Future Tracker R&D Directions

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Snowmass Muon Collider Forum

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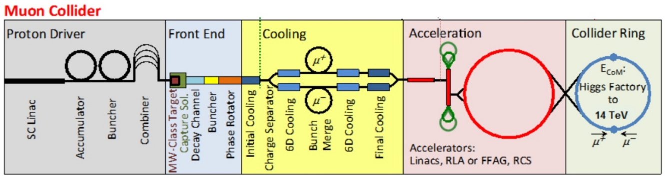
Future trackers will be 4D!

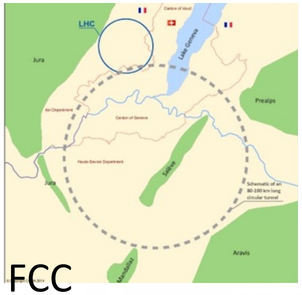
- The 4D-trackers will play a key role at the future machines
  - Reduce backgrounds, track reconstruction, triggering at L1: all will benefit from precision timing information, in addition to precision position
  - Enhanced capabilities: PID and LLP reconstruction
  - Unique challenges, and opportunities to detector and electronics design
- Active R&D ongoing to address these challenges

Measurement	Technical requirement
Tracking for e^+e^-	Granularity: 25x50 μm^2 pixels
	5 µm single hit resolution
	Per track resolution of 10 ps
Tracking for 100 TeV pp	Generally the same as e^+e^-
	Radiation toleran up to $8x10^{17}$ n/cm^2
	Per track resolution of 5 ps

Technical requirements for future trackers: from [DOE's HEP BRN]



MC



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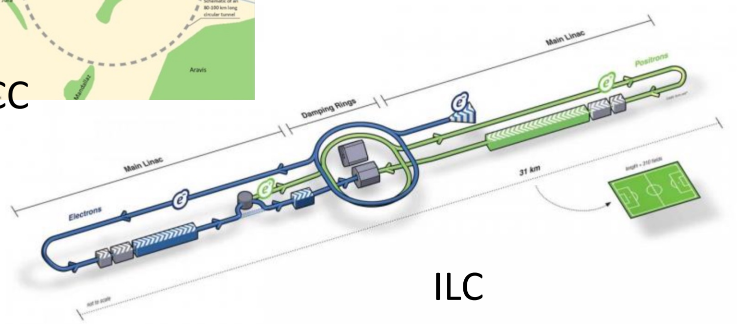
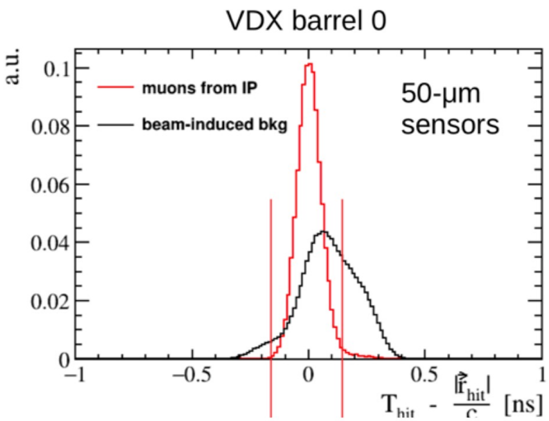
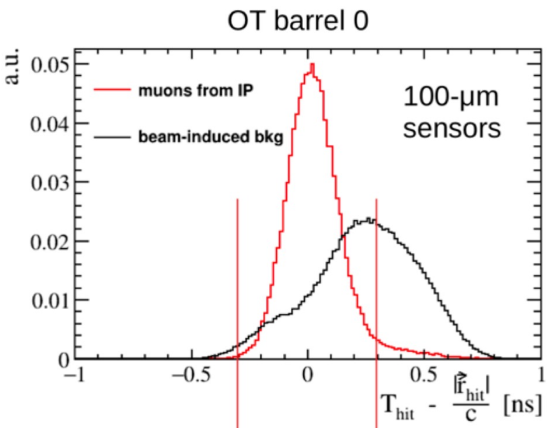


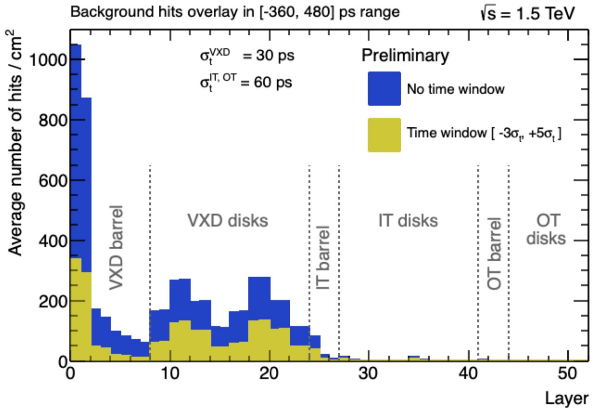
ILC

Requirements for muon colliders

- The challenge for a muon collider detectors are decays in flight: the BIB creates a huge occupancy in all detectors
- A time window cut ±150 ps (assuming 50 ps detector time resolution) significantly reduce occupancy
  - Sensors with 50 ps or better time resolution required
- Directionality of hits, e.g. stubs, may also help to reduce combinatorics



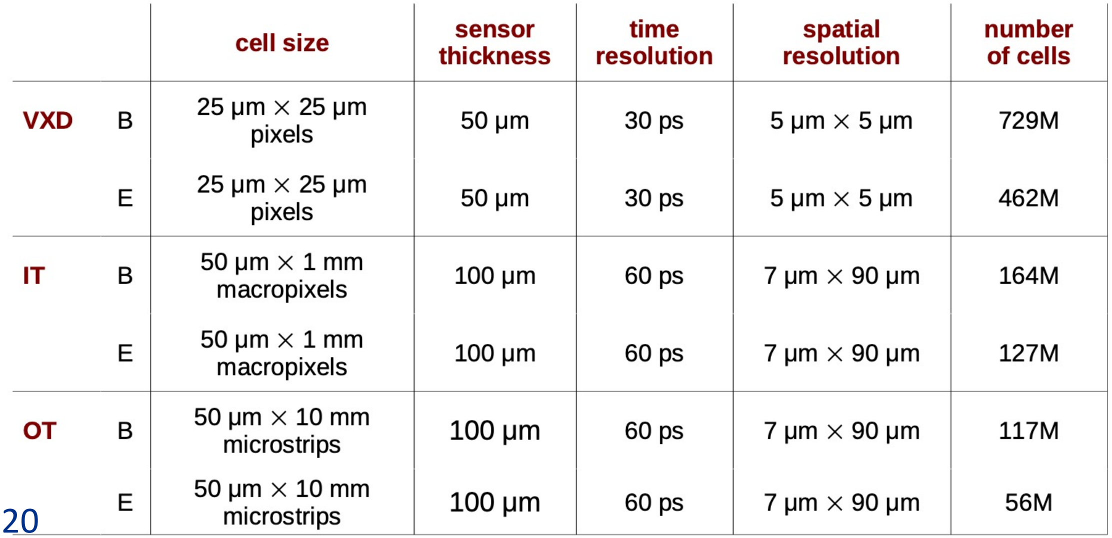




N. Pastrone, ECFA roadmap 2021

Requirements for muon colliders

- A simulation study to scan pixel sizes and time resolutions presented in Snowmass 2020 by H. Weber
  - https://indico.fnal.gov/event/46571
- Assuming a per-pixel occupancy goal of ~1%, we need good timing and small pixels for the innermost layers
  - "Preferable to have good timing everywhere so that we can reduce the number of unwanted hits that will relieve the system as much as possible."

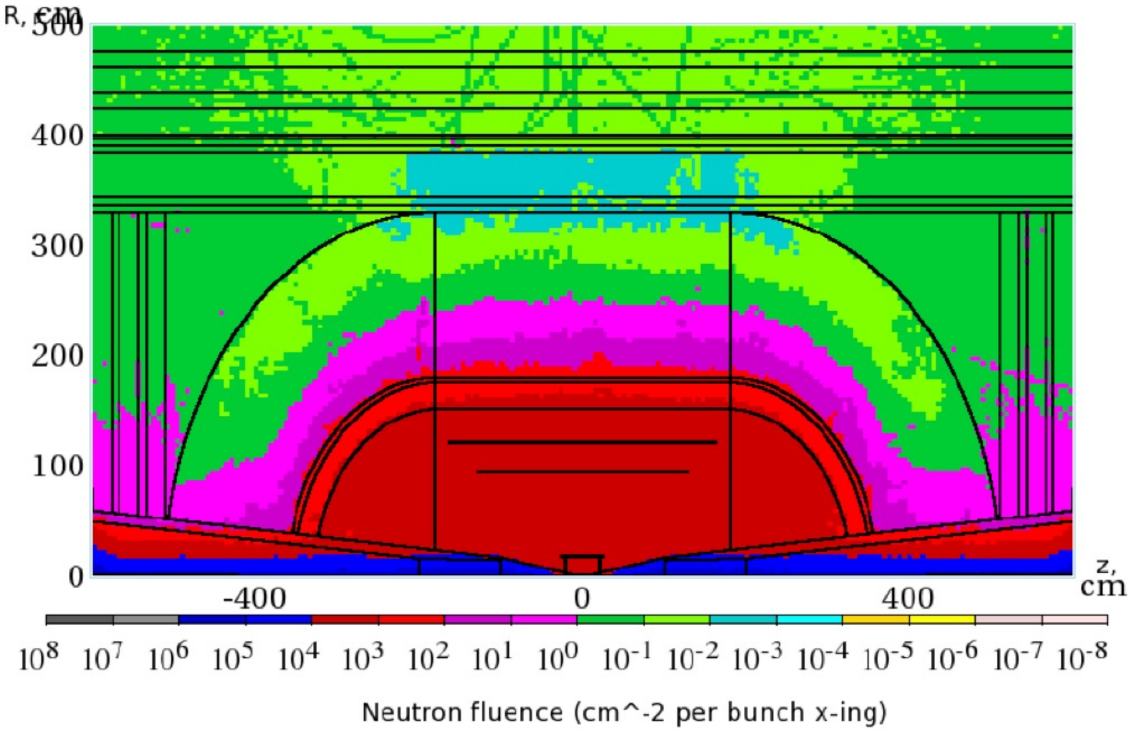


		cell size	sensor thickness	time resolution	spatial resolution	number of cells
VXD	B	25 μm × 25 μm pixels	50 μm	30 ps	5 μm × 5 μm	729M
	E	25 μm × 25 μm pixels	50 μm	30 ps	5 μm × 5 μm	462M
IT	B	50 μm × 1 mm macropixels	100 μm	60 ps	7 μm × 90 μm	164M
	E	50 μm × 1 mm macropixels	100 μm	60 ps	7 μm × 90 μm	127M
OT	B	50 μm × 10 mm microstrips	100 μm	60 ps	7 μm × 90 μm	117M
	E	50 μm × 10 mm microstrips	100 μm	60 ps	7 μm × 90 μm	56M

H. Weber, Snowmass 2020

Radiation environment in the muon collider

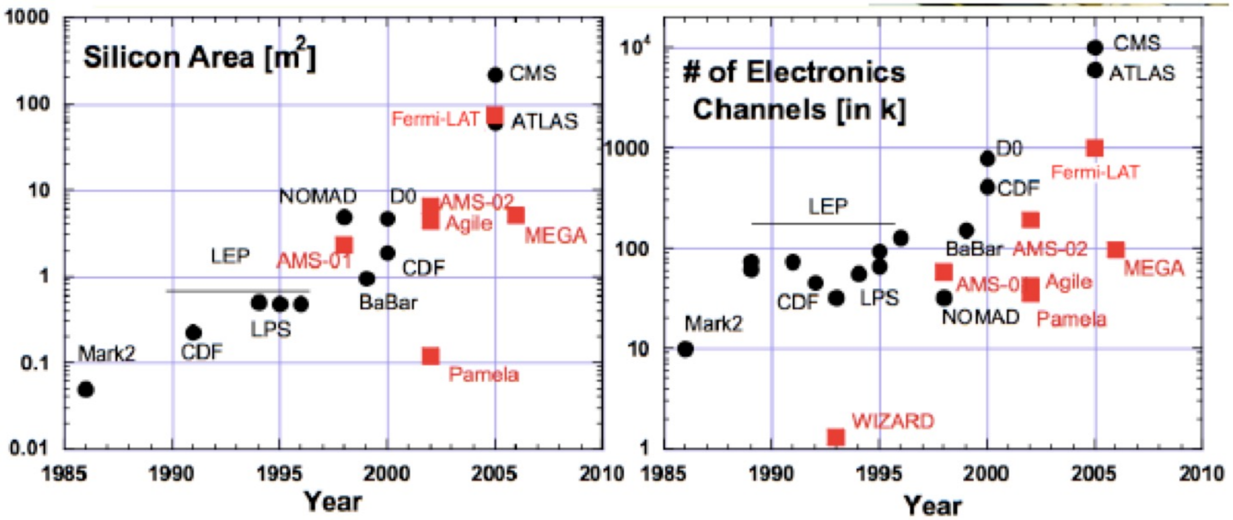
- Neutron fluence estimates suggest the need for trackers to be resilient up to ~10^{15}-10^{16} n/cm^2
  - Comparable to those at the end of life of HL-LHC detectors.



From N. Mokhov: https://indico.cern.ch/event/980924

Trends in tracking technologies

- Silicon trackers are a key ingredient of collider detectors
  - A lot of experience with the technology and radiation tolerance
  - Industrial availability at large producers at affordable costs
  - Easy patterning for experiment’s needs: strips or pixels of various shapes
- Requirements are typically similar:
  - Excellent position resolution, low mass/power, radiation tolerance, timing, low noise, low cost



From H. F.-W. Sadrozinski, “Applications of Silicon Detectors”, IEEE Trans. Nucl. Sci., Vol. 48, No. 4, (2001), 933

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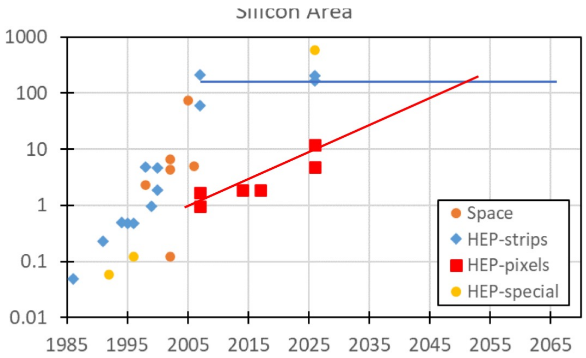
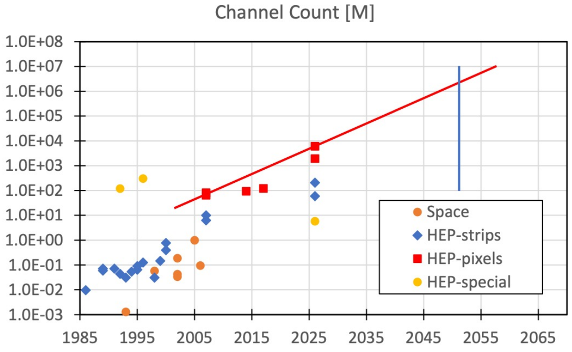
Pixel trackers:

- Continue to increase in area and channel counts.
- Possible that the next tracker will be pixel-only?





V. Fadeyev, Snowmass 2021

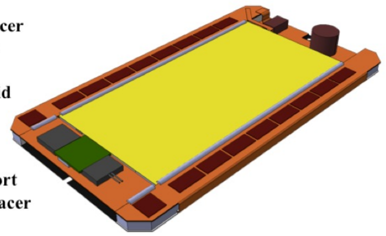
Examples from HL-LHC: CMS

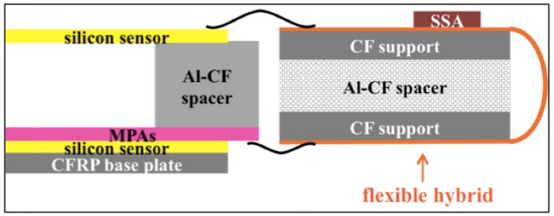
Requirement	Reason
radiation tolerance & cold(er) operation	withstand fluence equivalent to 3000 fb^{-1}
higher granularity	keep occupancy O(1%) to deal with PU 150-200 and for robust track separation
track trigger capabilities / identify high pT tracks @ 40 MHz	contribute to the CMS L1 Trigger
deep front-end buffers and high readout bandwidth	to be compatible with longer L1A latency of 12.4 us and higher L1A rate (750 kHz)
reduction of material budget	improve tracking performance / momentum resolution
extend acceptance to η~4	particle flow in deep forward region

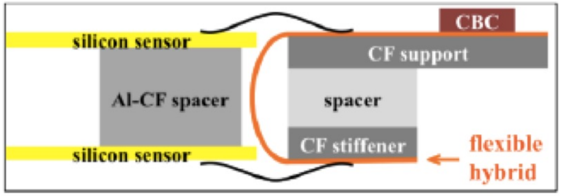
- PS-modules with two layers of silicon
  - Measured the direction of the track by correlating hits between two layers
  - Data reduction by x10-20 at trigger readout
  - Stubs used as input for L1 track finding
  - Utilize extensive parallel processing to tackle above challenges

PS Modules

1. PS-s silicon sensor
2. PS-p silicon sensor
3. MPAs
4. Al-CF sensor spacer
5. CFRP base plate
6. FE Hybrid
7. Opto-Link Hybrid
8. Power Hybrid
9. SSA
10. CIC
11. Hybrid CF support
12. Al-CF Hybrid spacer

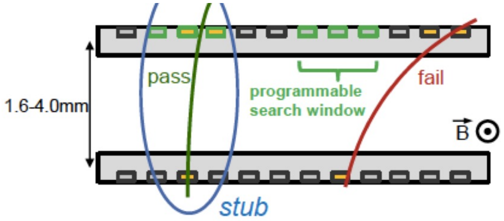






2S Module

Modules designed to support tracking at L1 trigger

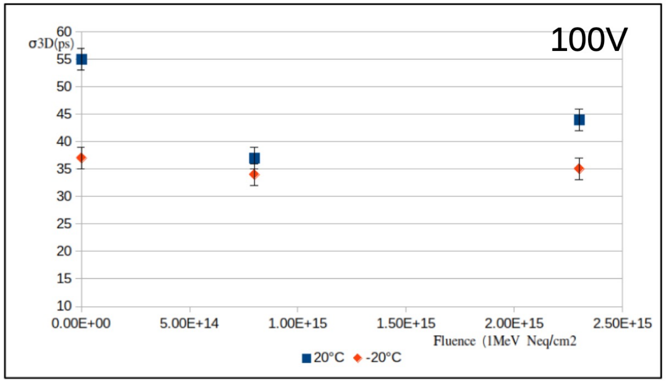


Upshot: every module delivers track stubs at BX rate (40MHz)

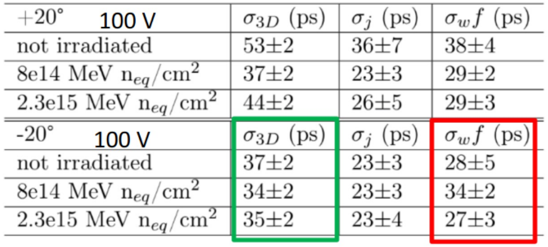
Examples from HL-LHC: ATLAS

- 3D silicon sensors (innermost layer)
  - Small pixels with high radiation tolerance
    - Large signal with short collection distance
    - Less charge trapping, fast charge collection
    - Radiation hardness up to 10^{16} n/cm^2
    - Very low full depletion voltage

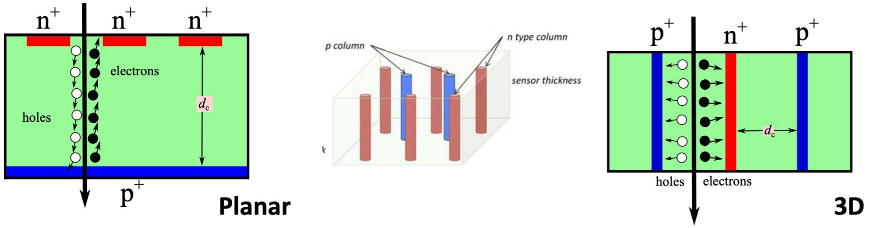
Timing Resolution of Irradiated 3D CNM sensors

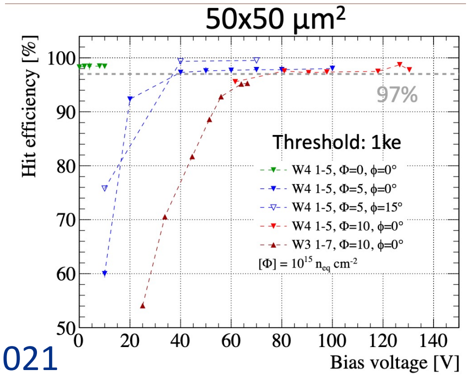


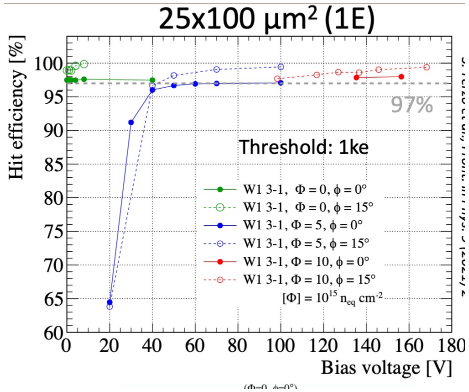
Moritz Wiehe, TIPP 2021



+20° 100 V	σ_{3D} (ps)	σ_j (ps)	σ_{wf} (ps)
not irradiated	53±2	36±7	38±4
8e14 MeV n_{eq}/cm^2	37±2	23±3	29±2
2.3e15 MeV n_{eq}/cm^2	44±2	26±5	29±3
-20° 100 V	σ_{3D} (ps)	σ_j (ps)	σ_{wf} (ps)
not irradiated	37±2	23±3	28±5
8e14 MeV n_{eq}/cm^2	34±2	23±3	34±2
2.3e15 MeV n_{eq}/cm^2	35±2	23±4	27±3



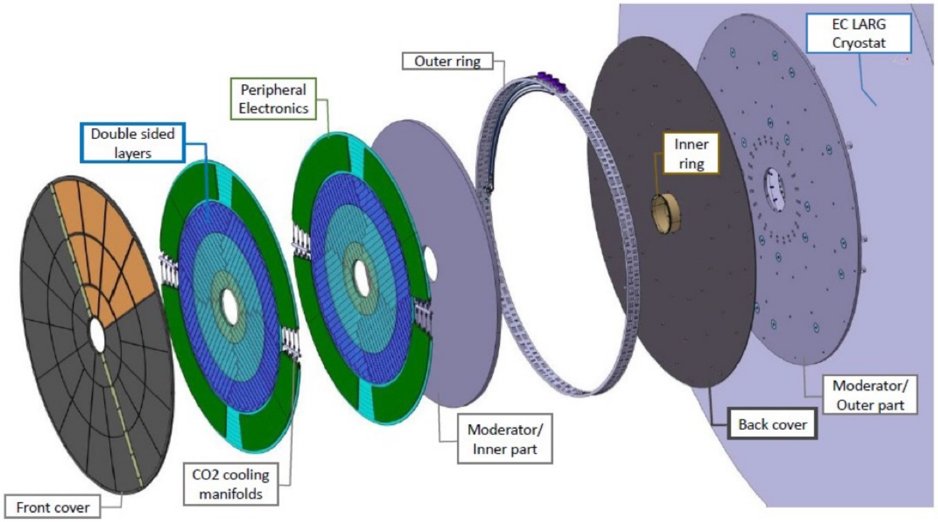




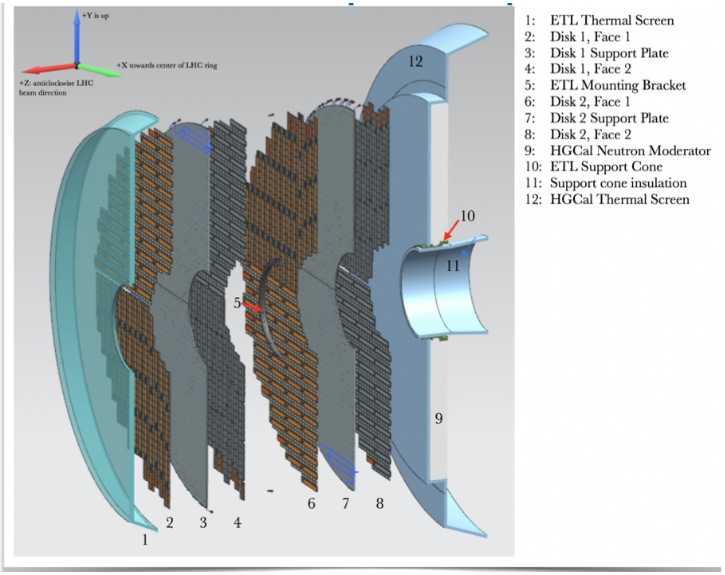
S. Terzo, TIPP 2021

4D trackers: present and future

- CMS and ATLAS are building Gen-1 4D-tracking detectors
  - Single or two hits per charged particle, and large pixels
  - Next generation detectors will be more sophisticated and replace tracker
- Active R&D on technologies to achieve the required performance for the future 4D-trackers
  - Sensors, ASIC, front-end electronics developments



ATLAS timing detector



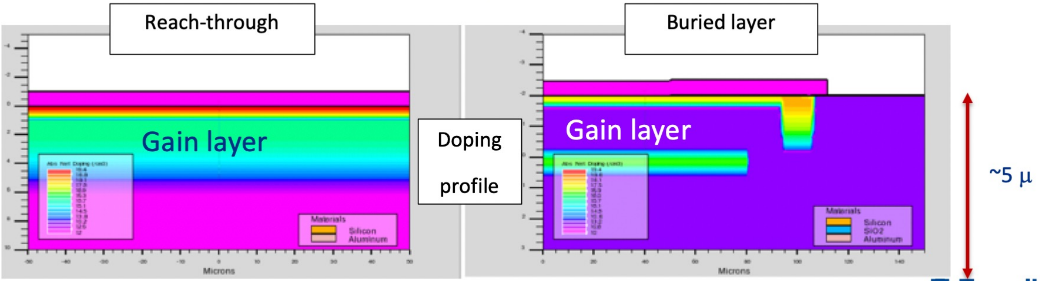
CMS timing detector

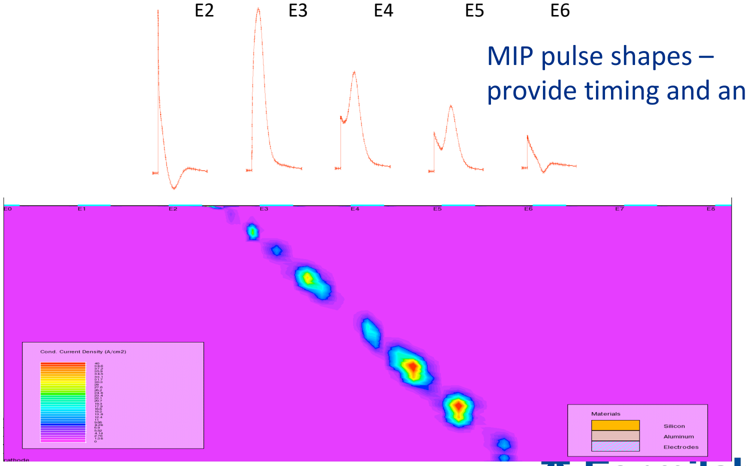
Ongoing efforts

- A snapshot of areas with active R&D for tracking applications
  - Low Gain Avalanche Detectors (LGADs): good timing, large pads
  - AC-LGAD: good position and timing resolution for MIPs
  - Monolithic detectors (HV/HR-CMOS) with embedded readout
  - Specially designed sensors to provide track position, angle and timing
  - Diamond detectors, 3D sensors, thin film detectors
- Common challenges for many technologies:
  - Services, cooling, low-power ASICs

Usual reach-through implanted from top – limited options

Gain layer grown over implant – can be denser, top can be custom processed

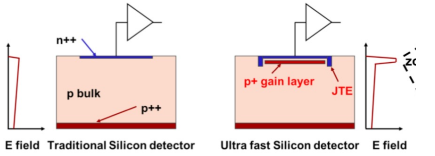




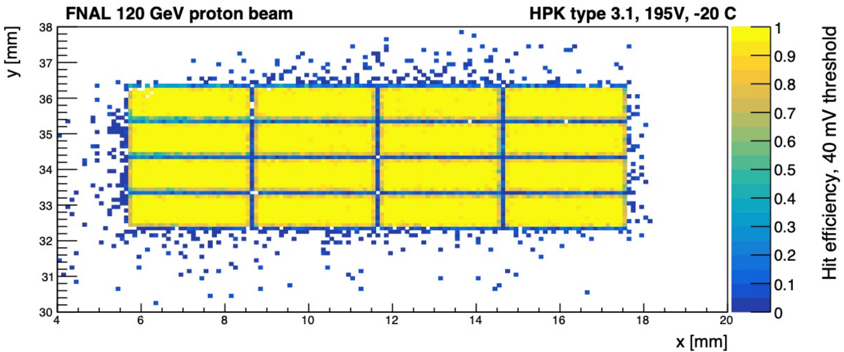
MIP pulse shapes – provide timing and angle

Advanced detector R&D for future experiments

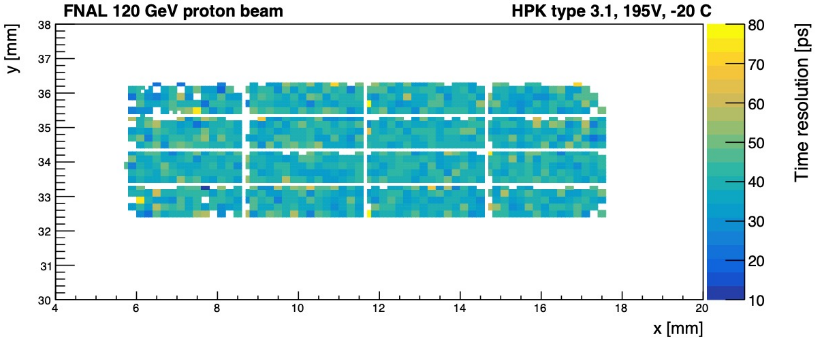
- A key breakthrough is the recent development of trackers with the addition of timing information: full 4-vectors (x,y,z, t)
  - Low-Gain Avalanche Detectors (LGAD)
  - Silicon detectors with internal gain



- Sensors developed for CMS and ATLAS show high degree of uniformity, excellent time resolution, rad hard up to **~3x10^{15} n/cm^2**
  - However, no-gain gaps between pixels: due to presence of JTE
- **Improve Gen-1 4D-trackers: achieve 100% fill factor, high position resolution**



Hit efficiency across surface of the 4x4 sensor

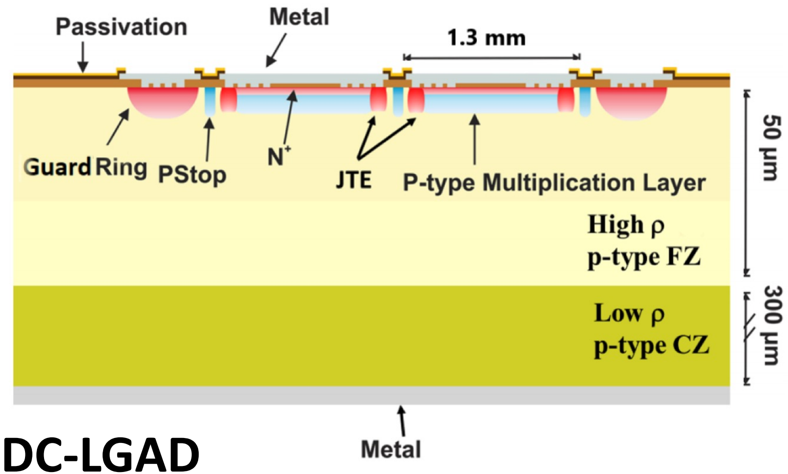


Time resolution across surface of the 4x4 sensor

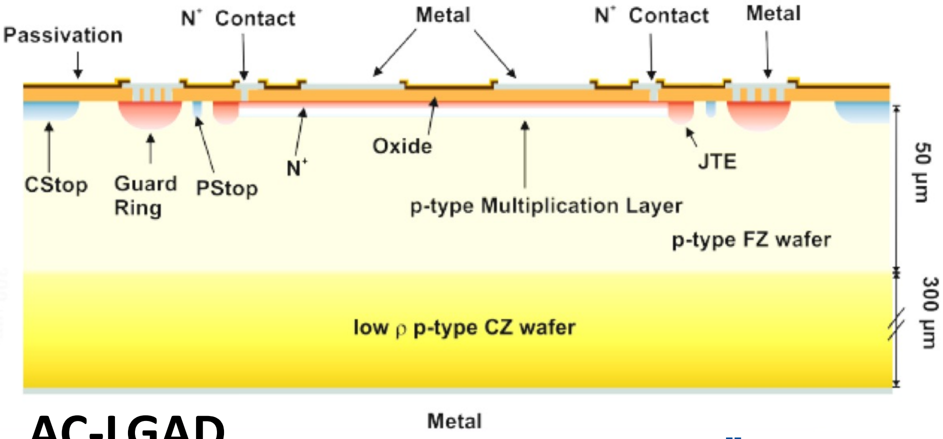
AC-coupled LGADs

- Ongoing R&D to eliminate dead area
  - Simultaneously improve position resolution via charge sharing
- Active R&D at different manufacturers (FBK, BNL, HPK, etc)
  - 100% fill factor, and fast timing information at a per-pixel level
  - Signal is still generated by drift of multiplied holes into the substrate and AC-coupled through dielectric
  - Electrons collect at the resistive n+ and then slowly flow to an ohmic contact at the edge.

Diagram credit: CNM



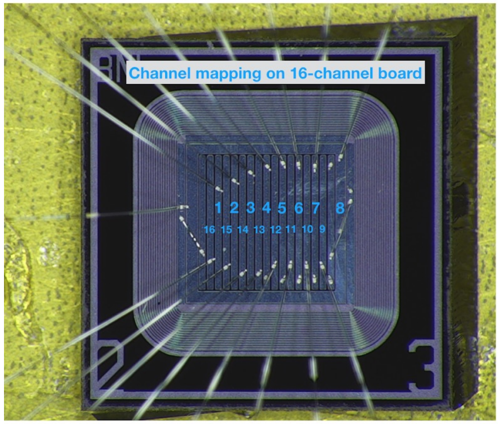
DC-LGAD



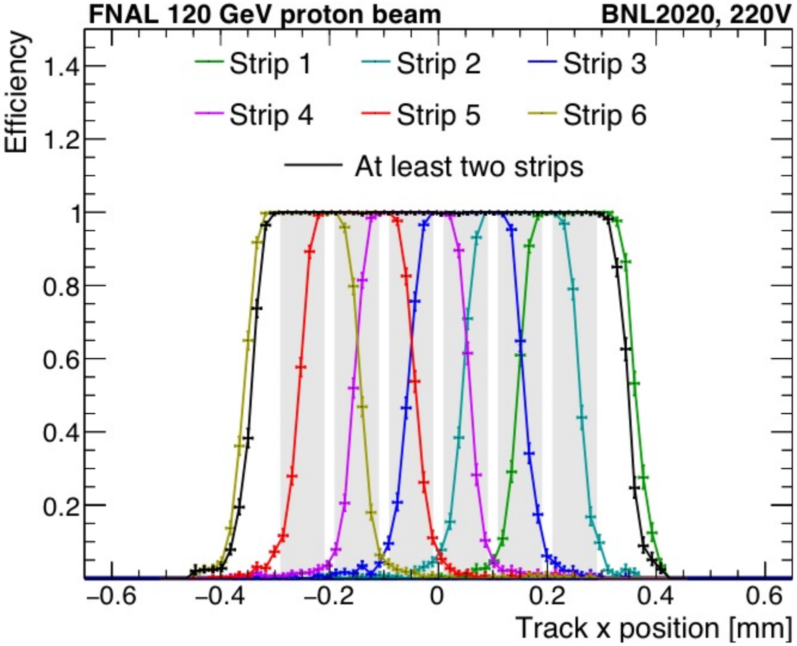
AC-LGAD

AC-LGAD measurements in beams

- Excellent performance in the beam showing high efficiency
  - Several measurements in FNAL test beams in 2020-2021
- Time resolution and position resolution achieved targeted goals
  - 100% particle detection efficiency across sensor surface

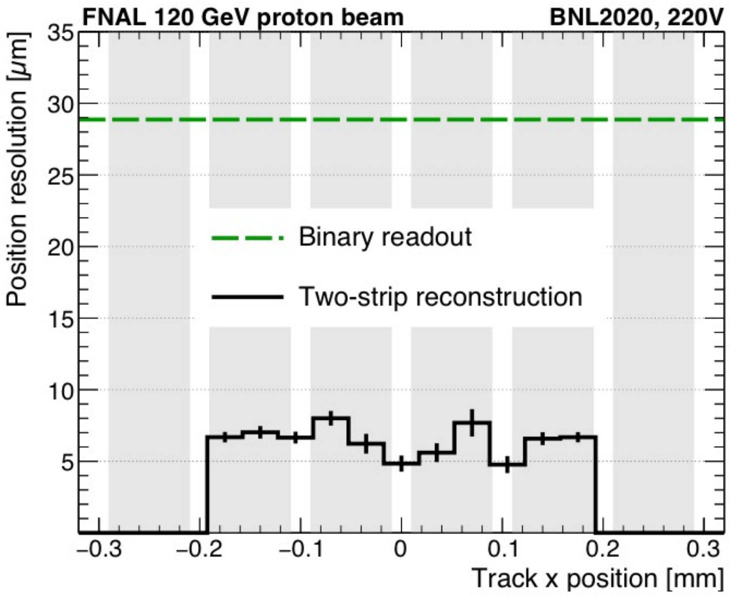


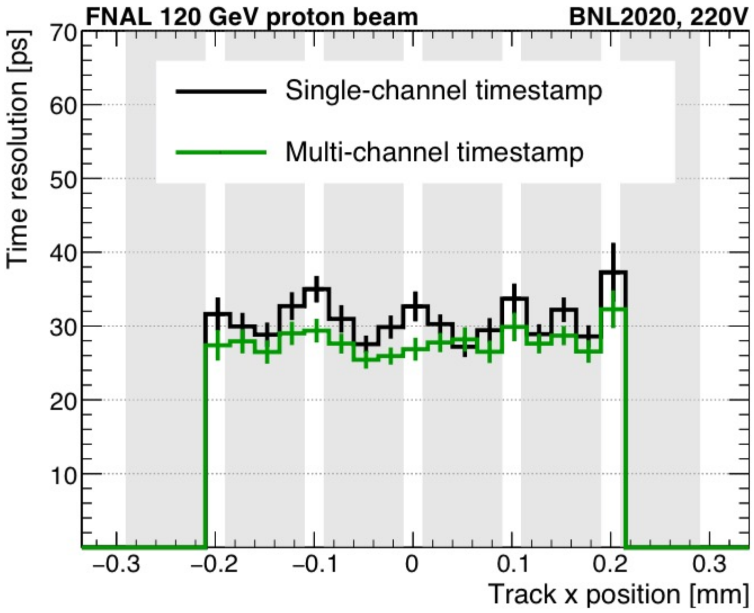
BNL strip AC-LGAD



AC-LGAD measurements in beams

- AC-LGAD strip detectors delivered position resolutions below 5–10 µm, at the limit of the measurement sensitivity.
  - These resolutions are 5–15x better than from binary readout
  - All sensors demonstrate uniform ~30 ps time resolution across surface

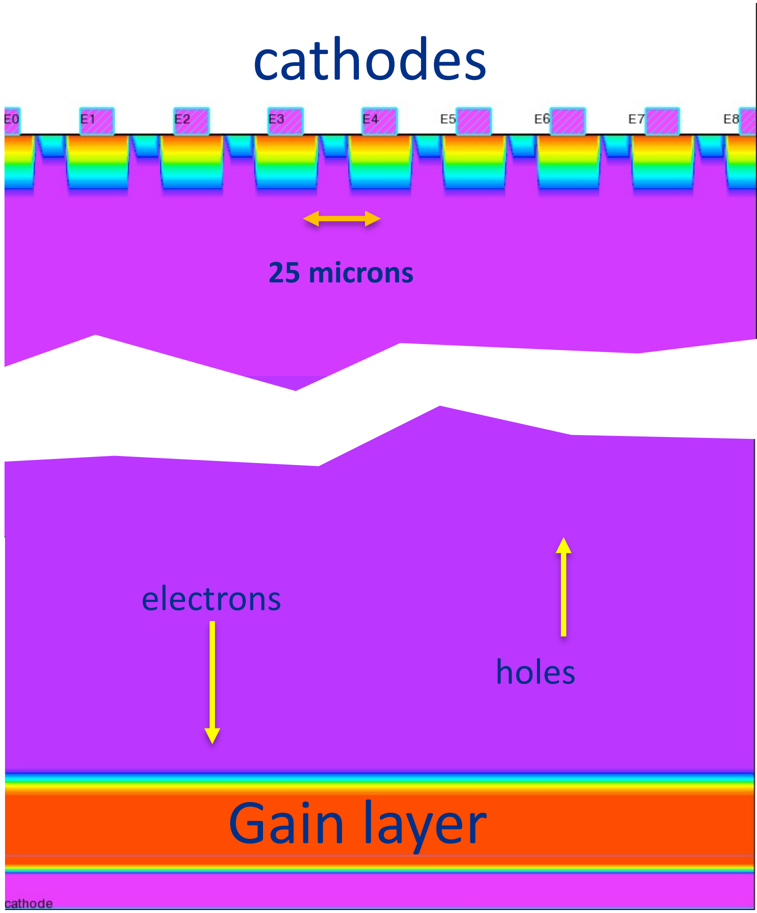




- **First demonstration with simultaneous 30 ps and 5 µm resolution!**

Double Sided LGAD

- Low Gain Avalanche Diode with fine pixels on the hole-collecting side
  - Anode can provide timing with coarse pitch
  - Cathode subdivided into small pixels
- Records "primary" hole collection, then holes from gain region – double peak that reflects charge deposition pattern
  - Lower power due to large signal from the gain layer
- Resulting current pattern can be used to measure angle and position.
- Detector can be optimized to measure angle or charge deposit location

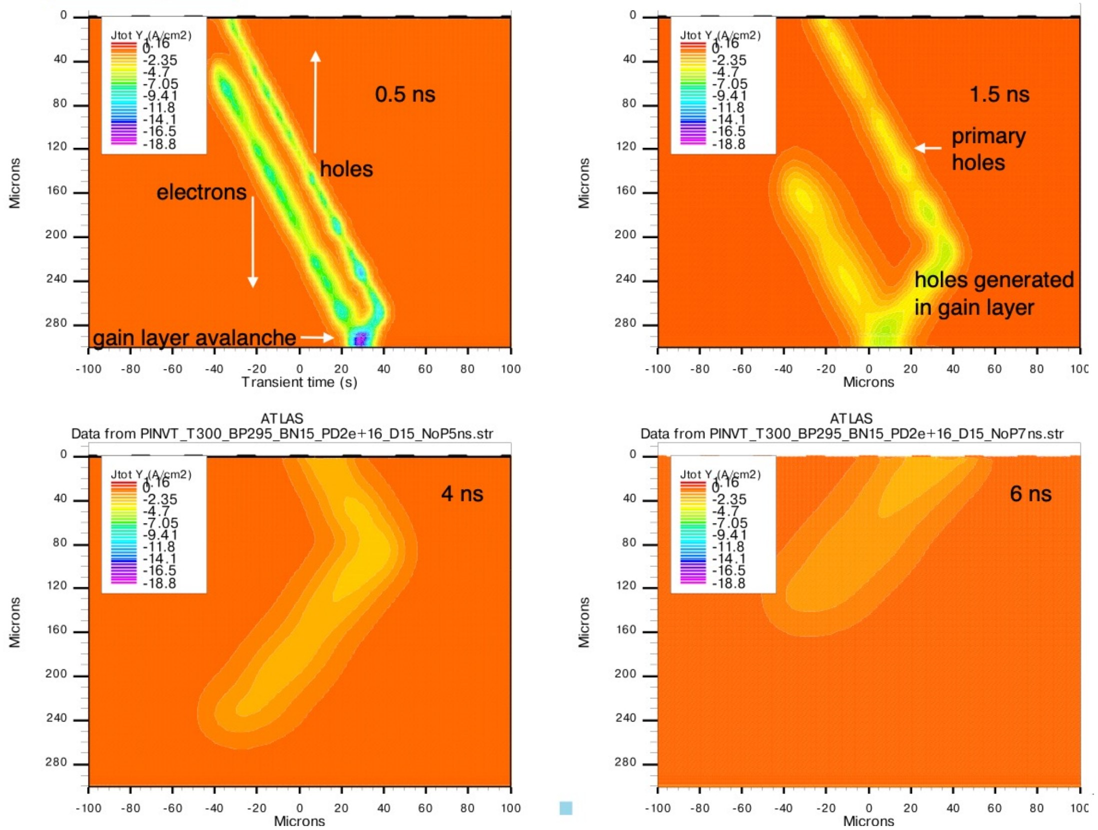


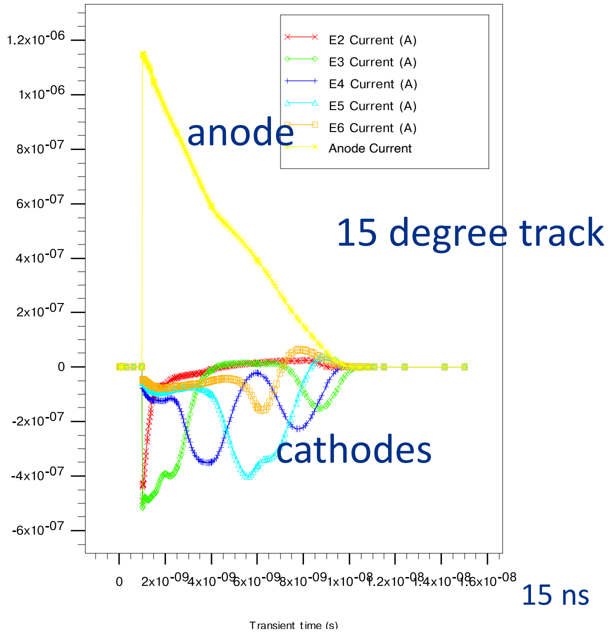
R. Lipton, Snowmass 2021

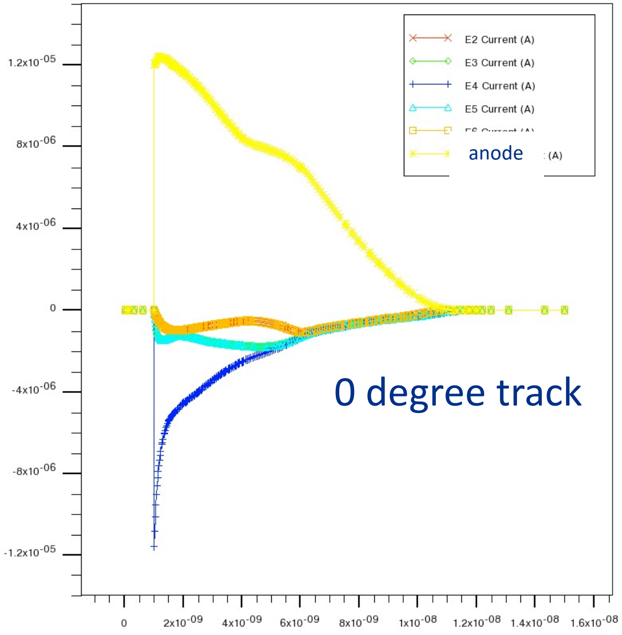
Double Sided LGAD Simulation

- Use anode for timing, cathodes for pulse shape discrimination

15 degree track detector internal current distributions







Induced currents sensors

R. Lipton, NIM A 945 (2019)

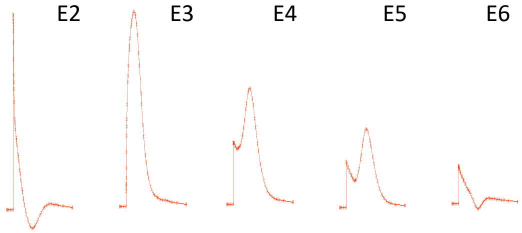
Capabilities enabled by new technologies that provide small pixels with low capacitance and sophisticated processing

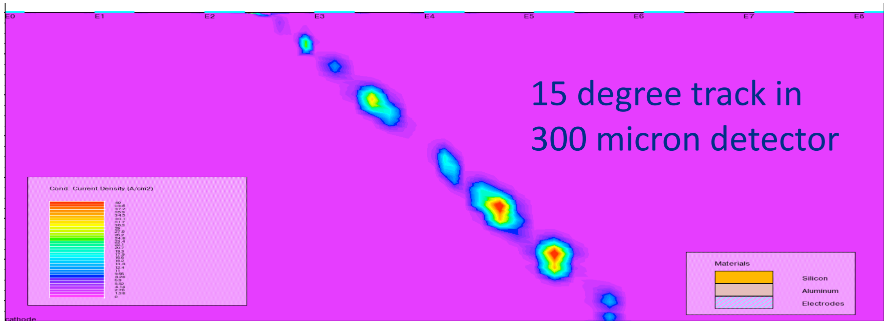
- 3D integration of sensors and electronics provide low C_L , dense interconnects and processing
- Enables 4D tracking detectors + directionality (X,Y,Z,T,θ)

If the signal/noise is high enough we can use fast induced currents rather than collected charge to provide additional time, position, and angle information

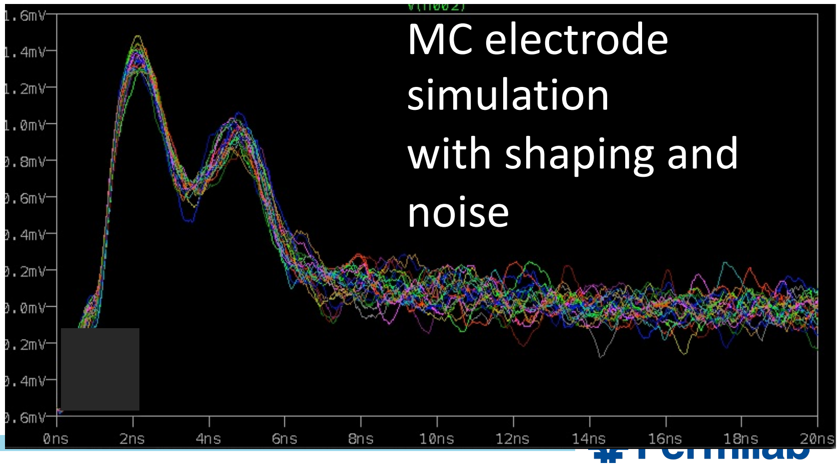
- Use the current pulse shape to characterize charge deposit, track angle
- Fast timing, radiation hard, precise, angle resolution

MIP pulse shapes – provide timing and angle





15 degree track in 300 micron detector



MC electrode simulation with shaping and noise

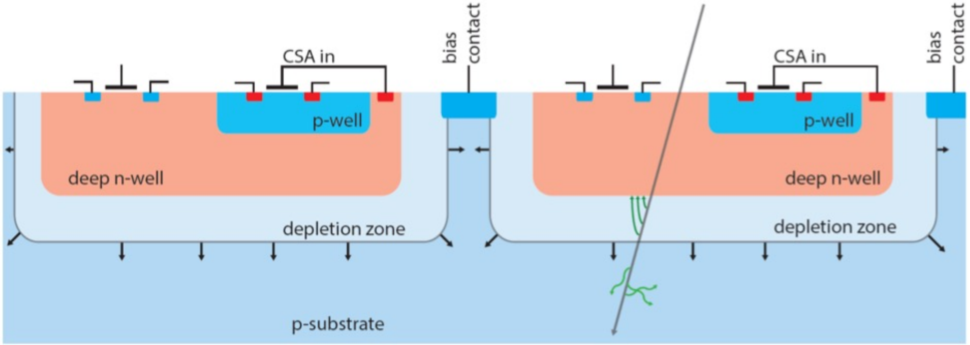
Electronics needs

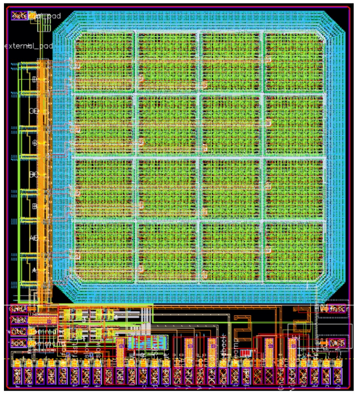
- The developments of the current CMS and ATLAS detectors are demonstrating the challenges of the electronics designs
  - For HL-LHC: pixel size is 1.3x1.3 mm^2, ~2 mW/pixel
  - Going to small pixels for muon colliders, e.g. 50x50 μm^2: need to reduce power consumption per pixel by ~x680 to stay within cooling budgets similar to CMS/ATLAS timing detectors.

- Significant advancements will be needed:
  - More power/cooling budget,
  - Larger pixel size: AC-LGAD is one potential way to get precision position resolution with relatively large pixel sizes
  - Advanced detector concepts, new materials, AI/ML processing on chip
  - Advanced technology nodes (e.g. 28 nm) to reduce power consumption

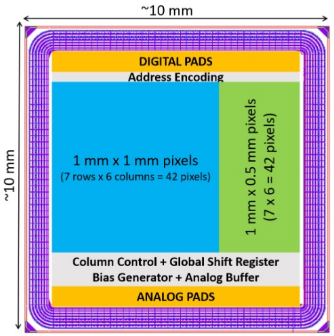
Monolithic sensors

- Monolithic sensors with embedded readout
  - Take advantage of electronics on top layer
  - Can achieve good signal-to-noise
  - Some R&D ongoing, developed for ATLAS, ALICE, mu3e
- These developments promise to be paradigm-shifting in the development of next-gen detectors





TT-PET chip: G. Iacobucci October 4, 2019 CERN seminar

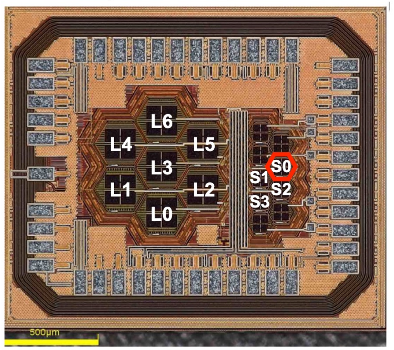


Cactμs chip: JINST 15 P06011

Monolithic sensors

- TT-PET prototype sensors measurements
  - SiGe 130 nm process, dedicated custom components developed together with foundry
  - Prototype sensor tested: hexagon shaped pixels 130µm and 65µm, with 10µm inter-pixel spacing
  - Impressive results achieved with multipixel sensors
- Monolithic AC-LGADs
  - Combine benefits of LGADs with monolithic process
  - Aim to fabricate prototypes with TJ 65 nm process

Small pixel S0, C = 70 fF



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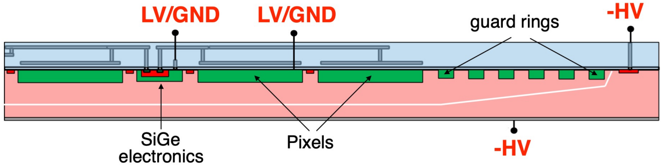
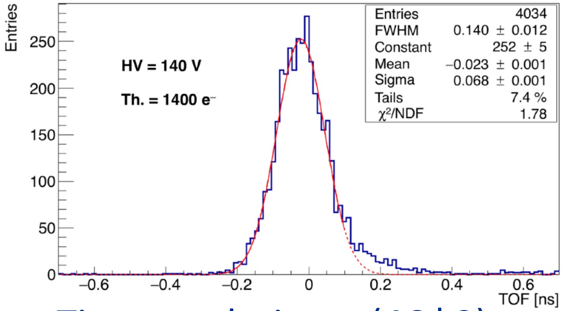
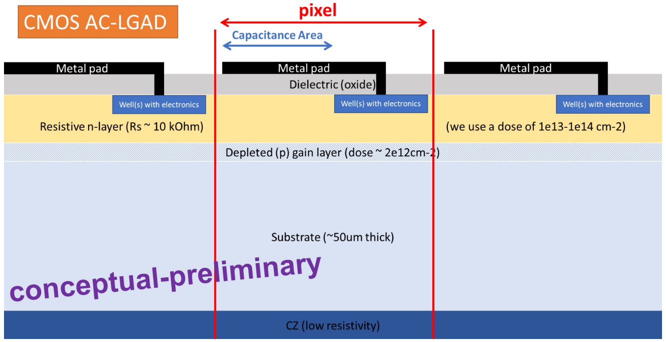




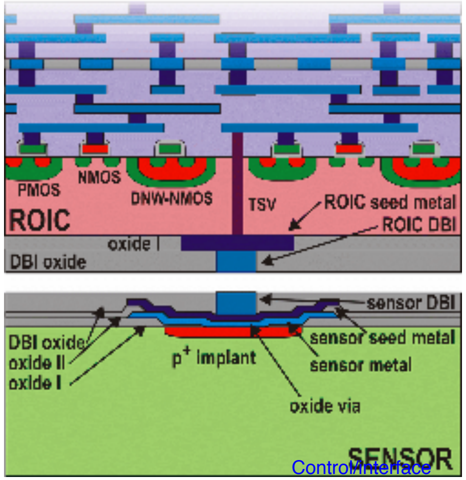
Time resolution≃ (46±2) ps



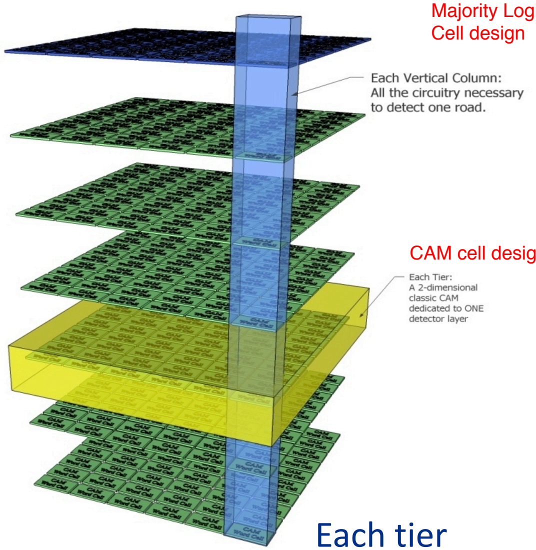
G. Deptuch, Snowmass 2021

Possibilities

- Advanced integration of technologies on the front-end
  - AI/ML on-chip to extract features for fast tracking and L1 triggering, on chip clustering to readout reduce data volume
  - Wireless communication between chips/layers of trackers to form tracks/stubs/vertices
  - Novel materials to design more power-efficient da processing on the front-end
- Extensive 3D integration
  - Very fine pitch possible, multiple layers of electronics for sophisticated signal processing, vertically integrated
  - Possible to integrate different technologies, each optimized for separate tasks



Control/Interface



Majority Logic Cell design

CAM cell design

Each tier ~tracking layer

Conclusion

- Future tracking detectors will be required to have significant timing precision: particularly critical for muon collider
  - Timing precision of ~30 ps achieved with several Si-based technologies

- The requirements for the tracker for the muon collider are ambitious
  - Simultaneous high position and timing requirements are challenging
  - However, the community is making fast and steady progress towards those goals, and many innovative ideas are emerging
  - Many promising directions with paradigm-shifting potential

- Exciting opportunities to get engaged in cutting edge detector R&D
  - Collaborative efforts are the key for progress