, full integration.
 - LGADs $\rightarrow$ precision timing, higher S/N.
- Major Variants include
 - DC-LGAD (segmented implants),
 - AC-LGAD (capacitive coupling for continuous 2D readout)
 - monolithic LGAD concepts that merge sensor and readout.

Operating Principle of LGADs

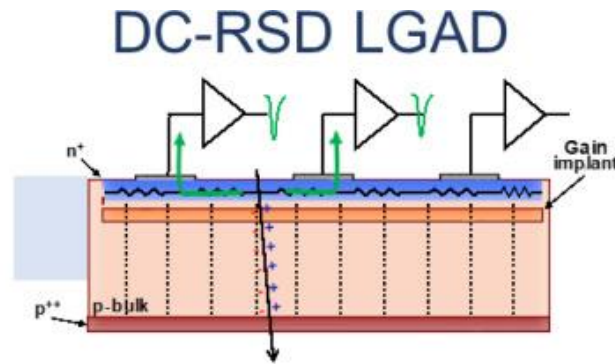
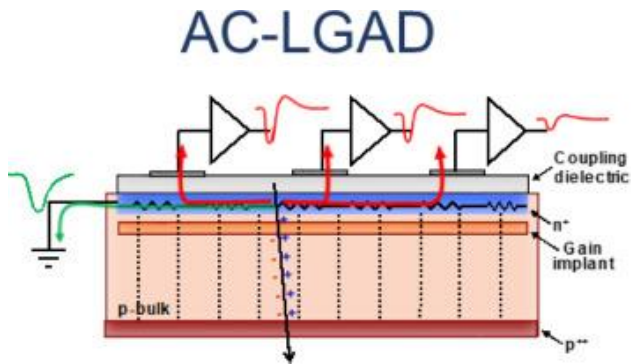


- Thin p⁺ gain layer induces controlled avalanche → internal gain $\approx 10\text{--}30$.
- Fast signal rise ($< 1\text{ ns}$) → timing resolution $20\text{--}40\text{ ps}$.
- Spatial resolutions possible at $\sim 10\text{ }\mu\text{m}$ level.
- Radiation tolerant with proper gain layer engineering (Carbon co-implant, N-in-P design).
- Gain is high to beat frontend noise but still linear enough to preserve **limited** amplitude info.
- Deploying in ATLAS & CMS Timing Layers (HL-LHC).

Core R&D Challenges and CERN Support



Design Variants: DC, AC, Monolithic



DC-LGAD

- ✓ Excellent timing ($\sim 20\text{--}30$ ps)
- ✓ Simple segmented pad readout
- ✗ Gaps between pads $\rightarrow$ incomplete fill factor
- ✗ Coarse spatial resolution ($> 100\text{ }\mu\text{m}$)

AC-LGAD

- ✓ Continuous resistive n-layer $\rightarrow$ full fill factor
- ✓ Fine spatial resolution ($\sim 10\text{ }\mu\text{m}$) with ~ 30 ps timing
- ✗ More complex fabrication, signal sharing
- ✗ Slightly lower S/N, needs reconstruction

Monolithic LGAD

- ✓ Gain + readout on one die (true integration)
- ✓ Compact, CMOS-compatible, radiation-hard
- ✓ Potential for most linear response.
- ✗ Still early R&D; gain uniformity and noise control challenging
- ✗ Hard to balance ps timing with low noise

Core R&D Challenges and CERN Support

- Technical challenges
 - Gain uniformity: keeping avalanche gain stable while avoiding premature breakdown, especially after irradiation.
 - Design limits: achieving both $\sim 10\ \mu\text{m}$ spatial pitch and ps-class timing stretches AC-LGAD layout and metallisation capabilities.
 - System integration: combining sensors with low-mass cooling, high-bandwidth readout, and trigger architectures for HL-LHC and beyond.
 - Low radiation tolerance
- CERN coordination and support
 - DRD3 – Solid-State Detectors Collaboration:
 - Strategic work packages
 - Links HL-LHC timing layers, future colliders, and applied domains (medical imaging, beam monitoring).
 - Establishes LGAD + HV-MAPS as a pan-CERN technology stack, not experiment-specific.

Multi-Use Applications of LGAD Technology

What HV-MAP can be envisaged to do, LGAD can most likely do it better based on current lab performances.

- **Automotive LiDAR: 50 ps timing → cm-level depth @ > 200 m.**
- Quantum optics / photon correlation detectors.
- **Space & atmospheric sensing: single photon capable.**
- Medical imaging & proton therapy: time-of-flight dosimetry.

Summary and Outlook

HV-MAPS for HEP

- HV-MAPS technology is sufficiently radiation-tolerant for use cases such as LHCb Upgrade 2

LiDAR adaptation

- Calculation allows enough photons at the receiver $\sim 2.5 \times 10^5$ keV, above the detection floor of ~ 5 keV per pixel
- Bridge between HEP detector electronics and robotic / automotive vision.

Astrophysics and quantum imaging

- Same drive for low noise, gain stability, and fast timing supports exoplanet spectroscopy and faint-photon detection.
- Dual-use R&D aligns HEP and space-instrumentation needs.

LGAD and beyond

- LGAD / AC-LGAD deliver sub-50 ps timing and is merging with HV-MAPS readout concepts.
- CERN DRD3 provides the framework linking collider timing layers, LiDAR, and astrophysics instrumentation.

Outlook

- Unified goal: extend HV-MAPS intelligence and integration into the picosecond regime.
- One technology continuum:
HV-MAPS $\rightarrow$ LiDAR $\rightarrow$ Astrophysics $\rightarrow$ LGAD.