Timing detectors R&D directions

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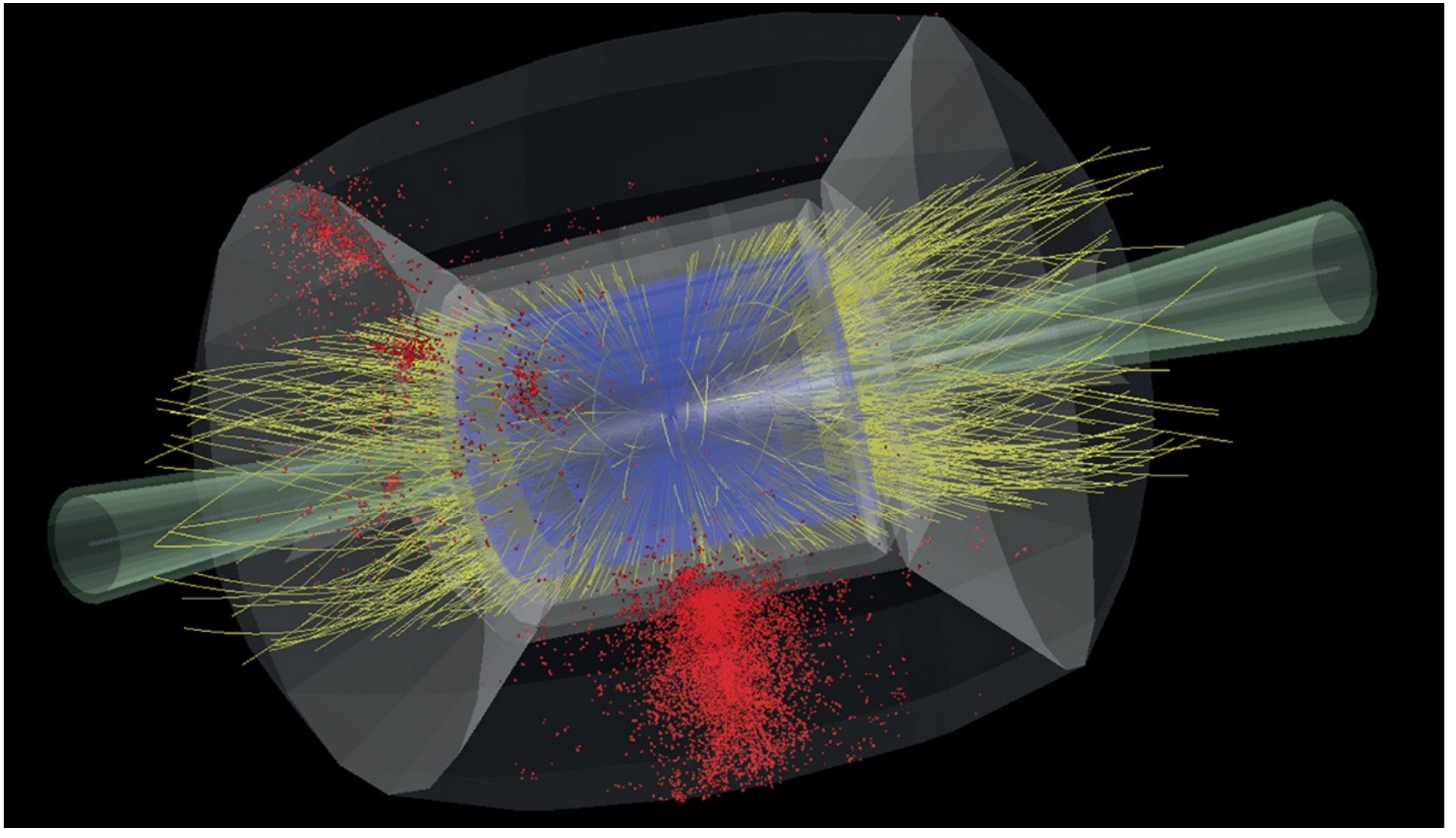
Inaugural US Muon Collider Community Meeting

August 8, 2024

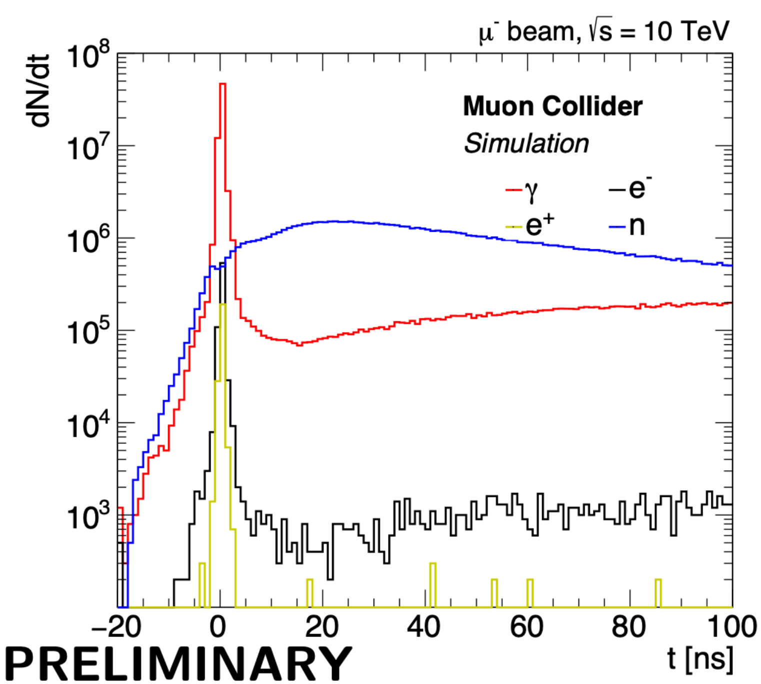
Muon Collider

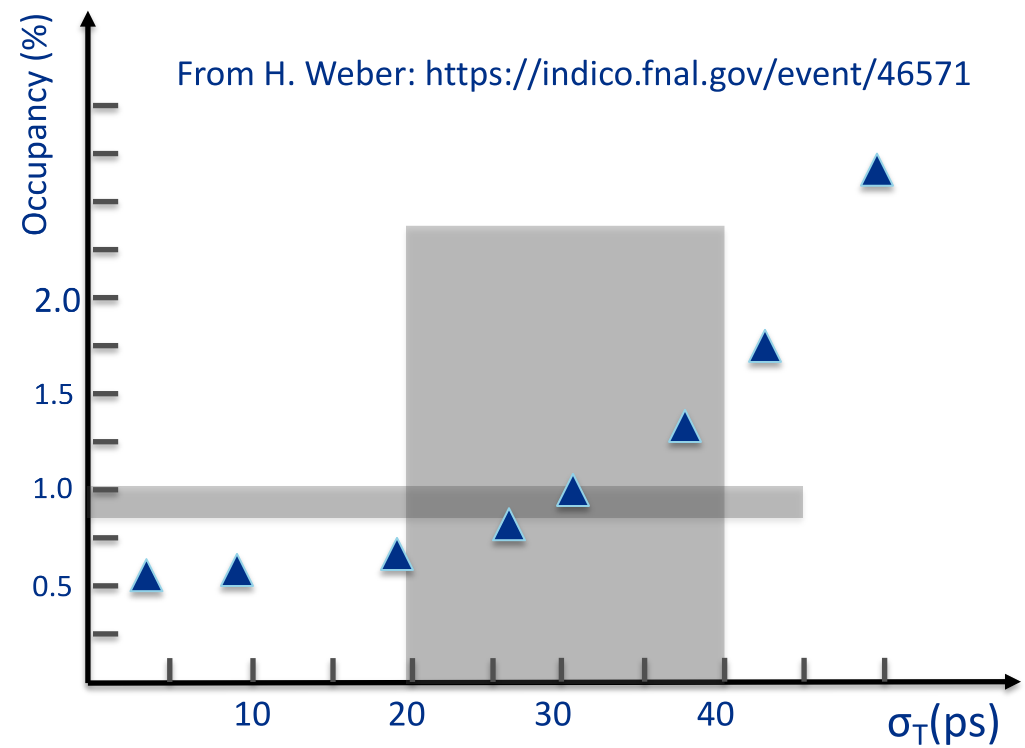
- An incredible machine with unparalleled physics potential



Challenges for Detectors at Muon Colliders

- Timing of BIB backgrounds is very different
  - Detectors with good timing to eliminate BIB
  - ***Tracker*** : need ~20-40 ps
  - ***Calorimeter and muon*** : need ~100 ps



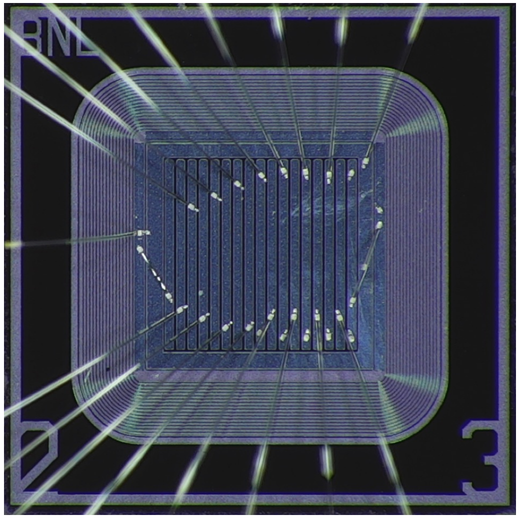


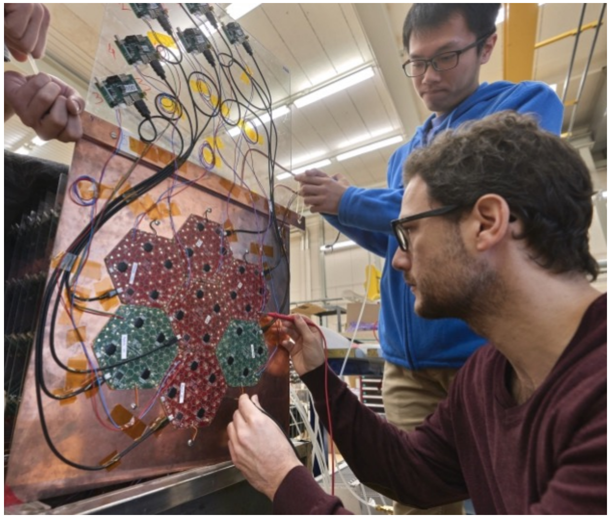
Precision timing

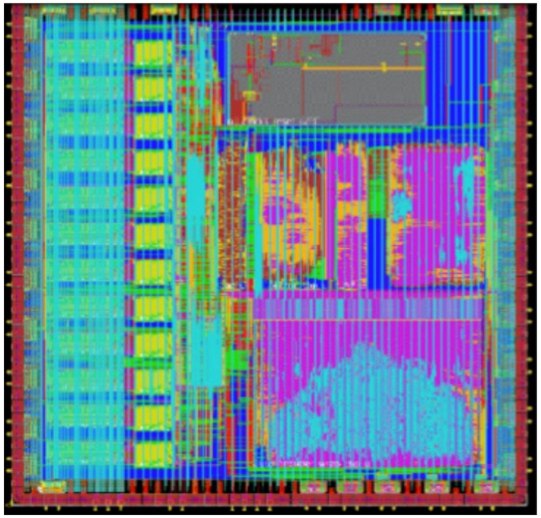
- Traditionally in collider experiments we measure very well
  - **Position**, **charge** and **energy** of particles

- Next-gen detectors will have high granularity also in **time**
  - Tracker, calorimeter, muon detectors, and L1 trigger
  - Move towards full **5D Particle Flow**

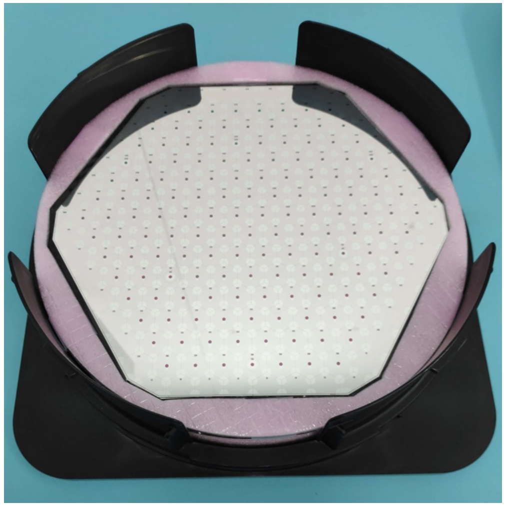
- Precision timing information will radically change the capabilities of future experiments
  - Improve **event reconstruction, Level-1** trigger, and new techniques in **searches** for New Physics

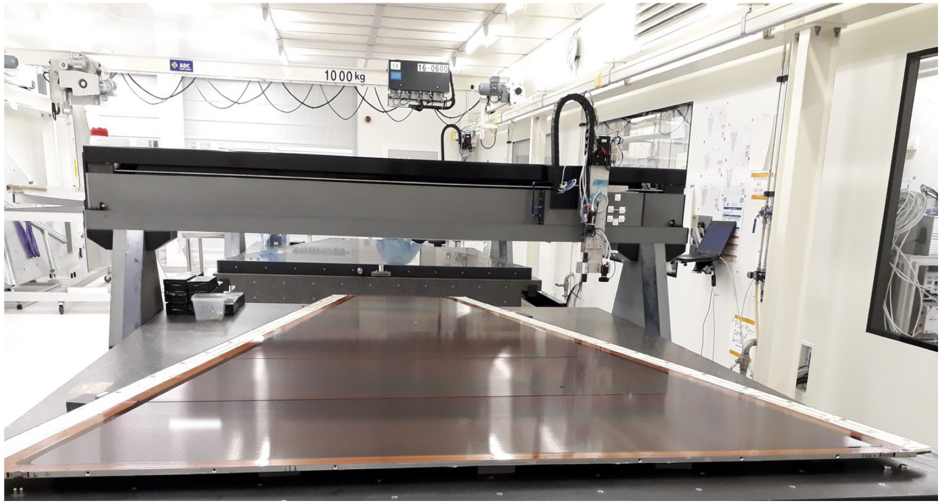




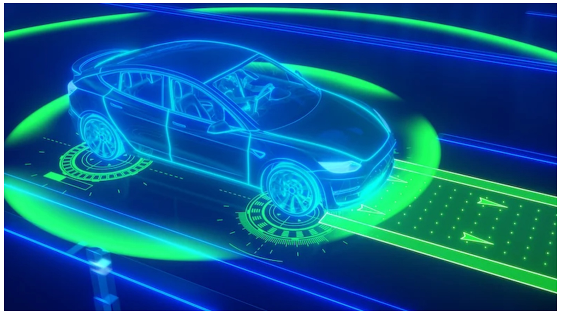


Cutting edge detector R&D is needed!

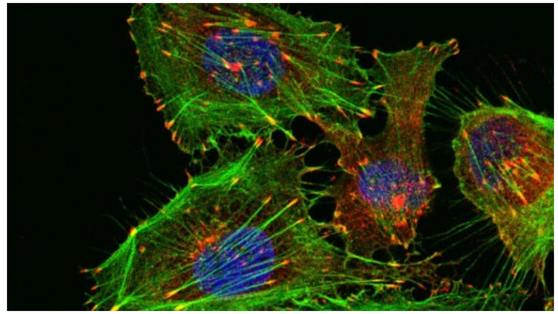




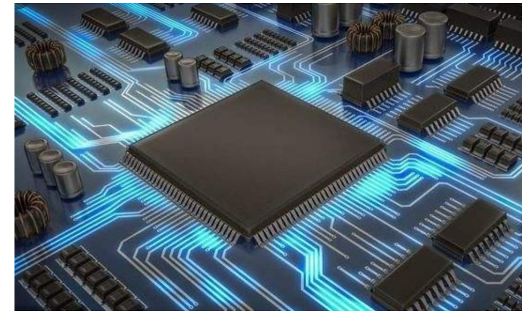
Synergistic developments across many fields



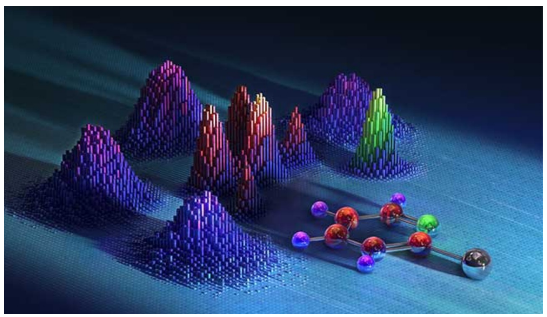
Lidars and Automotive



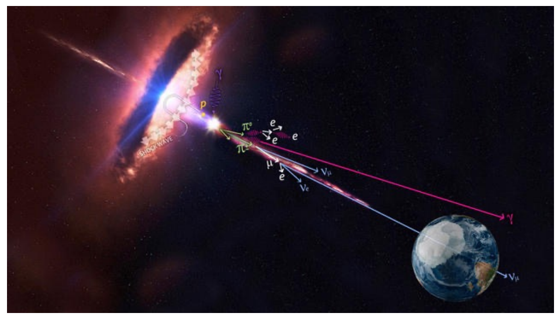
Bio Imaging and Life Science



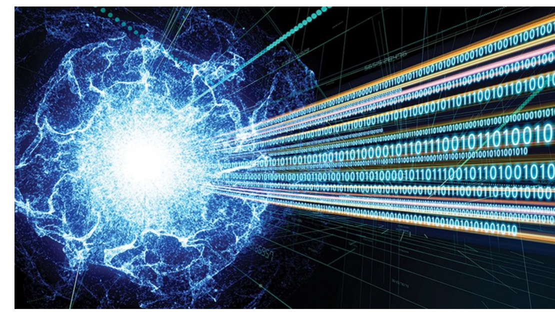
Fast timing applications



Coulomb explosion imaging

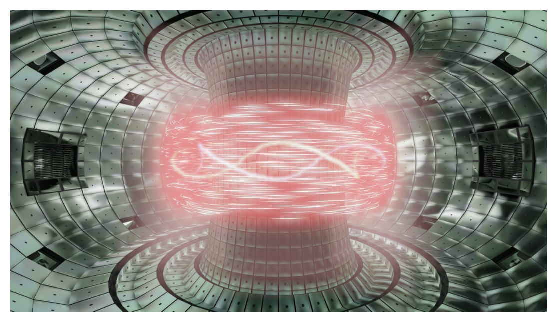


Astro-particle physics



Quantum science and cryptography

Advanced manufacturing



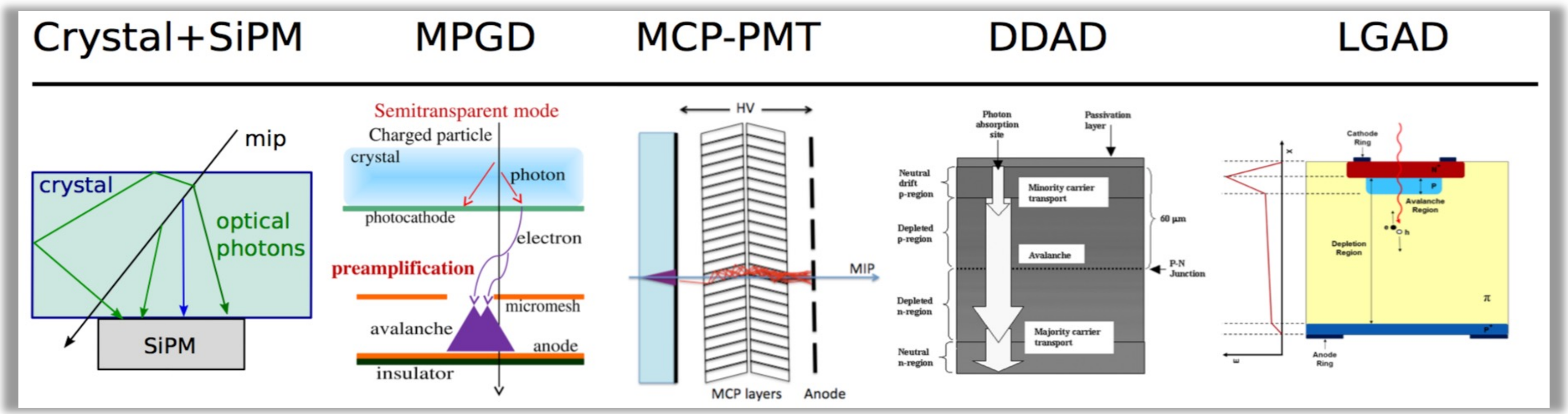
Fusion Energy Research

Technologies for precision timing detectors

- Complex systems need to be developed and implemented
  1. Rad-hard detecting **sensor** capable of high precision timing
  2. High precision, rad-hard, and low-power **readout electronics**
  3. Low noise detector system with high fidelity precision **clock**
  4. Integration into **trigger** and **event reconstruction**
  5. Continuous **monitoring** and **calibration**

Technologies for precision timing detectors

- Active area of R&D for future collider experiments
  - One of the priority areas highlighted in DOE BRN, European Strategy for Particle Physics, and Snowmass
- Optimized solutions for various applications
  - Trackers: high granularity and low mass
  - Calorimeters: dense volume interspersed with fast detecting medium
  - Muon detectors: fast gas detectors with low mass



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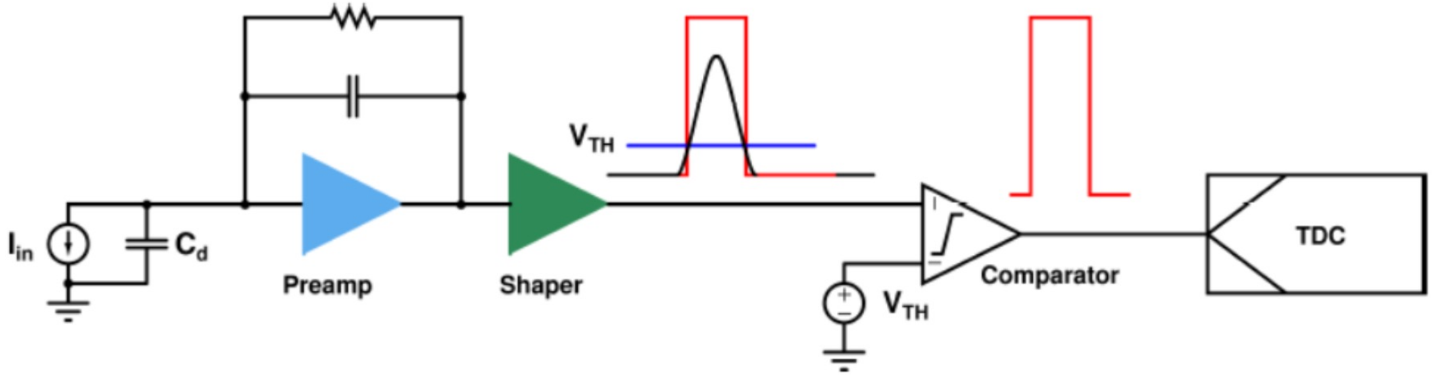
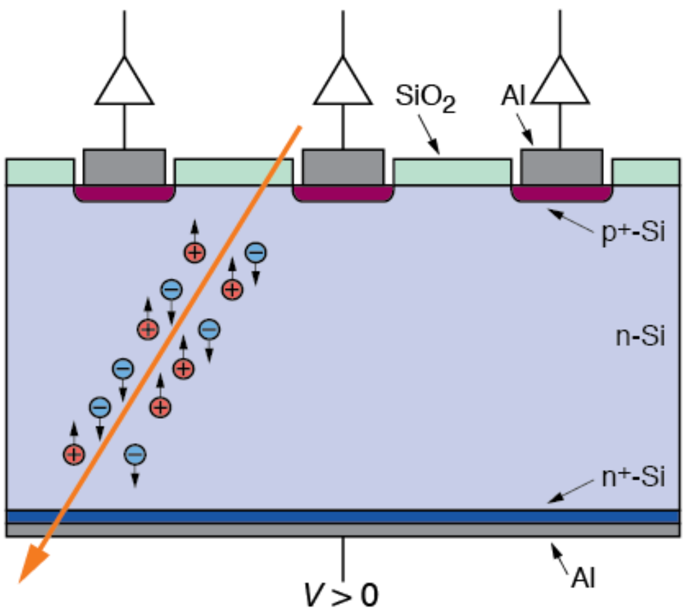
Timing resolution

- Particles passing through medium generate signals which are then measured to *time-stamp* the arrival
  - Depending on detector type (tracker, calorimeter) the dominant effects that impact resolution slightly vary
- The goal is to design sensors that deliver the best timing information, while optimized for a specific application
  - Let's walk through an example of charged particle passing through silicon sensor



Signal attributes

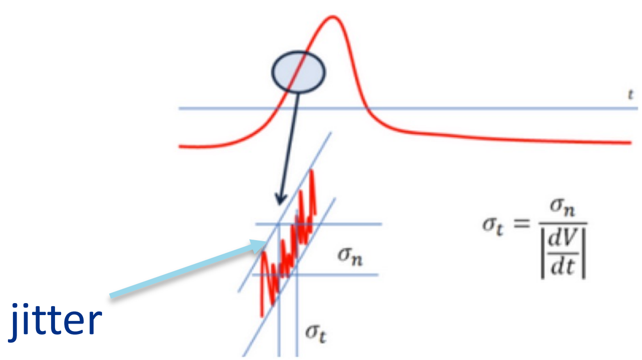
- Signal of MIP passing through a silicon detector depends on the thickness of the depletion zone and dE/dx
- The noise in a silicon detector system depends on various parameters: geometry of the detector, the biasing scheme, the readout electronics, etc.



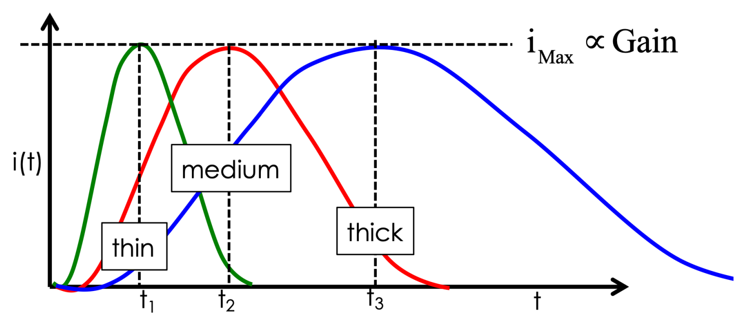
Time resolution components

- Optimize detector timing resolution
  - Increase Signal/Noise to minimize jitter
  - Fast rise time to reduce impact of electronic noise: thinner sensor
- Non uniform charge deposition:
  - Landau fluctuations: cause fluctuations in signal shape and amplitude
  - Effect is reduced in thinner sensors

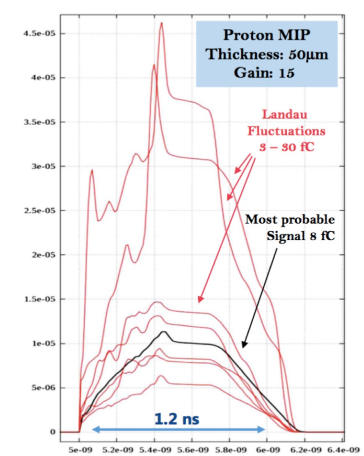
$$\sigma_t = \frac{\sigma_V}{\frac{dV}{dt}} = \frac{N}{\frac{S}{t_r}} = \frac{t_r}{S/N}$$



$$\frac{dV}{dt} \propto \frac{G}{d}$$



Rise time dependance on Si thickness



Landau fluctuations

Time resolution components

- Once the sensor medium is optimized need to design the rest of the system
  – Front-end Readout Chip (ROC) that can optimally extract the timing information available from the sensor

- Power and overall system design impose constraints on the ROC precision

Timing resolution

- Putting together various components

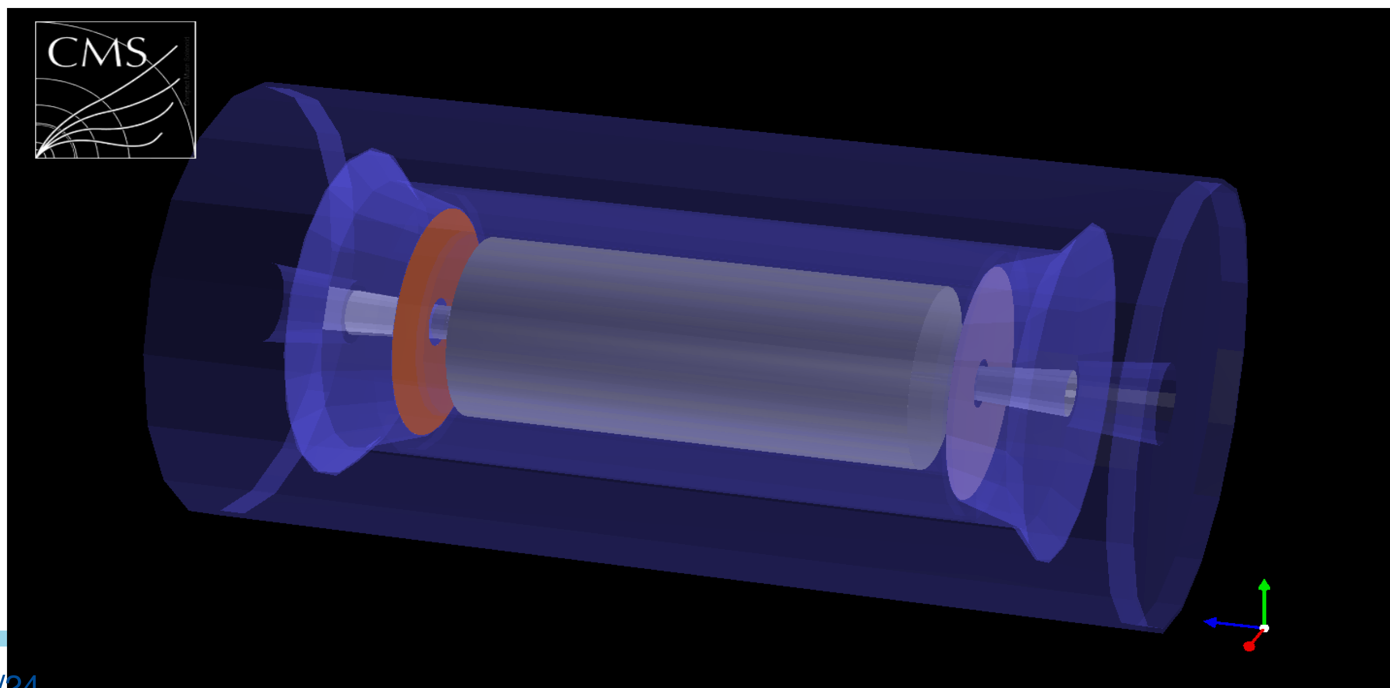
$$\sigma_t^2 = \sigma_{Landau}^2 + \sigma_{timewalk}^2 + \sigma_{jitter}^2 + \sigma_{TDC}^2 + \sigma_{clock}^2$$

- Ideal detector components
  - Fast signals with large S/N ($\sigma_{jitter} = t_{rise}/(S/N)$)
  - Thin sensors to minimize σ_{Landau}
  - Stable and uniform signals across sensor area
  - Optimized electronics to reduce time-walk and clock jitter
  - Electronics with low power consumption

- Radiation damage complicates things, so all these need to be also resilient to high fluences in hadron colliders

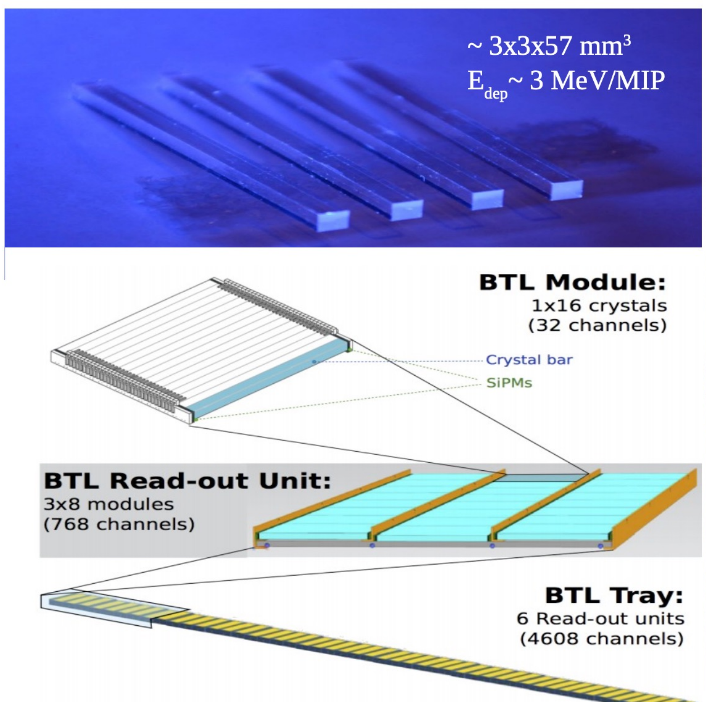
Example: precision timing for CMS in HL-LHC

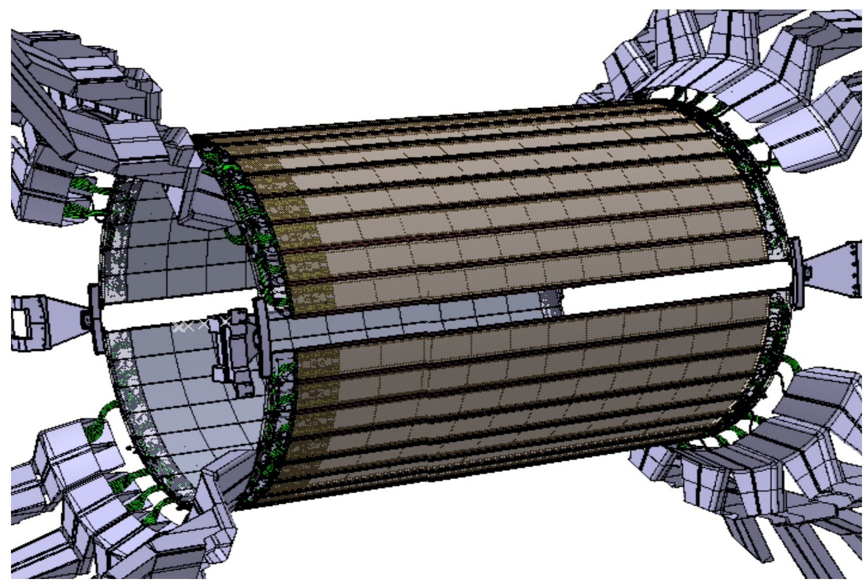
- CMS Phase 2 Upgrade is the **Gen-0 approximation** towards 4D detectors
  - **In ECAL barrel**: new electronics to achieve ~30 ps resolution for photon/electron
  - **In HGCal**: design to achieve ~50 ps timing resolution per layer in EM showers, multiple layers can be combined
  - **MIP timing detector:** cover up to |η|<3.0 to time stamp charged particles in the event: ~30 psec timing resolution
    - **LYSO + SiPM** layer in the barrel,
    - **Low Gain Avalanche Detector** (LGAD) layer in the endcap



Barrel Timing Layer

- Small SiPM cells: fast readout, robust vs. magnetic field/radiation and low power consumption.
- LYSO crystals as scintillator with an excellent radiation tolerance and fast rise and decay times.
- Time resolution of 35 ps at the beginning of lifetime and 60 ps by the end.





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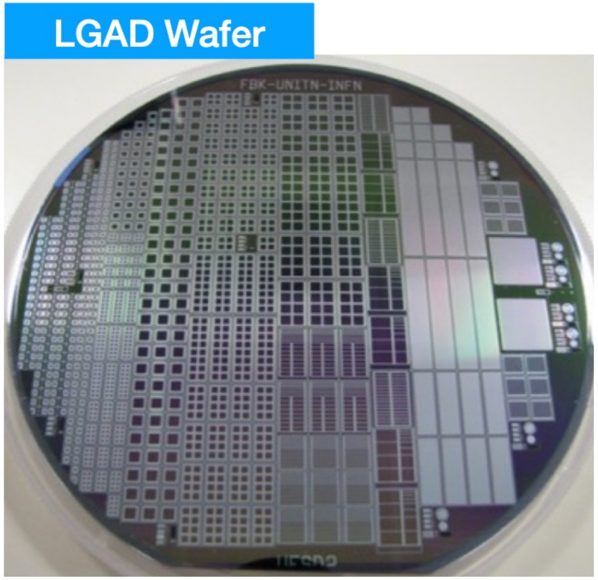
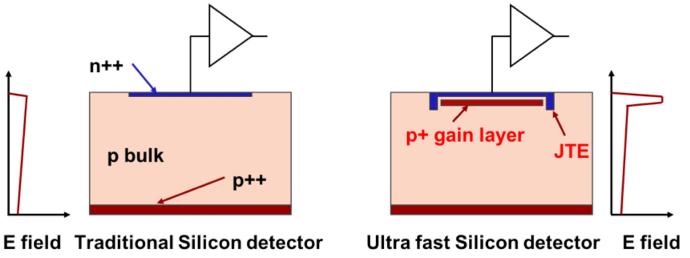
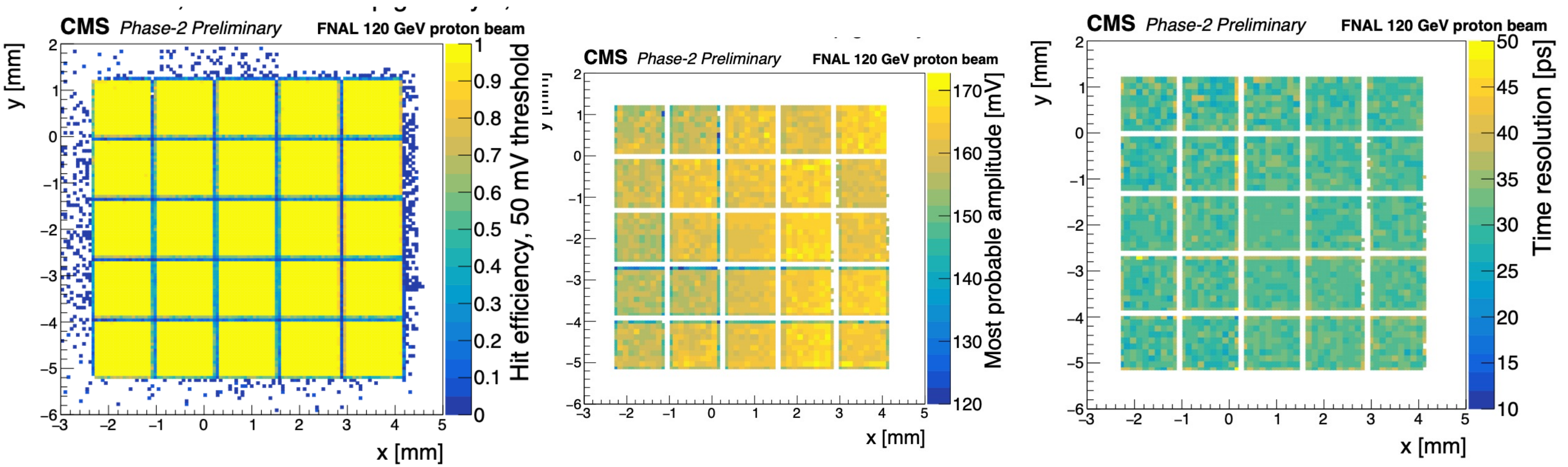
Endcap Timing Layer



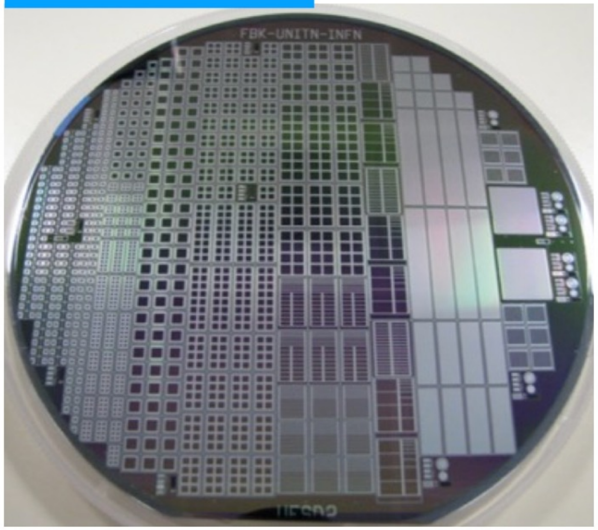


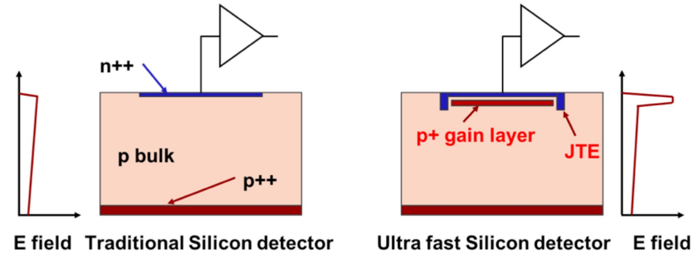
- Breakthrough development of last decade
  - High field in gain region ~ 300 kV/cm, **causes avalanche**
  - High gain → high signal → faster rise → smaller "jitter"
- Sensors demonstrate
  - Efficiency is 100 % inside pixels
  - Signal size uniform across area



Endcap Timing Layer

LGAD Wafer





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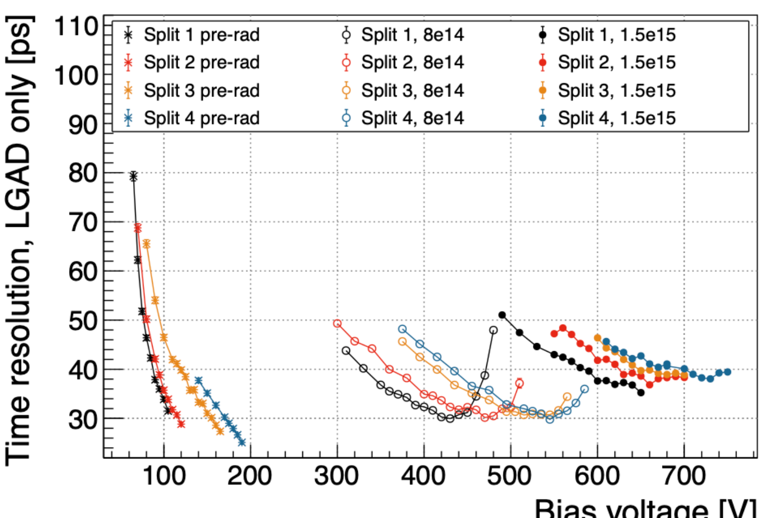
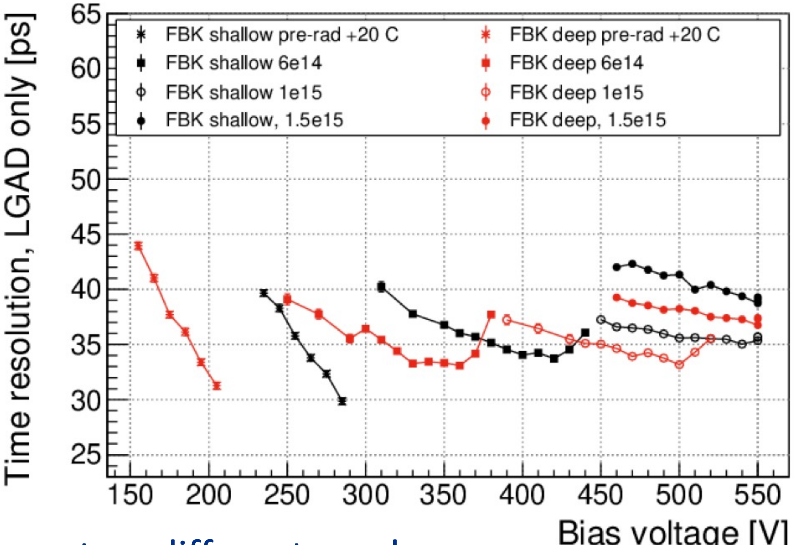
  - High field in gain region ~ 300 kV/cm, **causes avalanche**
  - High gain → high signal → faster rise → smaller "jitter"
- Sensors demonstrate
  - Efficiency is 100 % inside pixels
  - Time resolution 30-40 ps up to $1.5\text{x}10^{15}$ n/cm^2

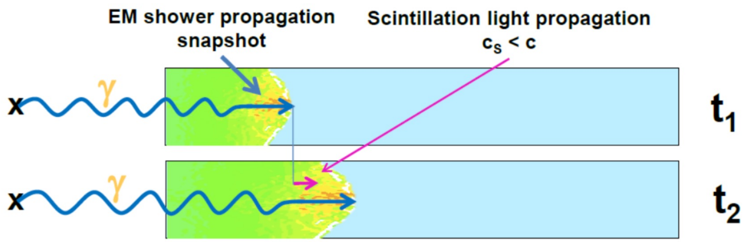


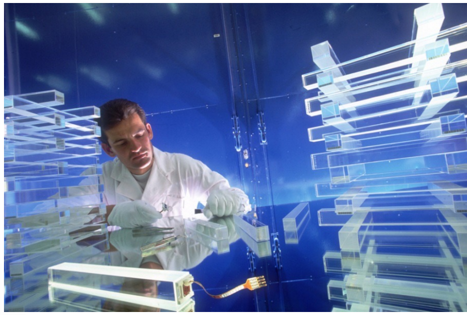


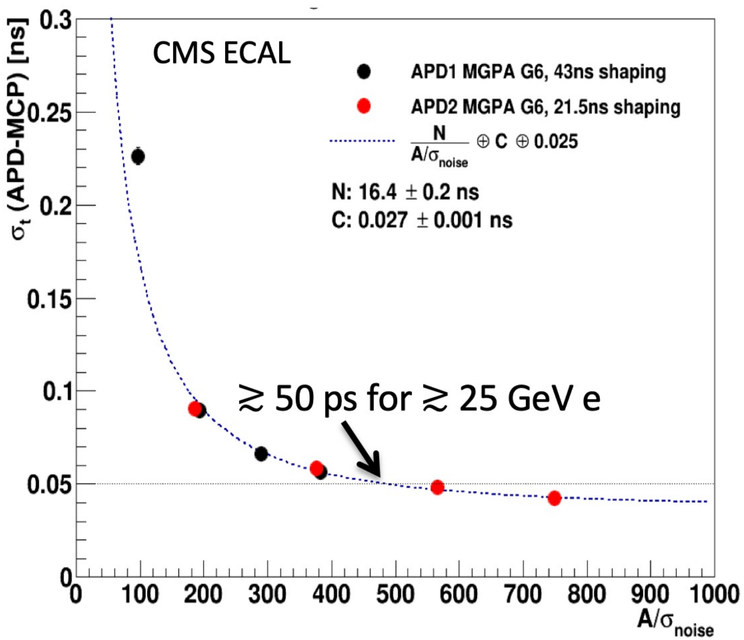
Performance of sensors from two different vendors

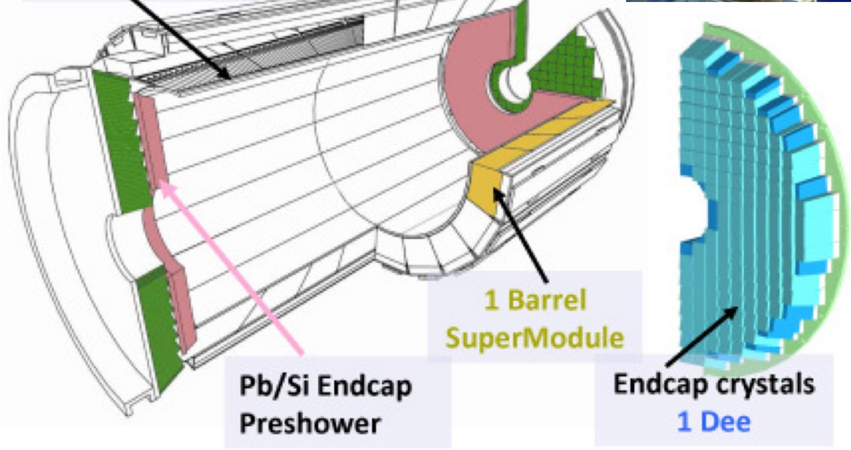
Calorimeters with timing

- ECAL with $PbWO_4$
  - High Light Yield ~100 photons MeV
  - Readout by fast APD
- New electronics for HL-LHC to take advantage of the fast signals to achieve <50 ps time resolution









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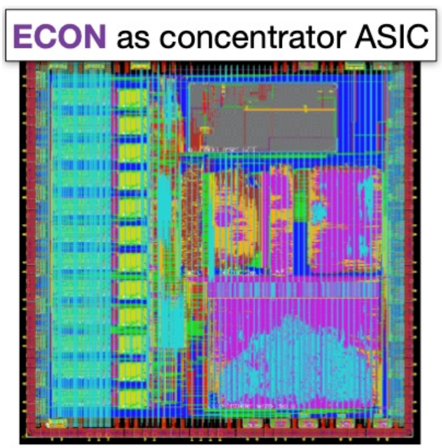
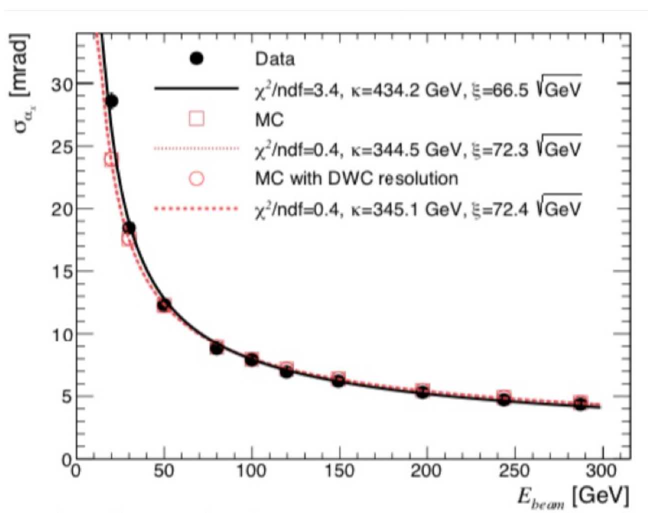
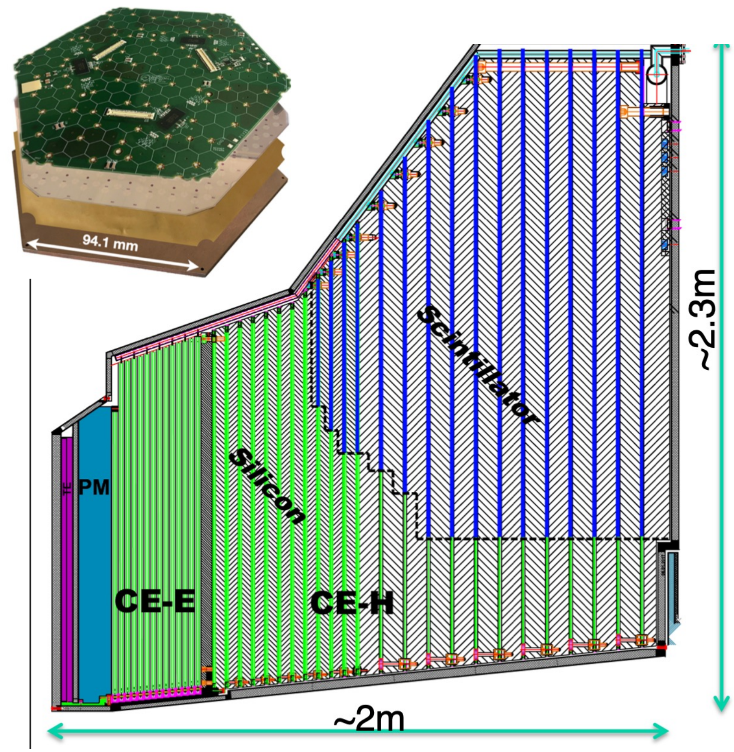
Calorimeters with timing

- Several 5D-calorimeters (E, x, y, z, t) in construction or R&D
  - CALICE R&D, CMS HGCAL, ALICE FoCal
- New front-end processing capabilities (e.g ECON) with AI
  - Radiation hardness to maintain 5D performance
  - Edge processing to reduce data flow







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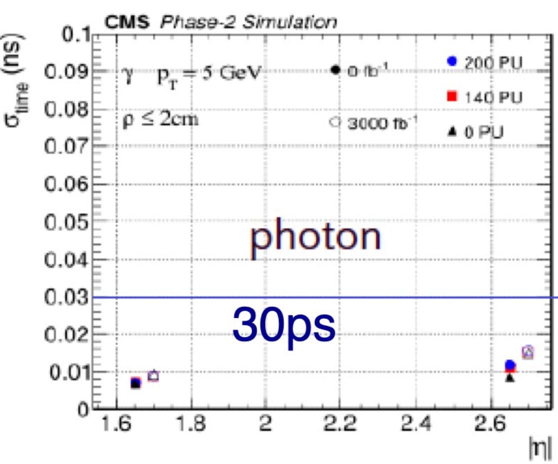
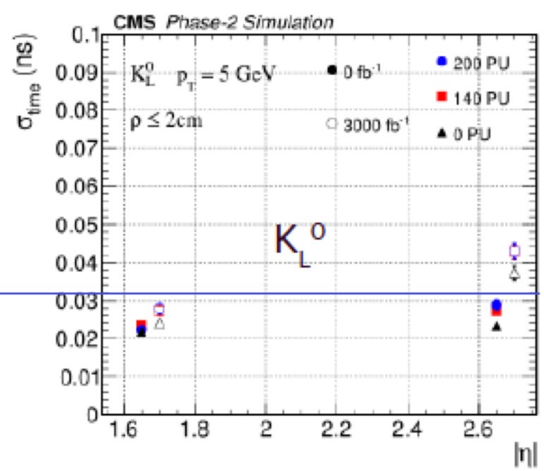
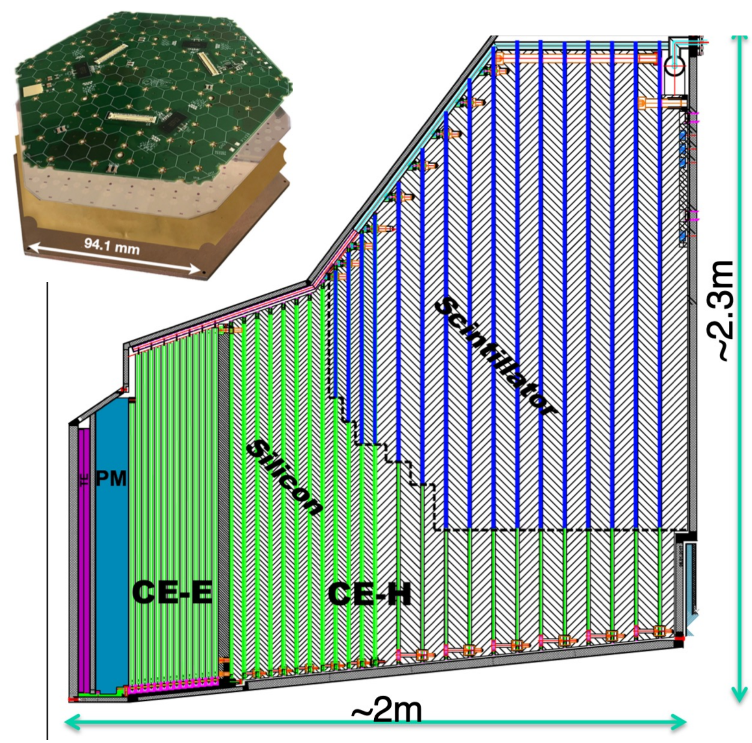
Calorimeters with timing

- First Particle Flow calorimeter in experiment
  - Hexagonal modules based on Si sensors in high-radiation regions
  - Scintillating tiles with SiPM readout in low-radiation regions
- Huge signals from showers: timing for all cells with Q > 12 fC
  - p_T =5GeV for e/γ: 10-15ps
  - p_T = 5 GeV for K_{0L}: 30 ps





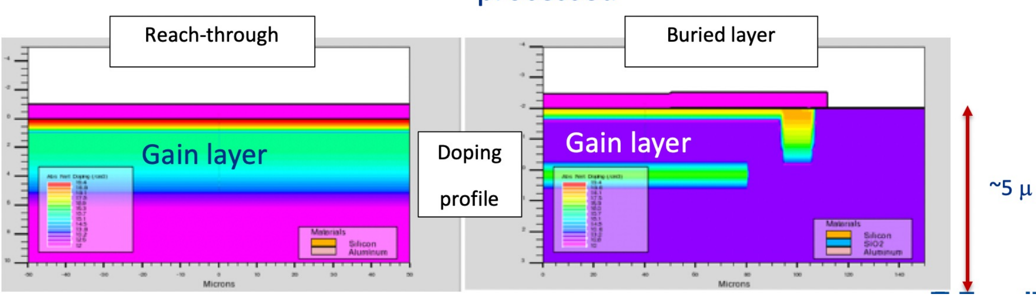


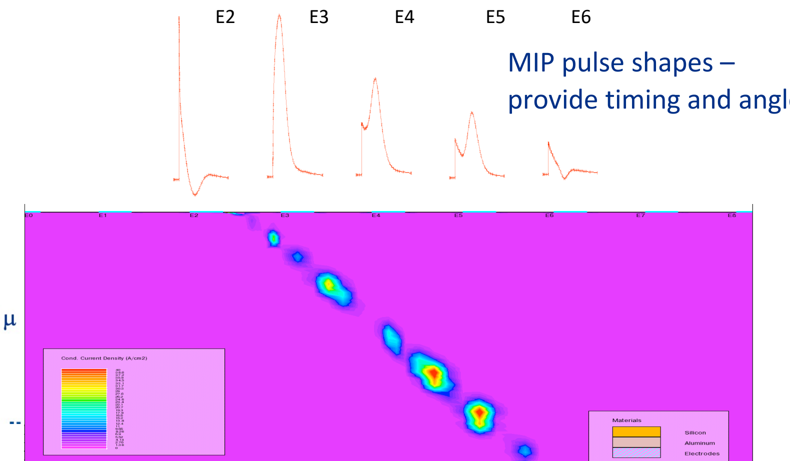
Active R&D on new directions

- A snapshot of areas with active R&D
  - AC-LGAD: excellent 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





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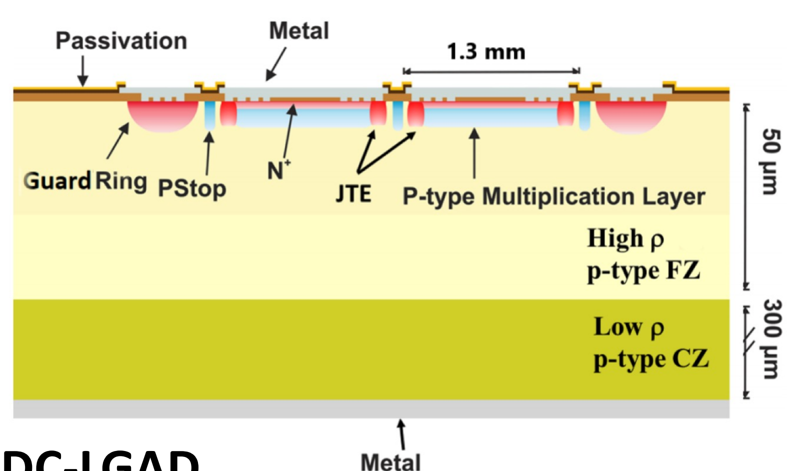
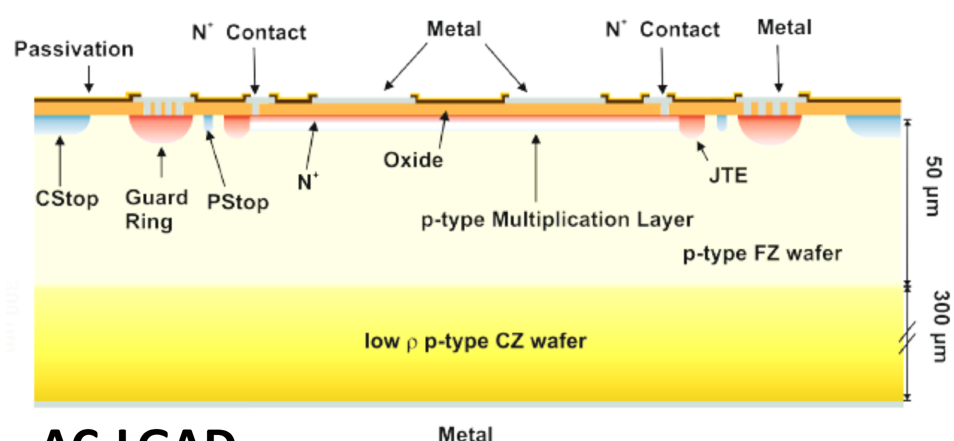
AC-coupled LGADs

- Ongoing R&D to eliminate dead area
  - Simultaneously improve position resolution via charge sharing
- Active R&D at different manufacturers
  - 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

Diagram credit: CNM



DC-LGAD



AC-LGAD

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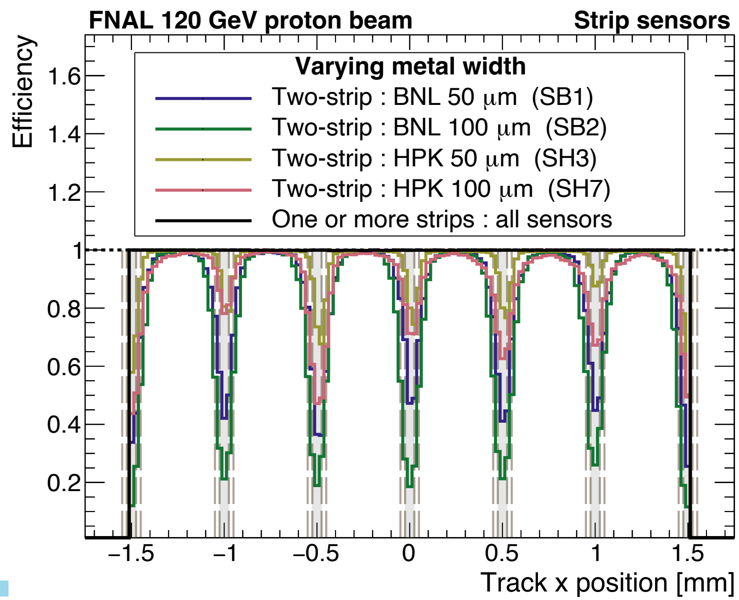
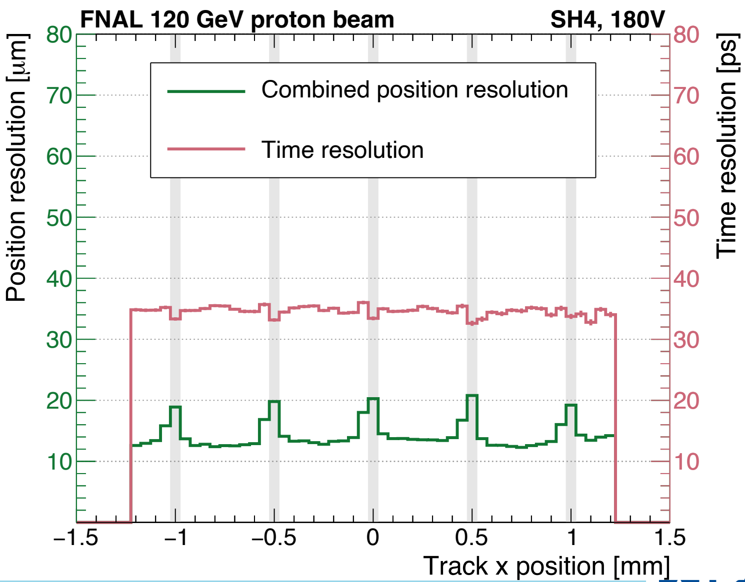
Long AC-LGAD strip sensors performance

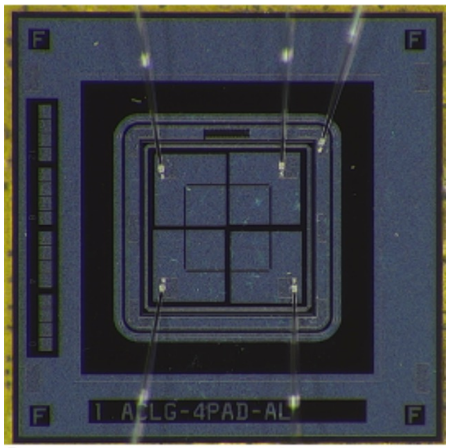
- Position reconstruction with ratio of amplitudes
  - Sensor provides 100% efficiency across surface
- Signal sharing: measure position based on ratio in neighbors
  - Achieve 15-20 µm resolution in 10 mm strips with 500 µm pitch
- Excellent time resolution
  - Achieve 30-35 ps for 10 mm strips



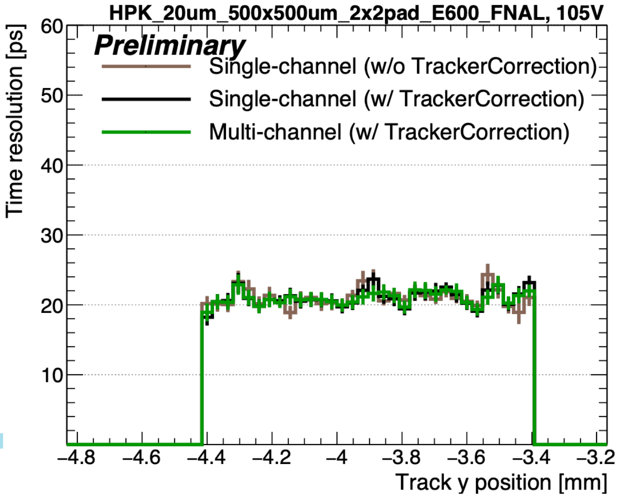


Towards better time resolution

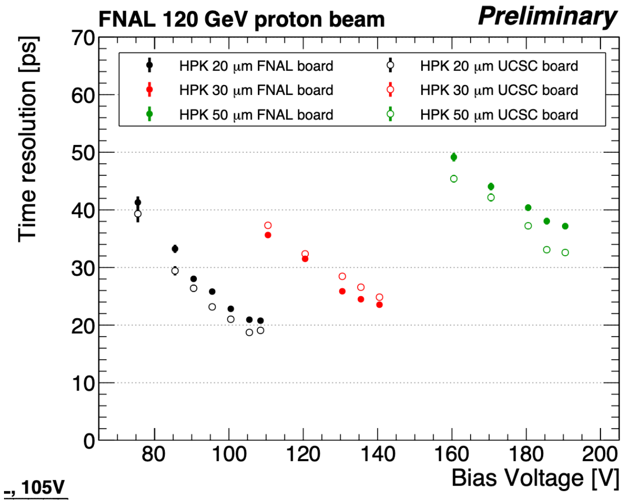
- How do you get better time resolution?
  - Thinner sensors to decrease Landau contribution
- AC-LGAD from HPK with 20, 30, 50 µm thickness
  - Almost fully metallized, optimized for timing performance
- Uniform time resolution across full sensor area
  - 25 ps for 30 µm thick sensor, 20 ps for 20 µm thick sensor



HPK 2x2, 500x500 µm^2 pixel size



20 ps across full sensor surface



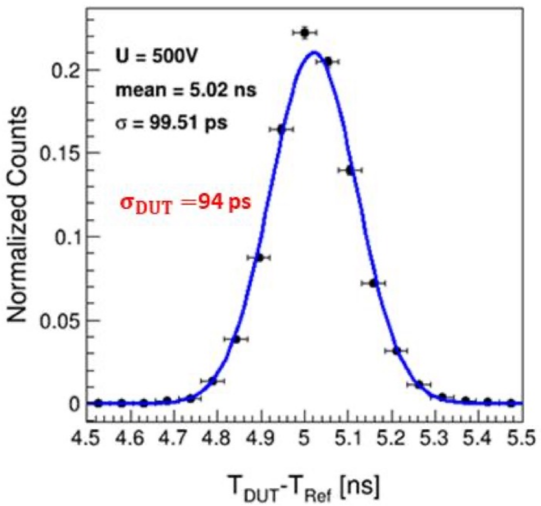
Time resolution for **20**, **30** and **50** µm-thick sensors

LGADs with SiC sensors

T. Yang: 40th RD50 Workshop
P. Gaggl: 41st RD50 Workshop
C. Haber: CPAD 2022

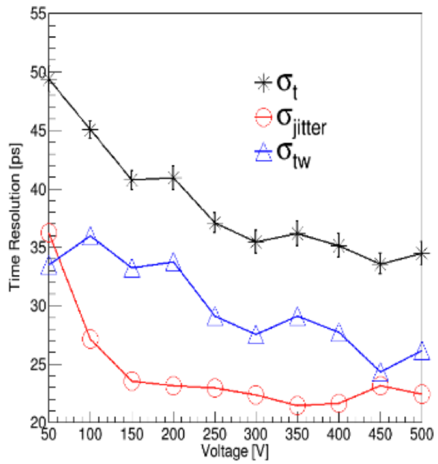
- Wide Band Gap Materials offer potential advantages
  - Enhanced radiation resistance
  - Reduced cooling requirements → reduced detector material mass
  - Increased commercial interest in wide band gap materials for power applications, HEP can benefit from these developments
- Several prototype runs recently produced
  - Early results look promising! Several new rounds of productions coming up

100 µm 4H-SiC PIN for MIPs (measurement)



doi: 10.3389/fphy.2022.718071

3D 4H-SiC Detector for MIPs (simulation)



doi: 10.3390/mi13010046

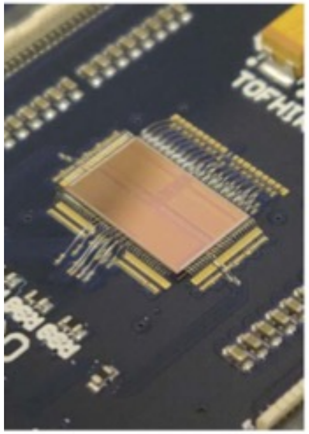
Electronics needs

- 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

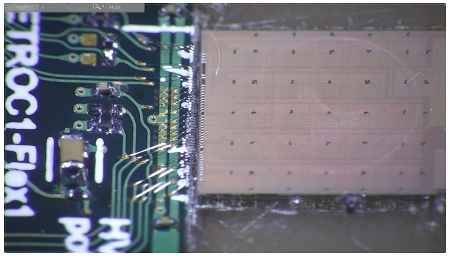
Electronics for HL-LHC timing layers

- BTL TOFHIR
  - Minimize impact of DCR noise and pileup on time resolution
  - Cope with very high rate of low energy hits per channel

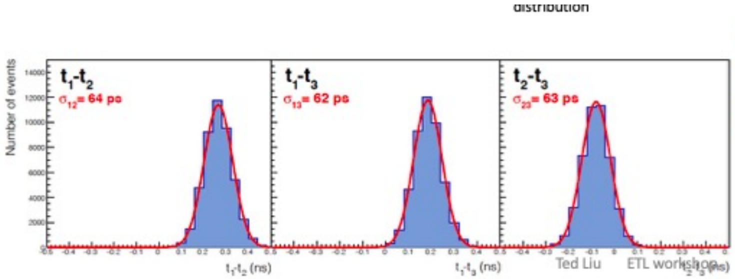


TOFHIR for CMS

- ETROC and ALTIROC
  - Bump-bonded to LGAD, with 1.3 mm x 1.3 mm pads
  - Deal with small signal size (~6fC, at end of operation)
  - Power consumption < 1W/chip



ETROC for CMS



From preliminary analysis of the data from ongoing beam test at FNAL, the time resolution of each LGAD+ETROC1 layer has reached:

$$\sigma_i = \sqrt{0.5 \cdot (\sigma_{ij}^2 + \sigma_{ik}^2 - \sigma_{jk}^2)} \quad \sim 42 - 46 \text{ ps}$$

(with LGAD HV=230V for all three channels)

*This measured time resolution includes all **four contributions** in the table*

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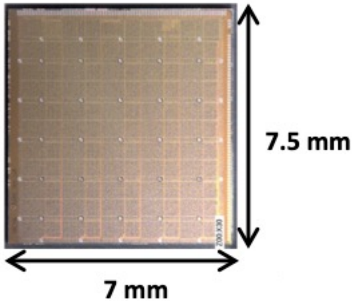
For more details, see ETROC1 testing results by Zhenyu Ye

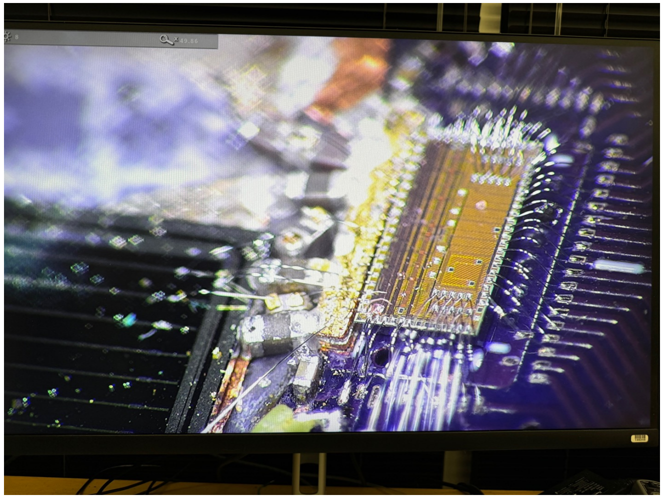
Prototypes performance validated in test beam



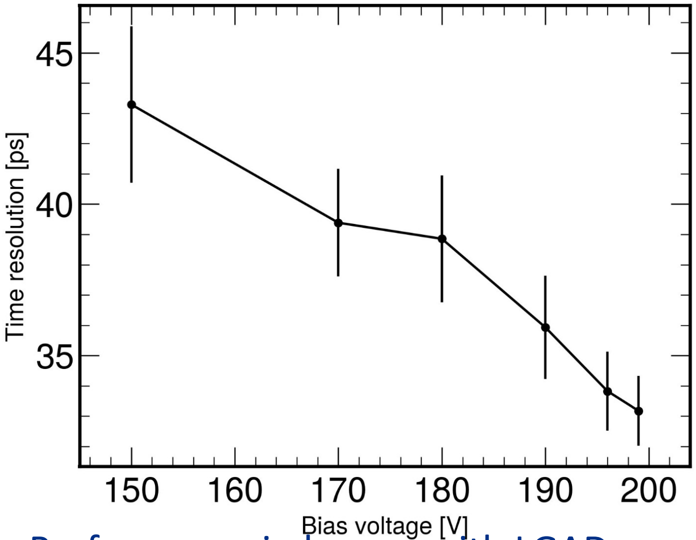
ALTIROC for ATLAS

Timing with Constant Fraction Discrimination (FCFD)

- A novel ASIC based on CFD for LGAD fast timing readout
  - Most timing ASICs need time-walk correction: each pixel timing needs to be corrected offline
  - CFD: **No need for time-walk** correction → directly get time-measurement
- Two generations produced, targeting DC- and AC-LGAD
- Excellent performance : ~30 ps time resolution and no time-walk demonstrated in beam-tests



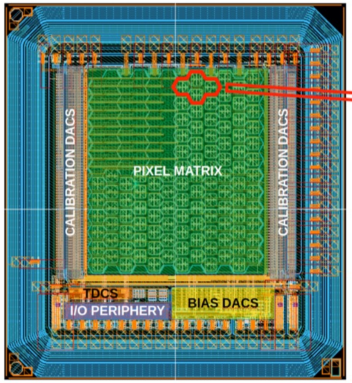
FCFD v1 ASIC with AC-LGAD strip sensor



Performance in beams with LGAD sensor

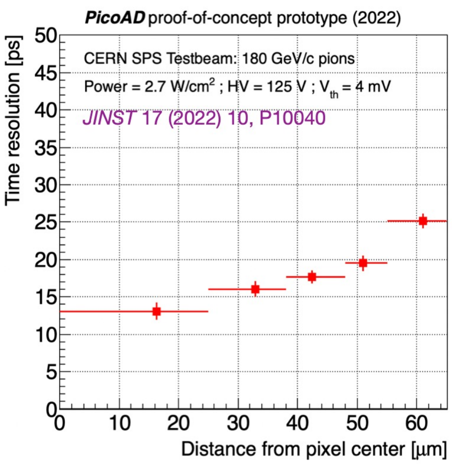
Monolithic sensors

- Monolithic sensors with embedded readout
  - Take advantage of electronics on top layer, good signal-to-noise
- Promise to be paradigm-shifting for next-gen detectors
  - MONOLITH project: several prototypes produced over last few years
    - Time resolution from ~13 ps at the center to ~25 ps at the edge
  - Cactμs project: two rounds produced
    - Time resolution around 65 ps demonstrated

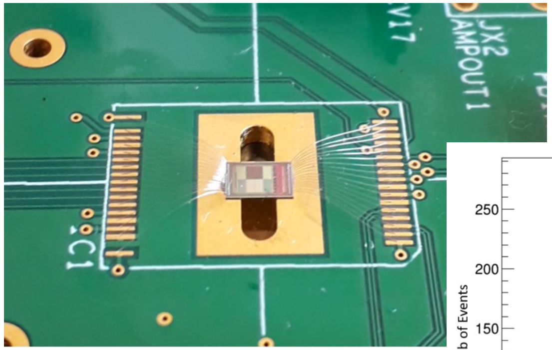


PicoAD

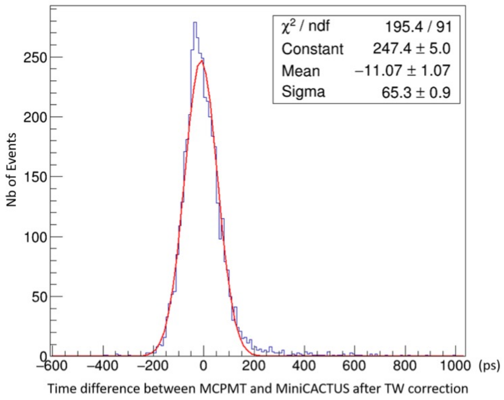
Time resolution



(13.2 ± 0.8) ps at the pixel center



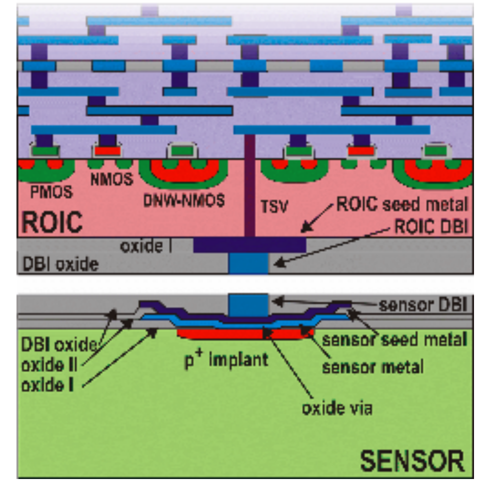
MiniCactus

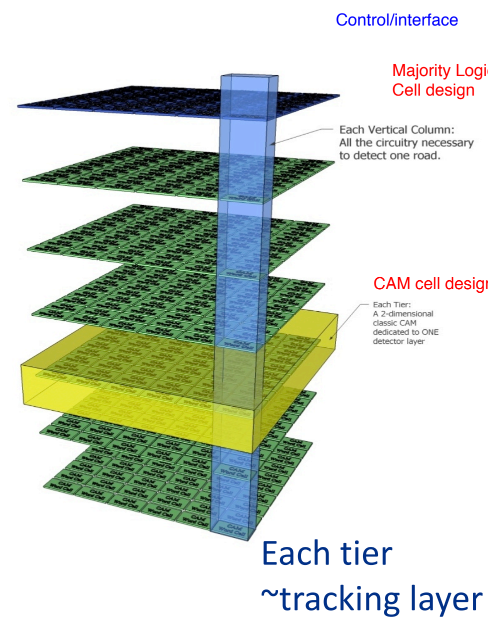


Fermilab

Possibilities

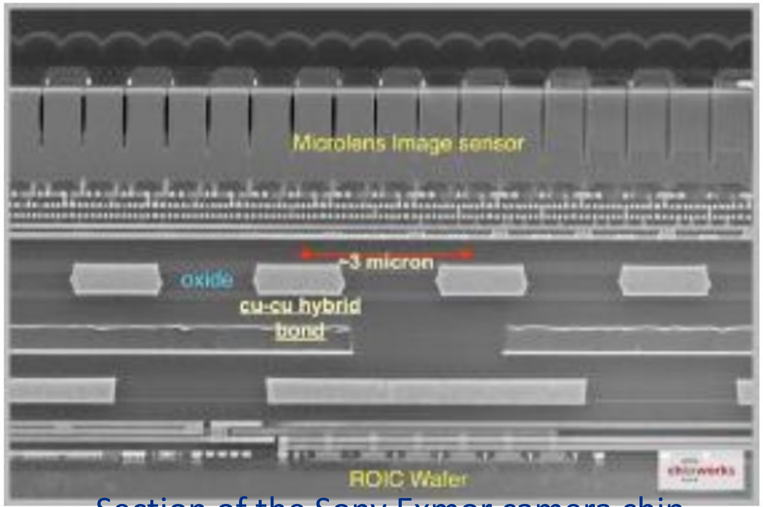
- Advanced integration of technologies on the front-end
  - AI/ML on-chip to extract features for fast tracking and L1 triggering,
  - On-chip clustering to readout reduce data volume
  - Wireless communication between layers
  - Novel materials to design power-efficient data processing on front-end
- Extensive 3D integration
  - Very fine pitch possible
  - Layers of electronics for complex signal processing
  - Integrate different technologies, each optimized for separate tasks



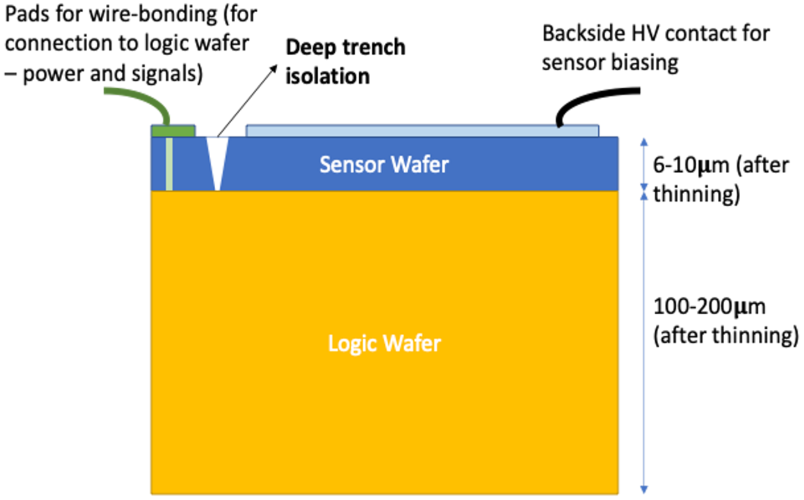


3D-Integrated sensors

- Development of low-power, highly granular detectors in ($\vec{x}$, t)
  - Required to achieve breakthroughs across HEP, NP, BES, and FES
  - Adoption of 3D-integration has been cost-prohibitive in academia
- Supported by DOE “Accelerated Innovation in Emerging Technologies”
  - Joint development effort of SLAC, FNAL and LLNL
  - Tower Semi to develop process for 12” wafer production, with 28 nm TSMC
  - Design goal is to achieve position resolution ~5 µm, timing ~ 5-10 ps



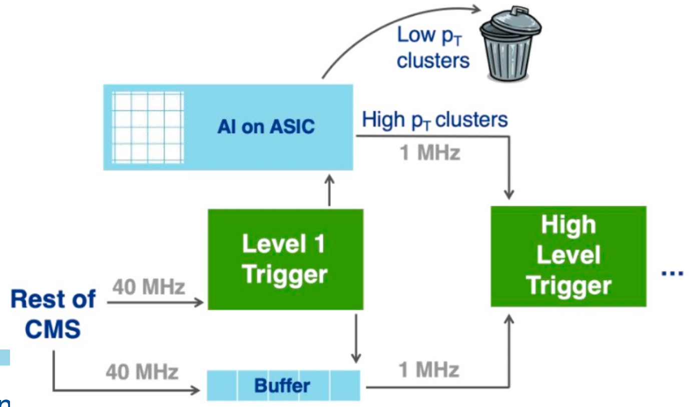
Section of the Sony Exmor camera chip showing the hybrid bond interface



Fermilab

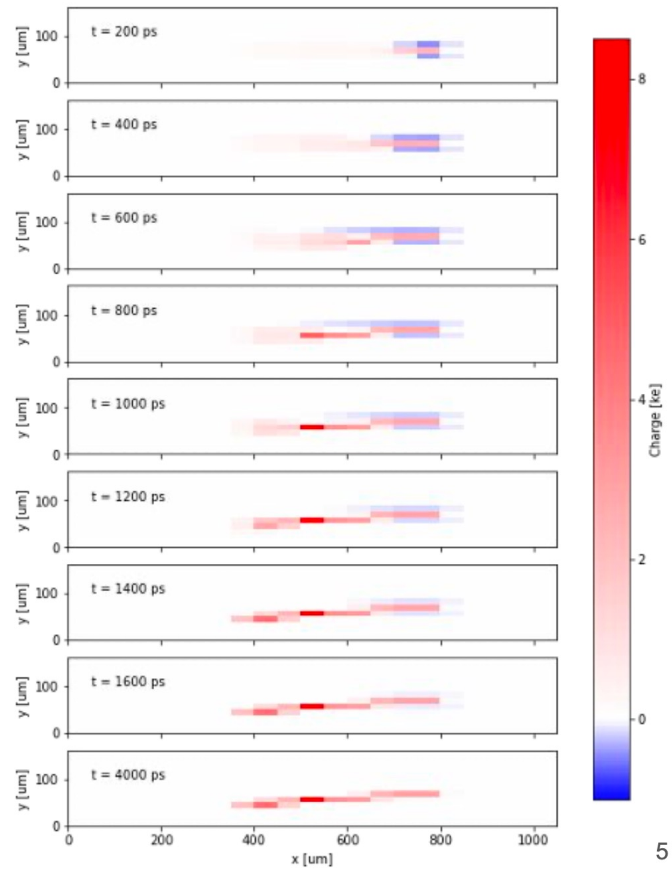
AI/ML on the front-end: Smart Pixels

- AI embedded on a chip to:
  - Filter data at the source to enable data reduction
  - Take advantage of pixel information to enable new physics measurements and searches
- Data reduction through
  - Filtering through removing low p_T clusters
  - Featurization through converting raw data to physics information
- Combination of approaches can reduce data rate enough to use pixel information at Level 1



Smart Pixels Simulation

- Simulated charge deposition from pions
- Assume a futuristic pixel detector
  - 50x12.5 μm pitch
  - Time steps of 200 picoseconds
- Use ML due to complicated pulse shapes, and drift & induced currents
  - y-profile is sensitive particle's p_T
  - x-profile uncorrelated with p_T
- Classification goals
  - Keep high p_T clusters, decrease data bandwidth
- Reprogrammable weights for NN are implemented directly in the front-end



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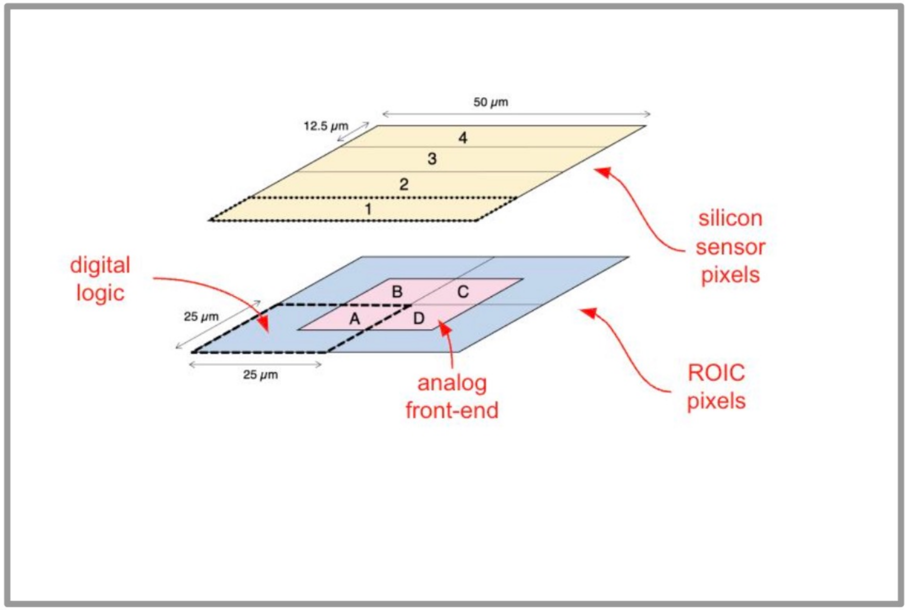
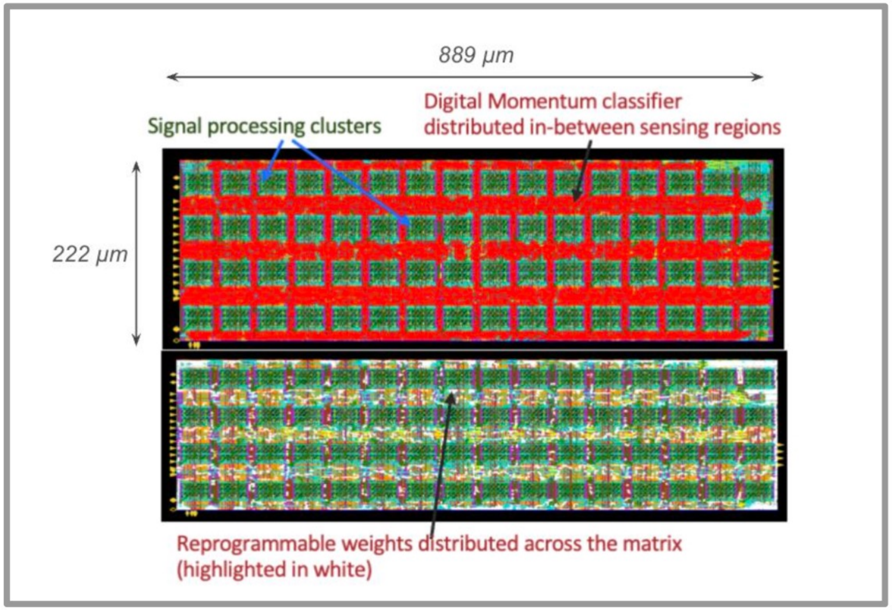
ROIC implementation





- 4 analog frontends, surrounded by a digital region
- Simulation: 13 x 21; Chip: 16 x 16

- Design expected to operate at < 300 µW
- Area < 0.2mm^2

- The second chip has been submitted for tape out and received this spring, testing in progress

Exciting Opportunities

- Transformative Detector R&D
  - **Emerging technologies** and **energy efficient** solutions
  - Advances in **quantum technologies** and **material science**, **AI/ML**
  - **Microelectronics** to advance the state-of-the-art in detector technologies

- Huge potential to make a mark
  - Especially for young researchers!
  - Design, build, and collect data with these detectors!

Conclusion

- Unique requirements for the detectors for the muon collider require **ambitious** and **exciting** R&D
  - Simultaneous high position and timing requirements
  - Many innovative ideas are emerging
  - Promising directions with paradigm-shifting potential

- Exciting opportunities to **get engaged** in cutting edge detector R&D
  - Many active and funded programs on generic R&D
  - Collaborative efforts are the key for progress