



Solid State Detectors Dedicated to Fast Timing

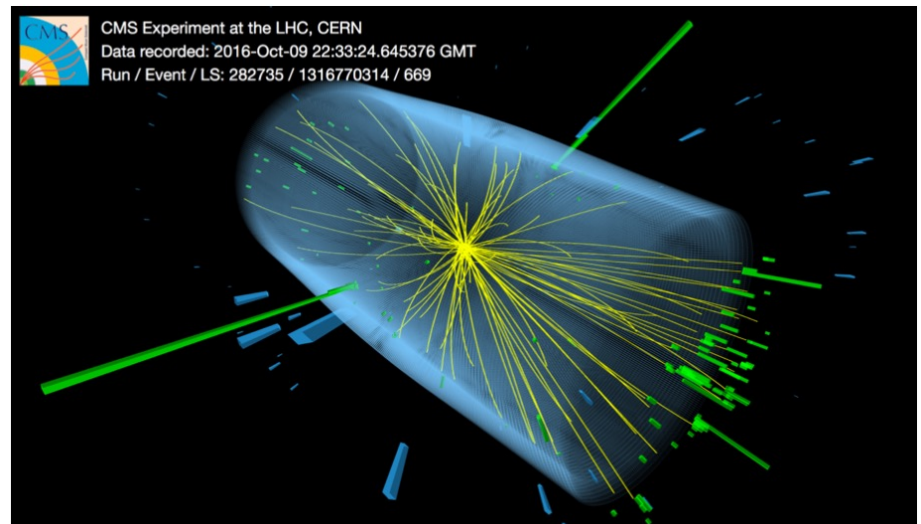
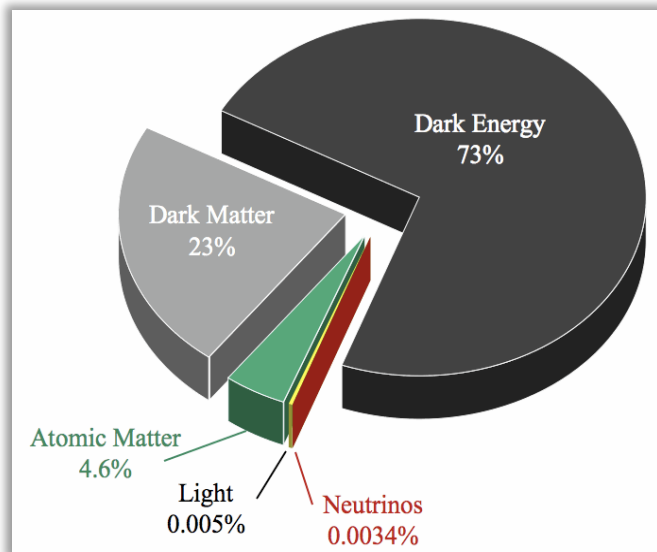
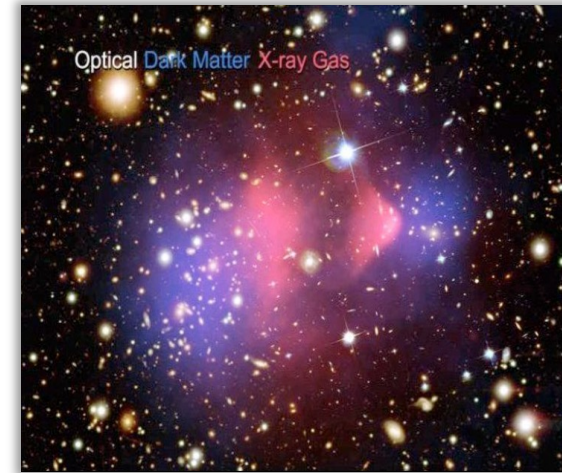
Artur Apresyan

15th Terascale Detector Workshop, Heidelberg University

Mar 1, 2023

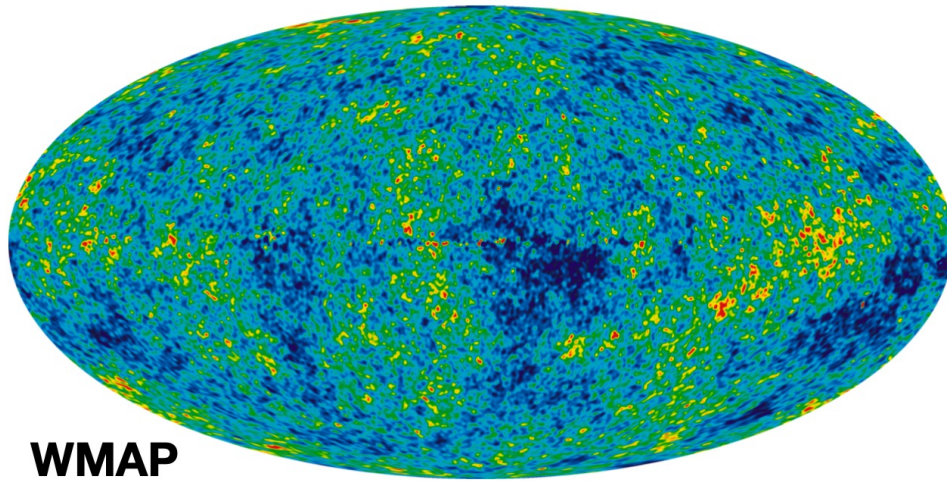
The grand challenges

- Many fundamental questions remain in SM
 - Higgs boson: "unnatural" mass
 - Dark matter: no candidate particle
 - Non-zero neutrino masses
 - Origins of the dark energy
 - Baryon asymmetry

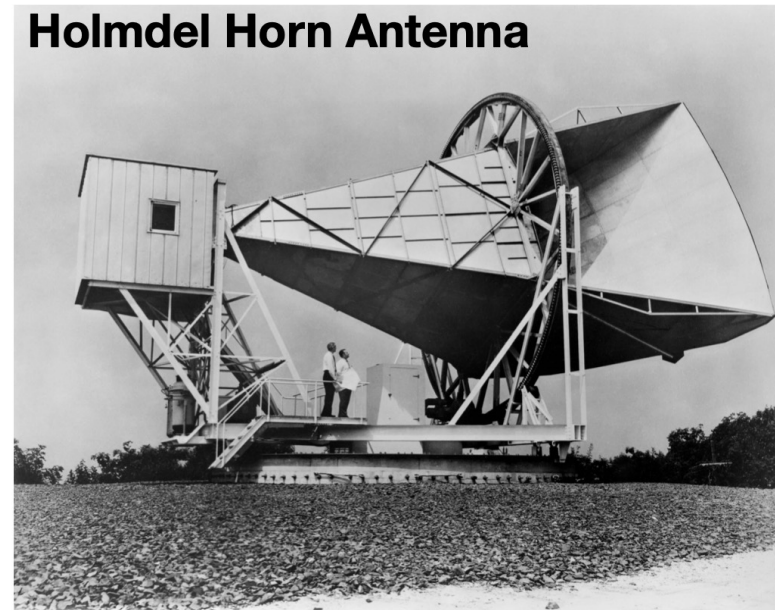


Transformative Physics Discoveries

- Explore nature at the frontier of detection-technology
 - New fundamental principles
 - Enable discoveries
 - New directions in science



WMAP



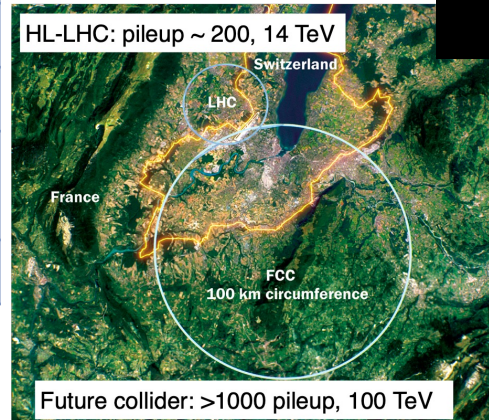
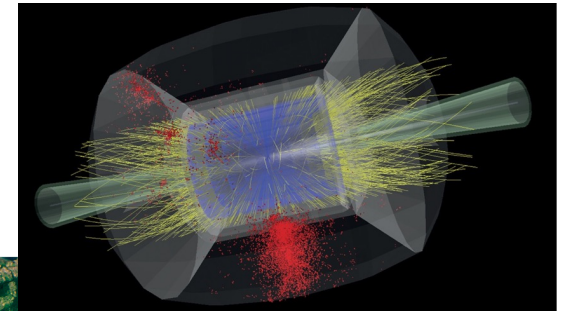
Holmdel Horn Antenna

Future trackers need timing

- 4D-trackers will play a key role at future machines
 - Reduce backgrounds, track reconstruction, Level-1 triggering
 - New capabilities: PID and LLP reconstruction
 - All of these pose unique challenges and opportunities to detector design

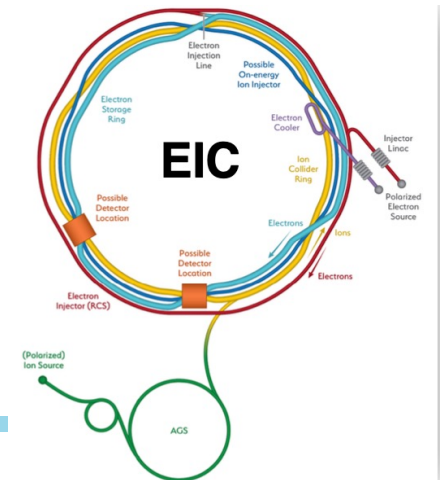
Measurement	Technical requirement
Tracking for e^+e^-	Granularity: $25 \times 50 \mu\text{m}^2$ pixels
	$5 \mu\text{m}$ single hit resolution
	Per track resolution of 10 ps
Tracking for 100 TeV pp	Generally the same as e^+e^-
	Radiation toleran up to $8 \times 10^{17} \text{ n/cm}^2$
	Per track resolution of 5 ps

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



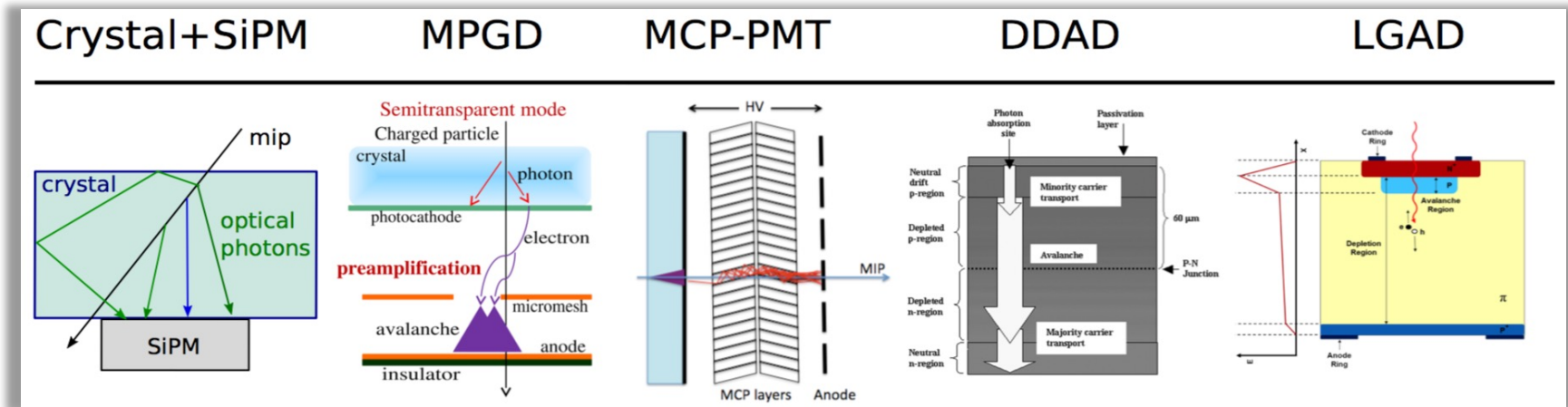
FCC

Muon collider



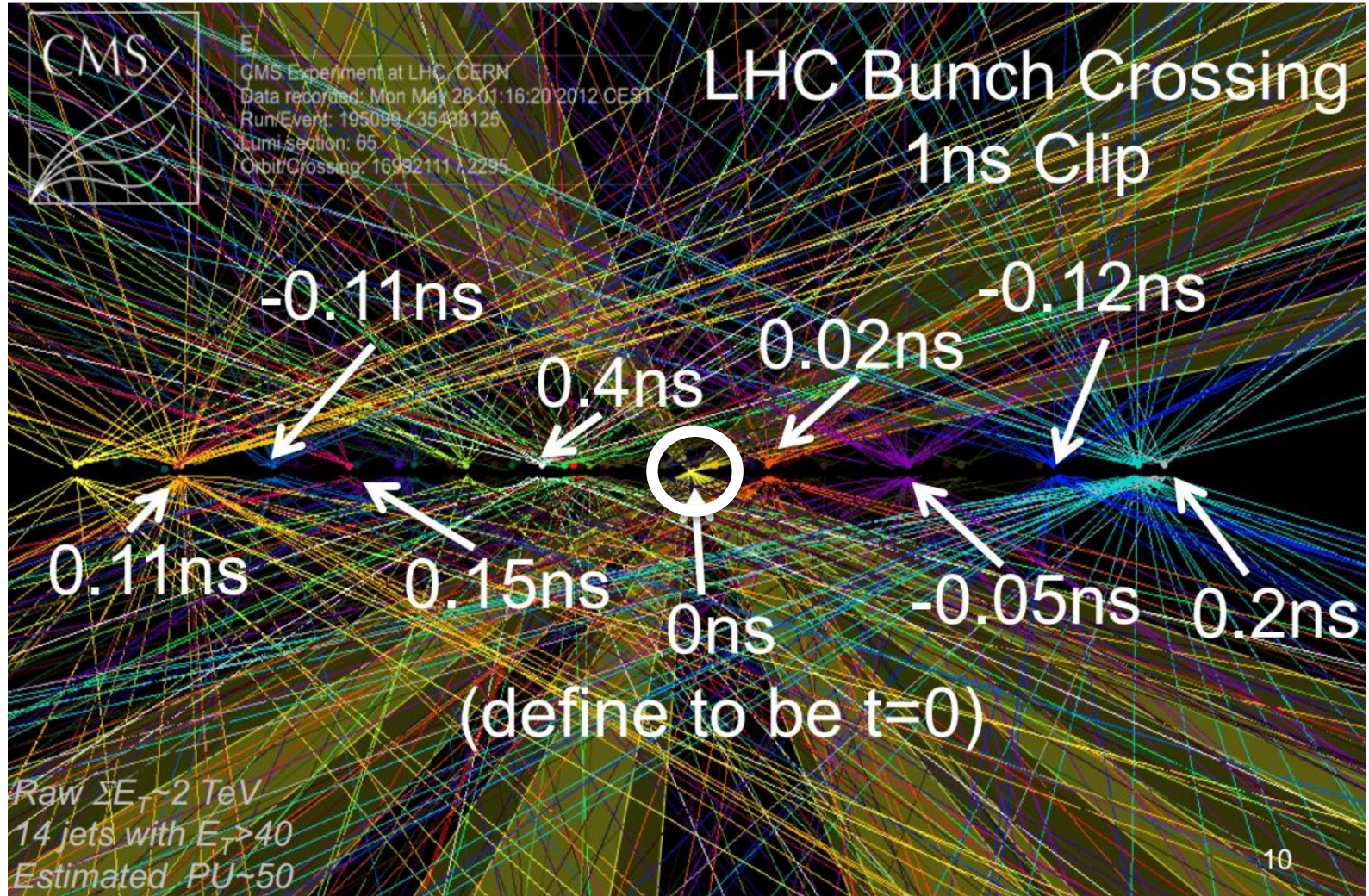
Technologies for precision timing detectors

- 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



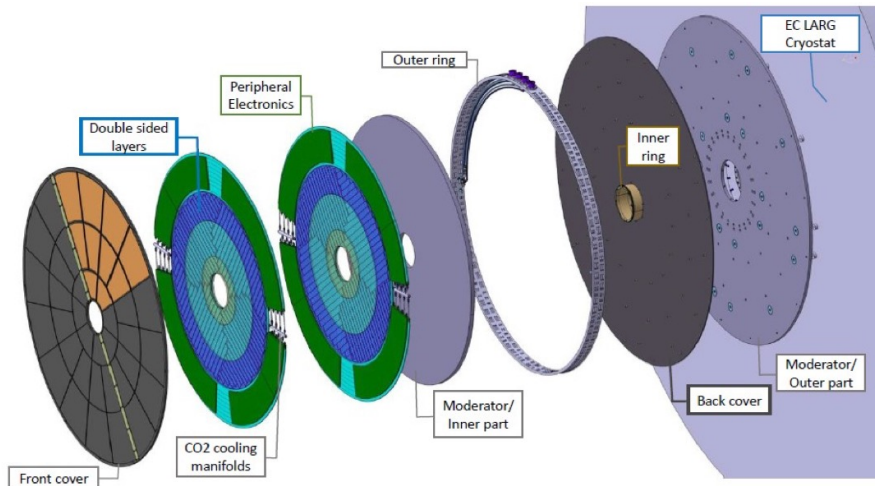
A common challenge in future experiments

More collision \rightarrow More confusion

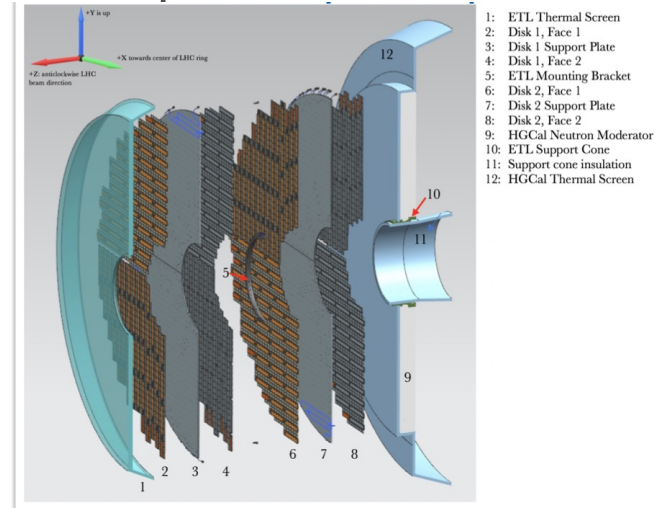


Precision timing

- Traditionally in collider experiments we measure very well
 - Position, charge and energy of particles
- CMS and ATLAS are building first-generation of 4D-detectors
 - Next-gen detectors will have high granularity also in **time domain**
 - At the tracker, calorimeter, muon detectors, and L1 trigger
- Future detectors moving towards full **5D Particle Flow**
 - Active R&D to achieve required performance for future experiments
 - Sensors, ASIC, front-end electronics developments

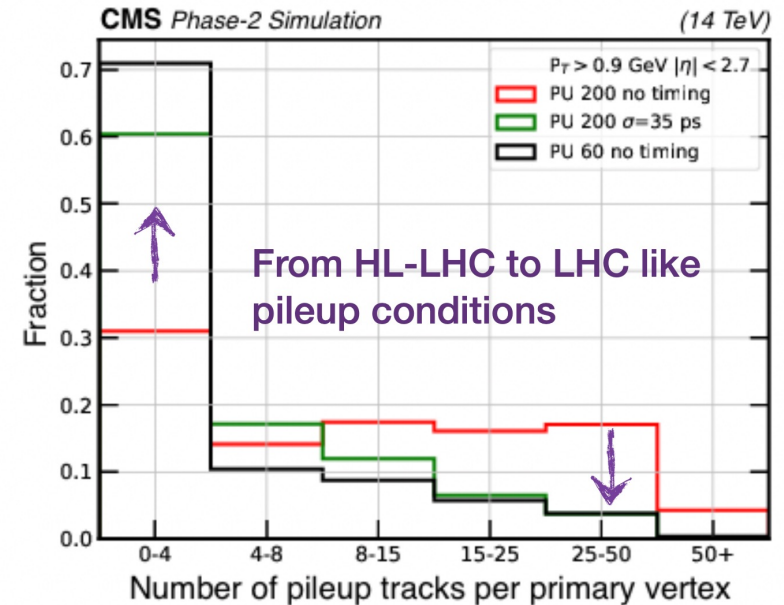
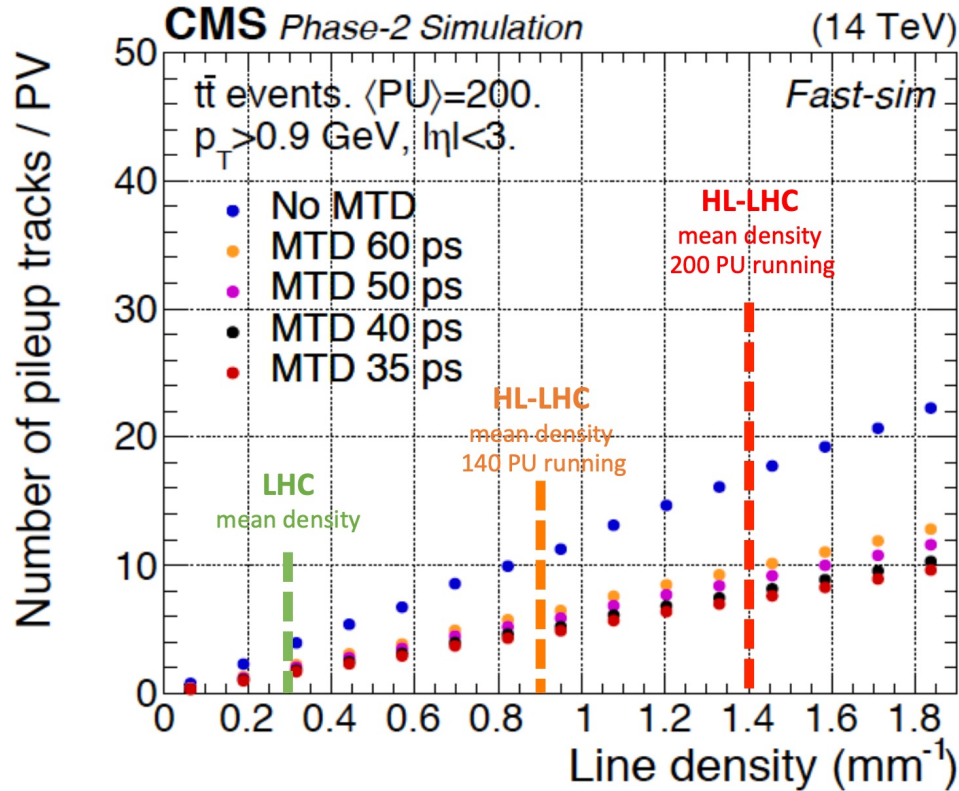


ATLAS timing detector



CMS timing detector 

Pileup rejection

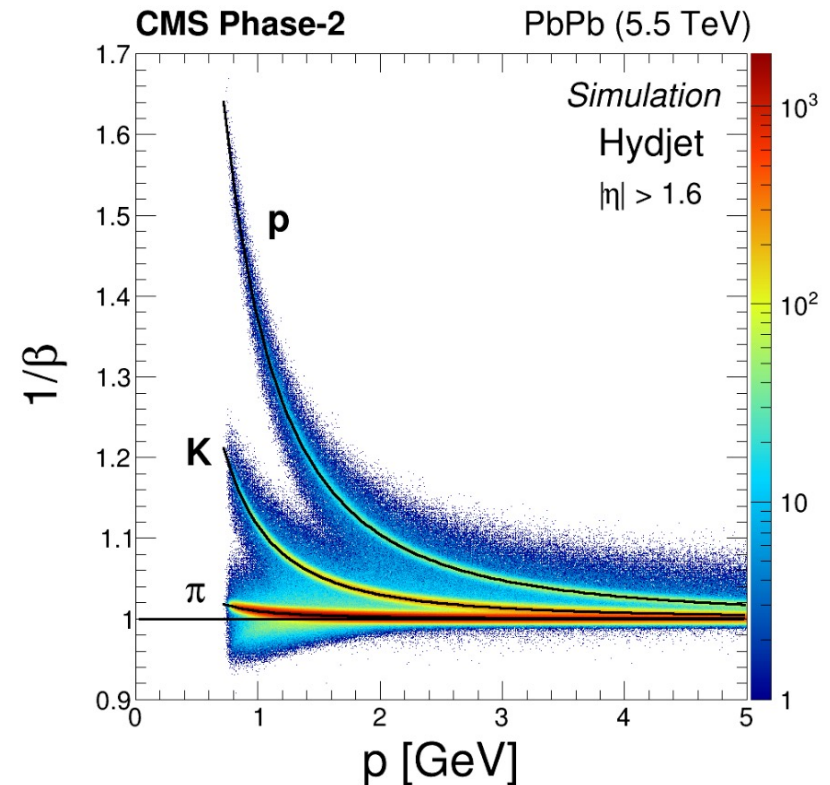
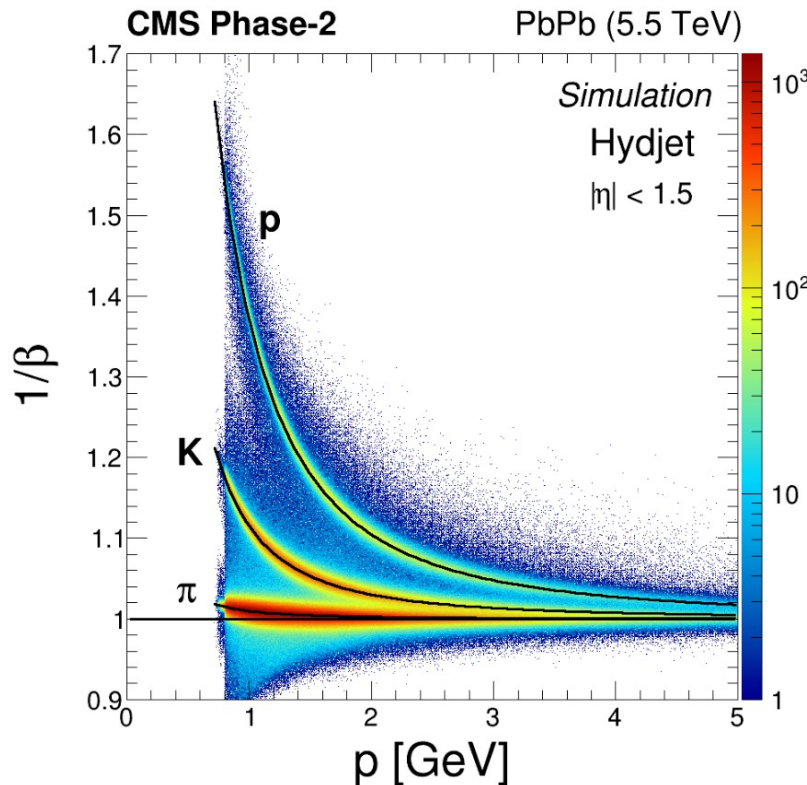


- Time-aware primary vertex reconstruction reduces incorrect association of tracks from nearby pileup interactions by a factor of 2:
 - Fully offsets the impact of the transition from 140 \rightarrow 200 PU running
 - Brings per-vertex track purity close to typical current LHC running conditions

Time-of-flight Particle ID

- Time-of-flight particle identification: 2σ π/K separation up to $p \sim 2$ GeV and K/p up to $p \sim 4$ GeV
 - New handle for CMS for heavy flavor physics

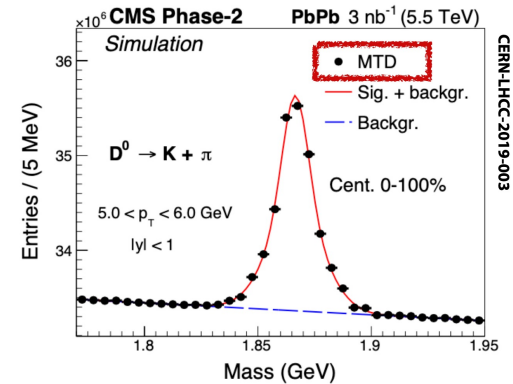
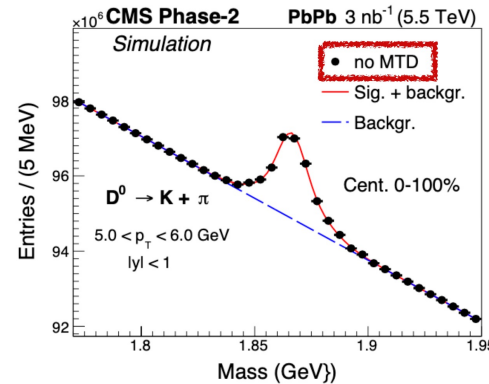
$$\frac{1}{\beta} = \frac{c(t_0^{\text{MTD}} - t_0^{\text{evt}})}{L}$$



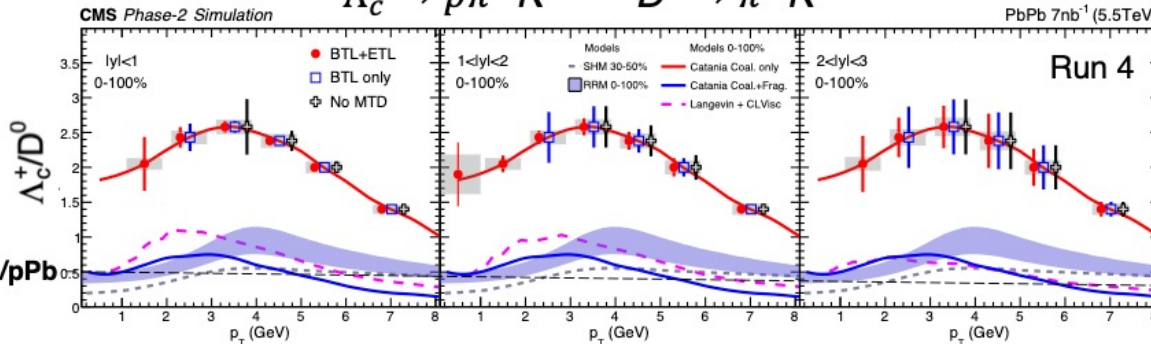
Physics impact: TOF Particle ID

- Competitive momentum coverage comparable to ALICE and STAR

- Significantly suppressed background candidates
- Signal significance is drastically improved
- The region of $|η| > 1$ is uncovered by other experiments



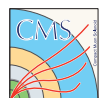
A benchmark



Comparison of performance with and without MTD

- Unique possibility to study charm and bottom hadrons production over a wide range of p_T and rapidity. Low p_T regions (inaccessible without MTD) should have the largest effect from QGP.

CERN-LHCC-2019-003



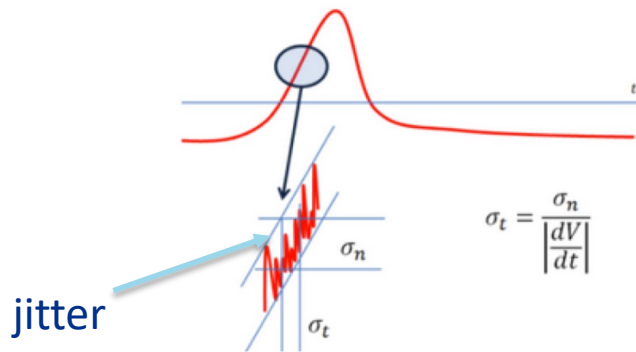
Technologies for precision timing detectors

- 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**

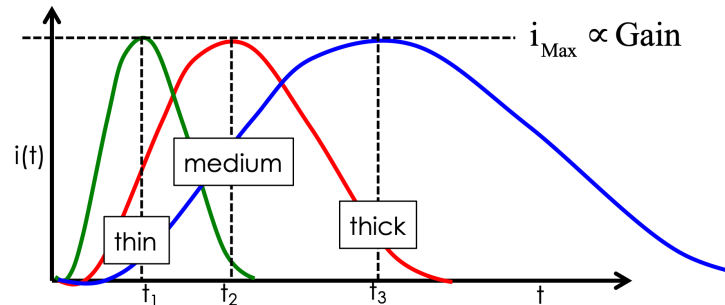
Time resolution components

- 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
- Thinner sensor means small signal: can we add Gain?

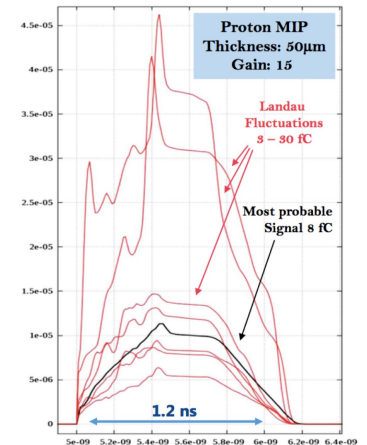
$$\sigma_t = \frac{\sigma_V}{\frac{dV}{dt}} = \frac{N}{\frac{S}{t_r}} = \frac{t_r}{S/N}$$



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



Rise time dependence on Si thickness



Landau fluctuations

Timing resolution

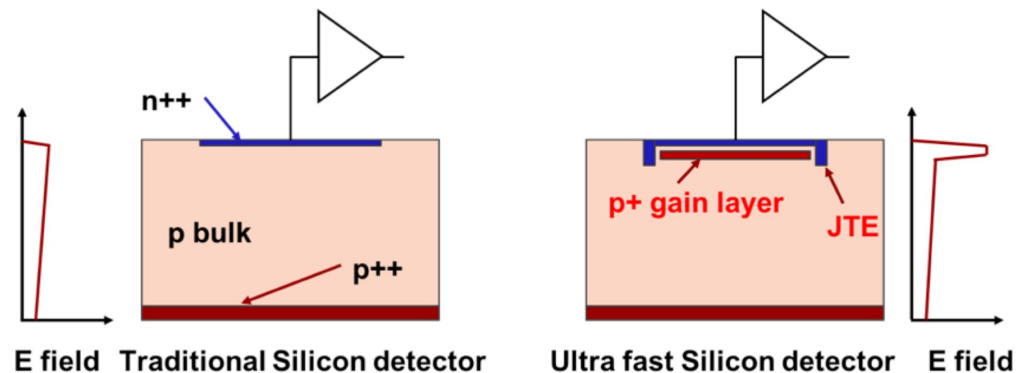
- Putting together various components

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

- 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

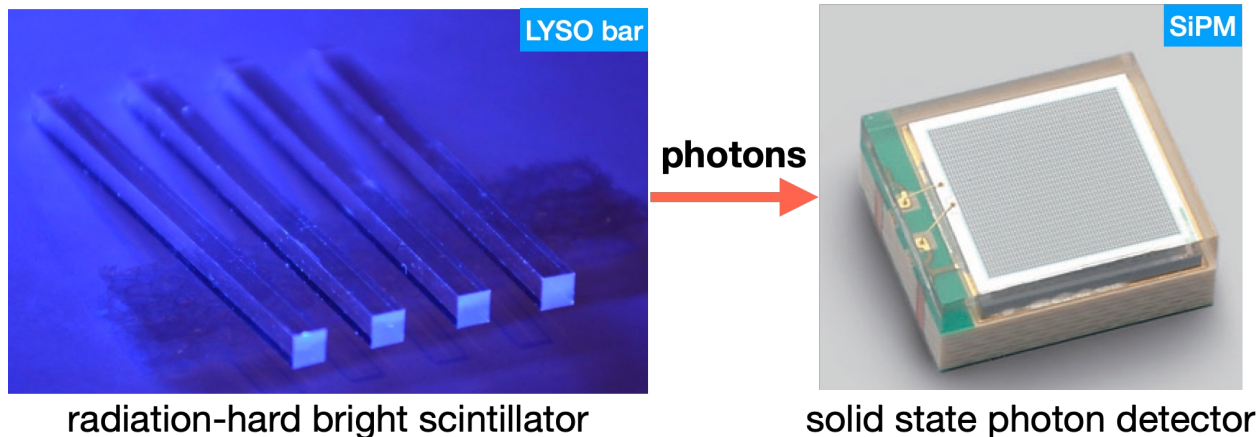
Low Gain Avalanche Diode (LGAD) detectors

- Increase the initial signal : Ramo's theorem: increase the E_{field}
- Could increase by doing:
 - Increase bias voltage
 - Gain everywhere in the bulk
 - **Add a specific gain layer**
- Turns out only the solution with gain layer provides a stable sensor
 - Key breakthrough in sensor design in the past decade!
 - High field in the gain region around 300 kV/cm, causes avalanche
 - High gain \rightarrow high signal \rightarrow faster rise \rightarrow smaller "jitter"



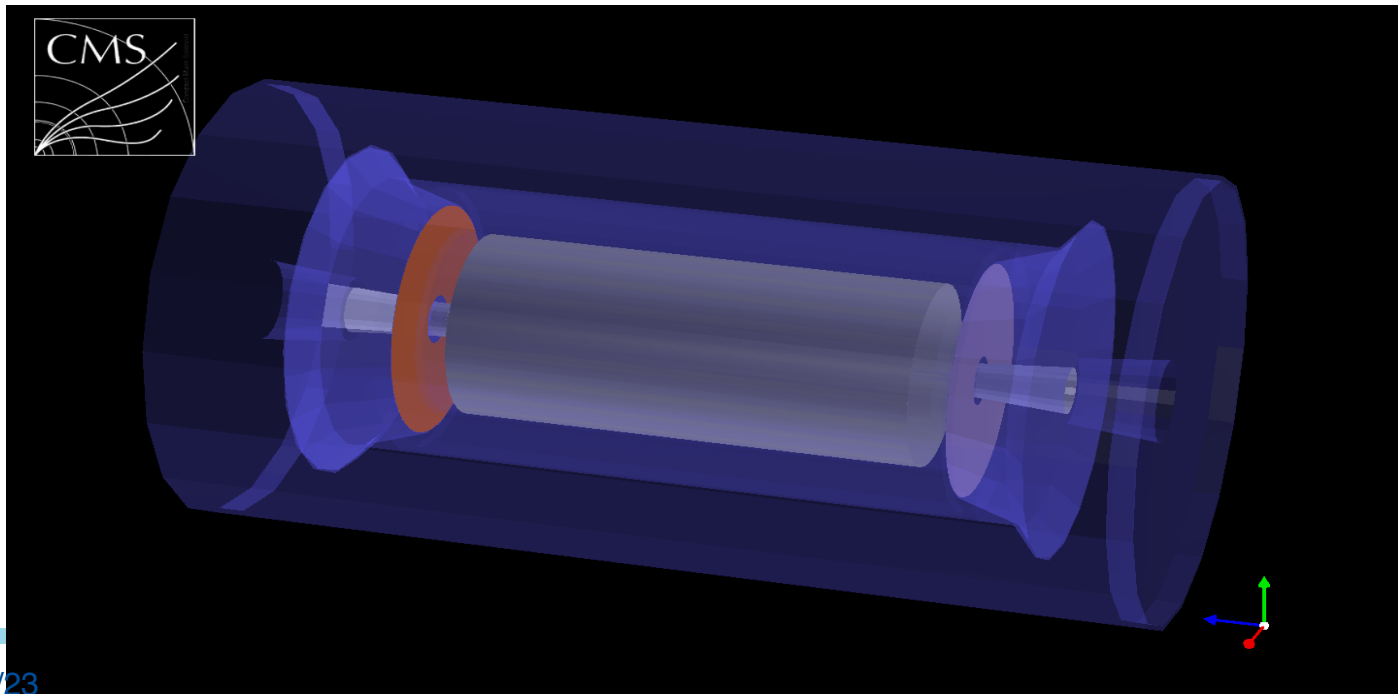
Crystals + Fast PMT

- LYSO with dual-end SiPM readout
- Signal properties
 - Large signal from LYSO (40,000 photons per MeV) + SiPM gain $\sim 10^5$
 - Fast rise time $O(100 \text{ ps})$, decay time $\sim 40 \text{ ns}$
- Silicon Photomultipliers as photo-sensors
 - Compact, insensitive to magnetic fields, fast
 - High dynamic range, rad tolerant
 - Photo Detection efficiency : 20-40%



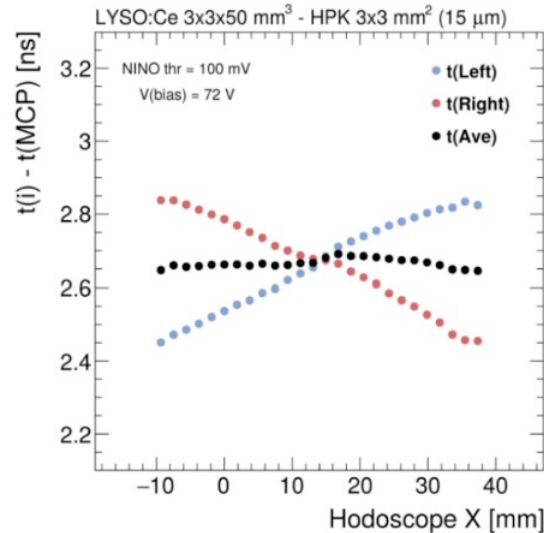
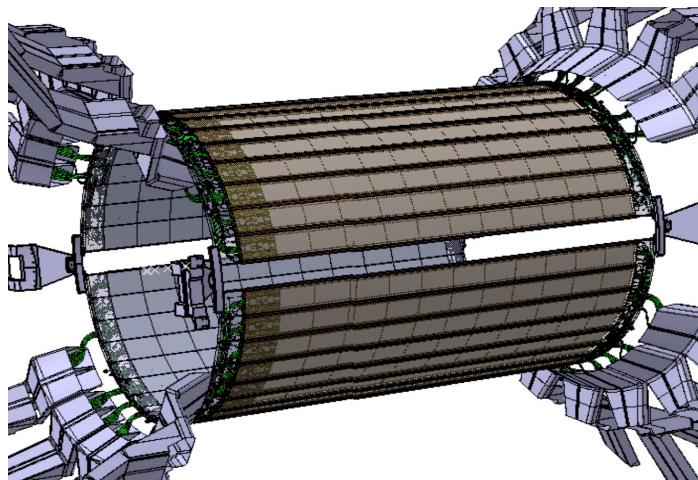
Precision timing for CMS in HL-LHC

- CMS Phase 2 upgrade aims to achieve high precision timing measurements
 - **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 $|\eta| < 3.0$ 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

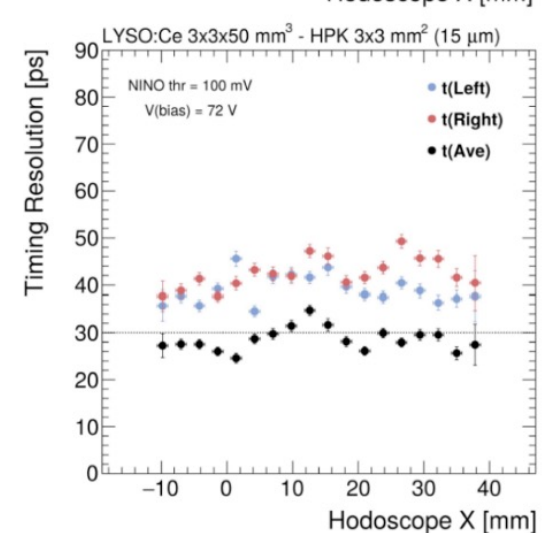


Barrel Timing Layer (BTL) design

- LYSO crystals as scintillator with an excellent radiation tolerance and fast rise and decay times.
 - 332k channels, organized in 6 Readout Units per tray.
- Small SiPM cells: fast readout, robust vs. magnetic field/radiation and low power consumption.
- Time resolution of 35 ps at the beginning of lifetime and 60 ps by the end.



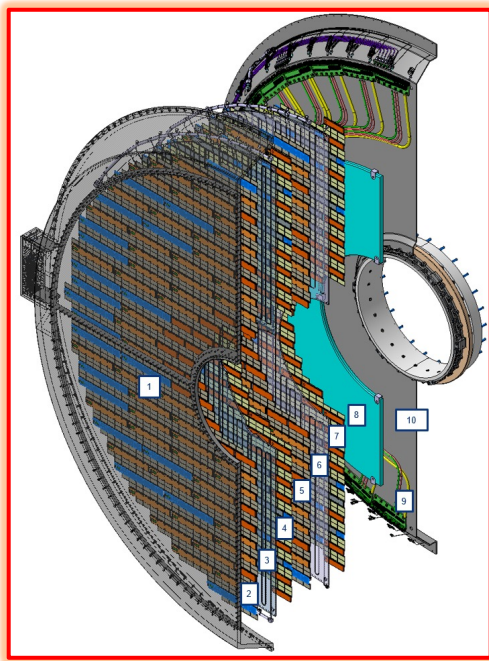
Time resolution per SiPM



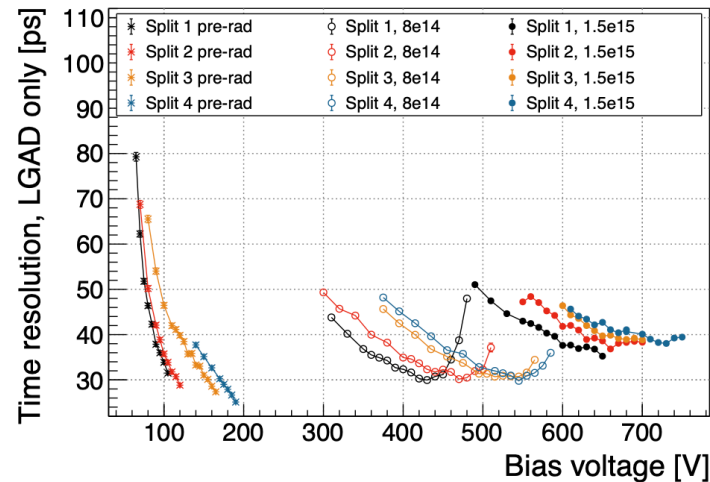
Combined time resolution

Endcap Timing Layer (ETL) design

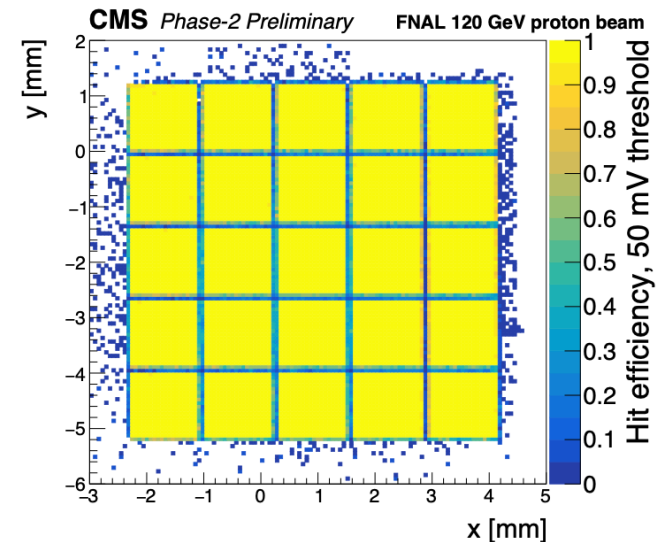
- Sensitive element are LGAD sensors
- Time resolution 30 ps at the beginning of life, 40 ps by the end
- Total silicon surface area of $\sim 14 \text{ m}^2$ for the two Z-sides
 - Two hits for most tracks to improve per track efficiency and resolution



CMS Endcap Timing Layer



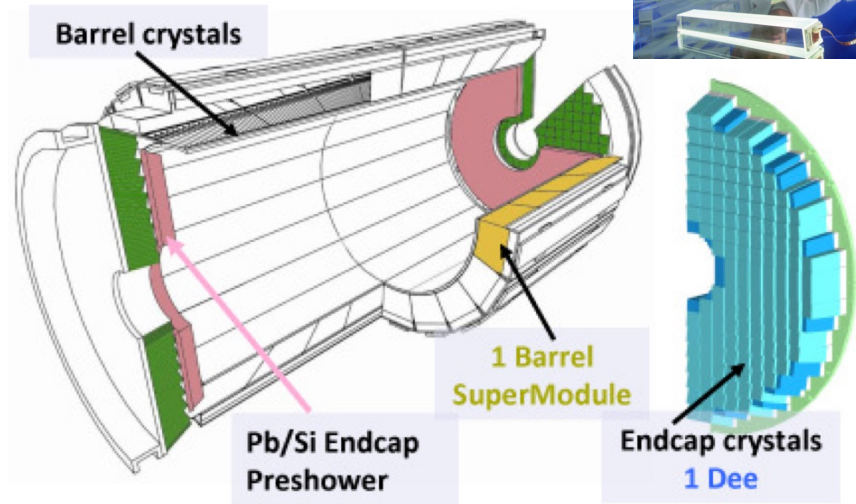
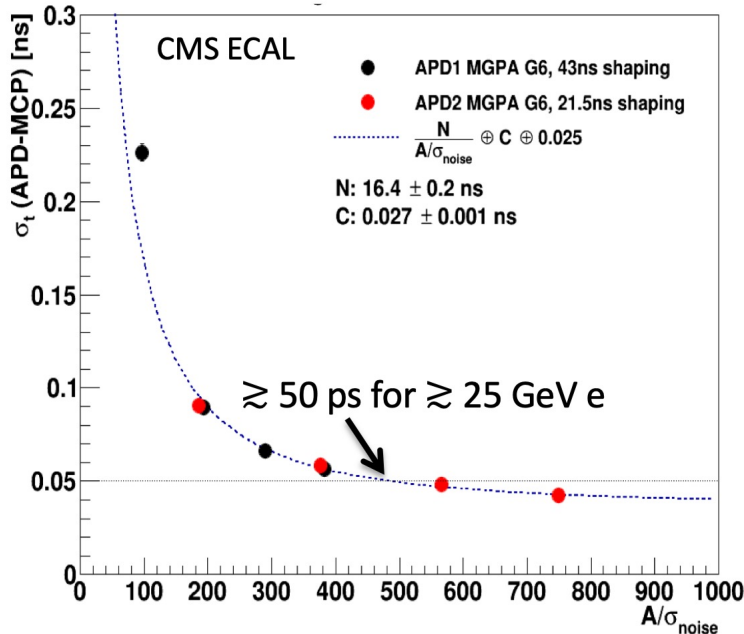
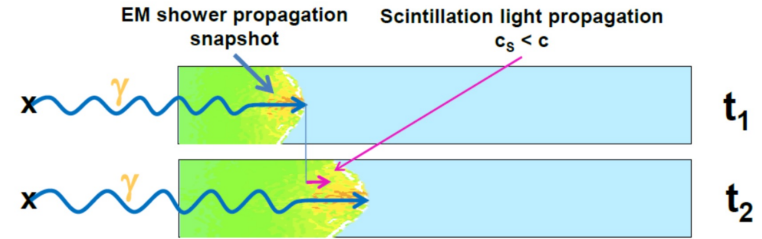
Time resolution for different fluences



Hit efficiency across sensor area

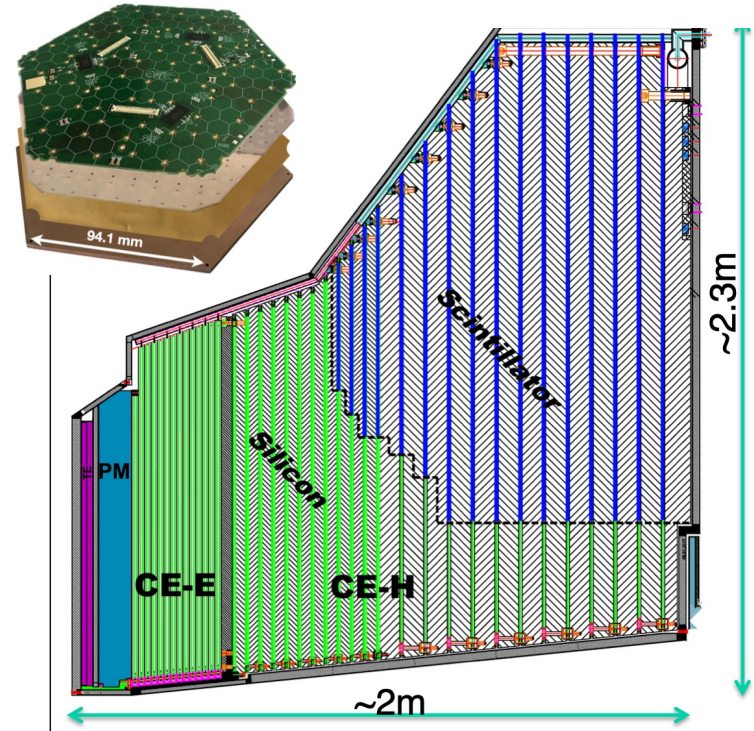
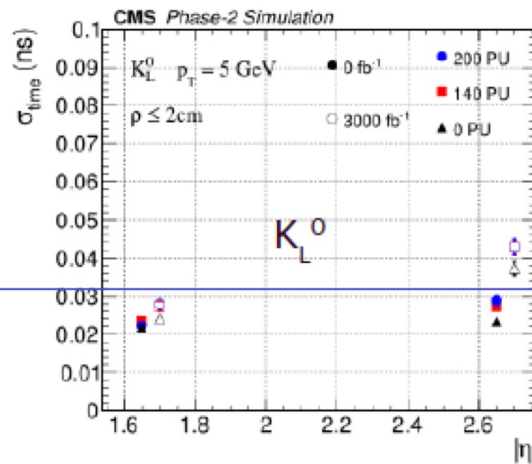
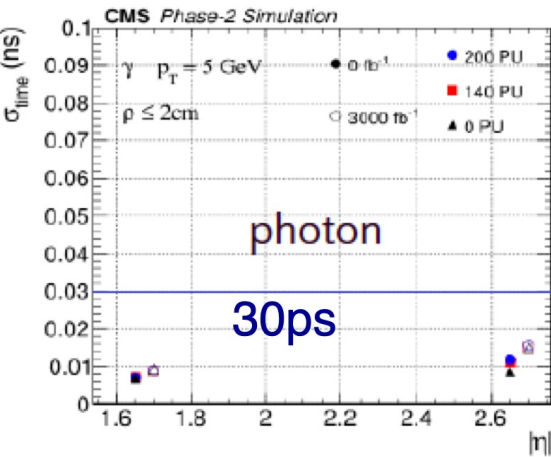
Calorimeters with timing

- 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



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
 - $p_T = 5$ GeV for e/γ : 10-15ps
 - $p_T = 5$ GeV for K_{0L} : 30 ps



AC-coupled LGADs

- Improve 4D-trackers to achieve 100% fill factor, and high position resolution
- 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.

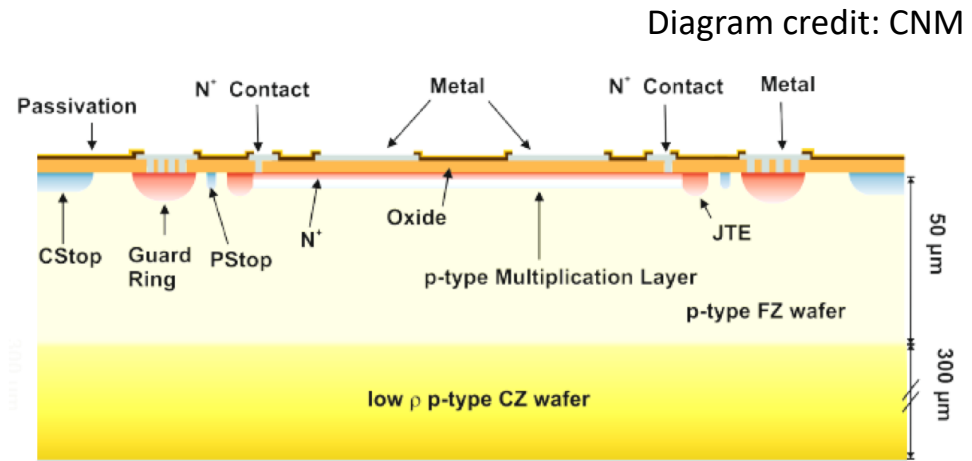
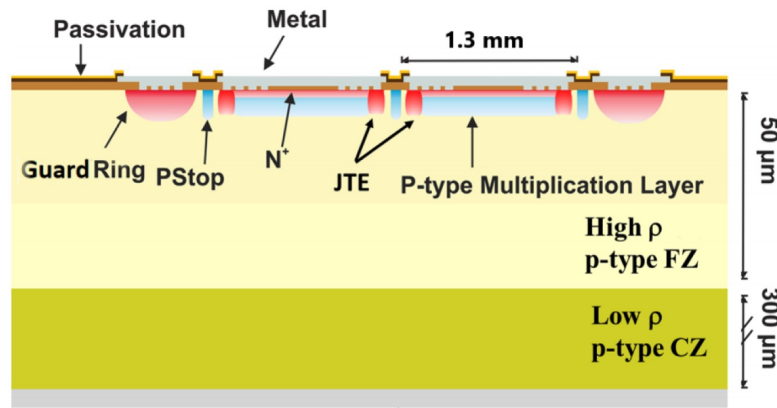


Diagram credit: CNM

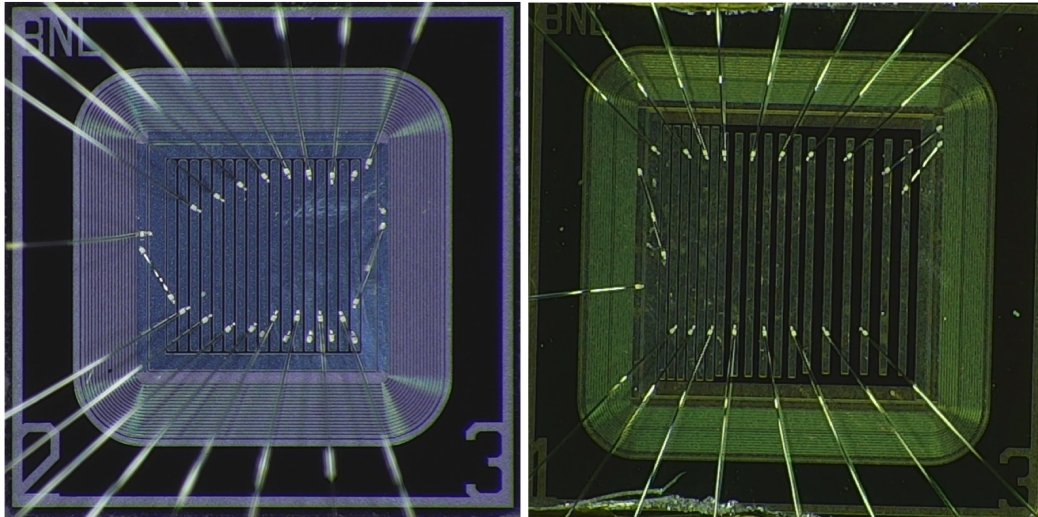
DC-LGAD

AC-LGAD

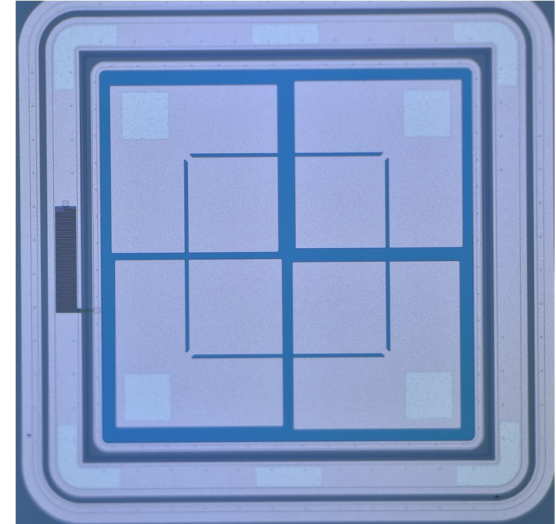
Fermilab

AC-LGAD sensors prototypes

- Several rounds manufactured over the last few years
 - R&D benefiting from developments for HL-LHC
 - Optimization for AC-LGAD sensors has unique challenges
 - Can optimize position resolution, timing resolution, fill-factor, ...
- Extensive characterization and design studies
 - Optimize the geometry of readout, and sensor design for performance



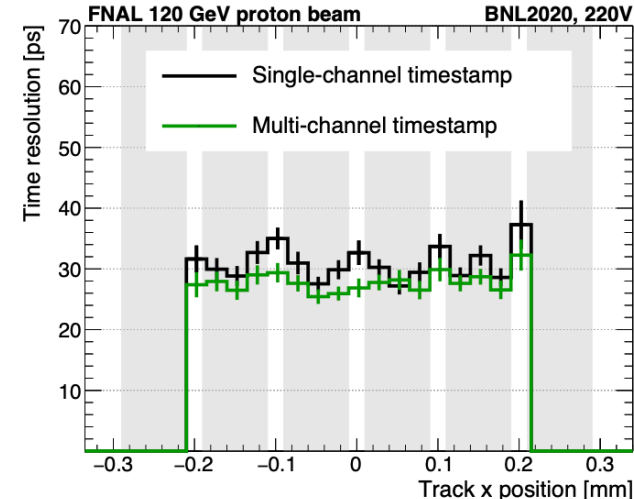
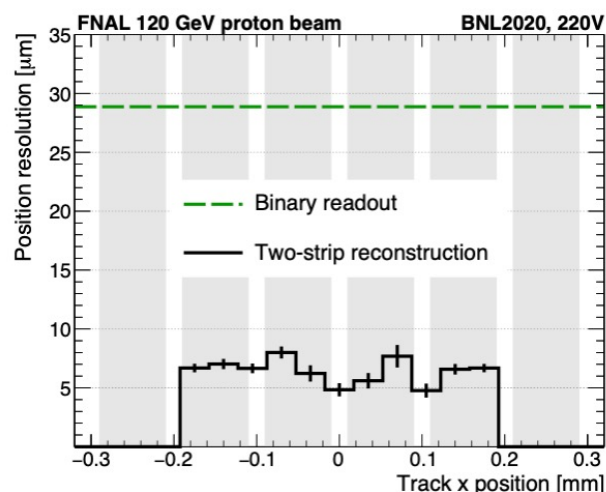
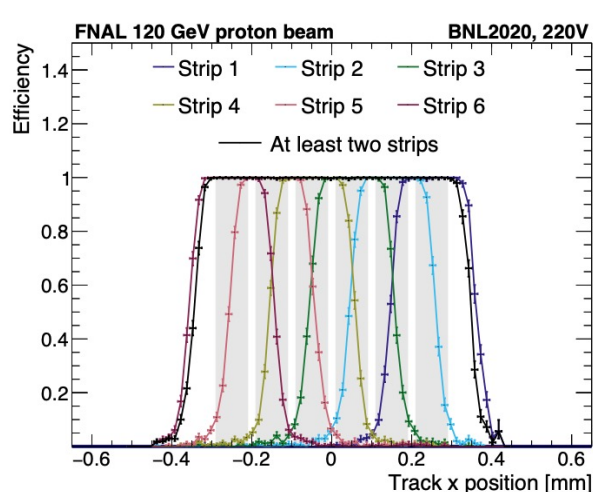
BNL strip AC-LGAD



HPK pads AC-LGAD

Strip-sensor AC-LGADs (short sensors)

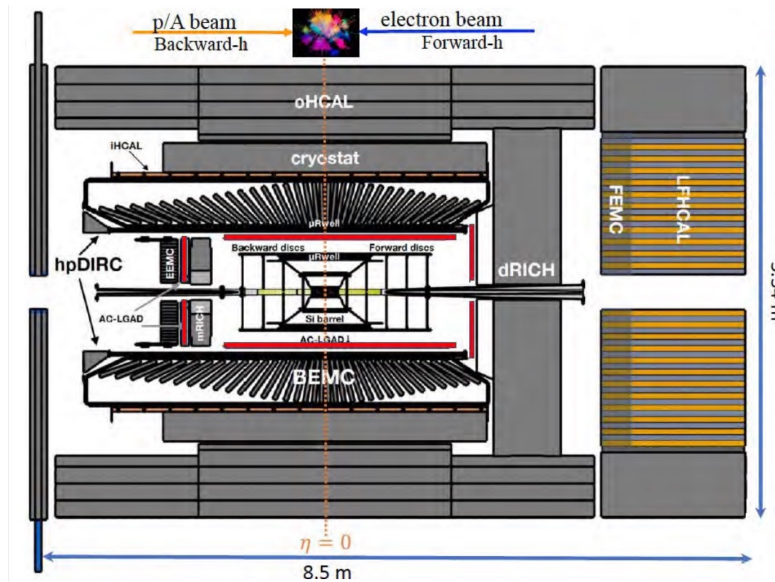
- Excellent performance from several strip prototypes
 - 100% particle detection efficiency across sensor surface
 - Signal shared between neighbors: measure position based on signal ratio
 - Well-tuned signal sharing \rightarrow uniform 5-10 μm resolution



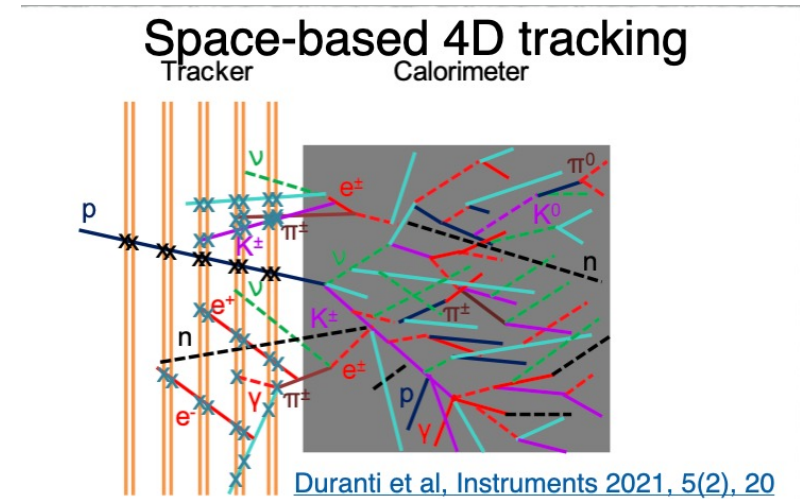
- First demonstration of simultaneous $\sim 5 \mu\text{m}$, $\sim 30 \text{ ps}$ resolutions in a test beam: technology for 4D-trackers!

Studies of long AC-LGAD strip sensors

- First studies of large AC-LGAD sensors
 - Technology demonstrator for 4D-tracking and detectors for EIC
 - Multiple sensors, geometries and designs studied
- Key insights for larger sensors
 - Metal vs. pitch size is important for position reconstruction



EIC experiments: TOF PID and tracking

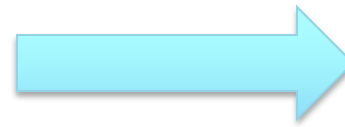
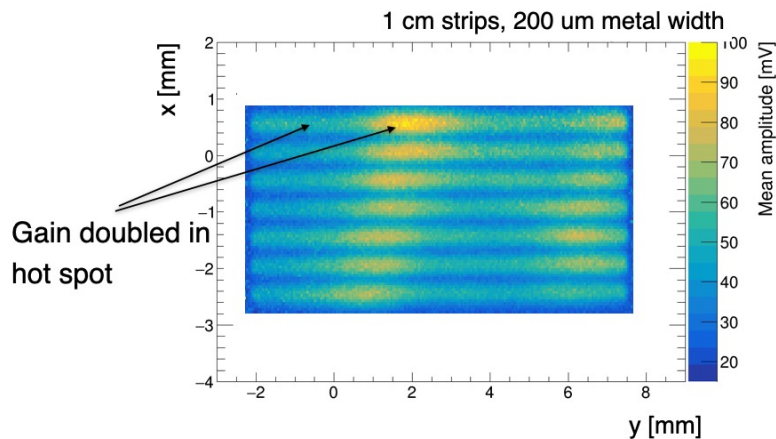


[Duranti et al, Instruments 2021, 5\(2\), 20](#)

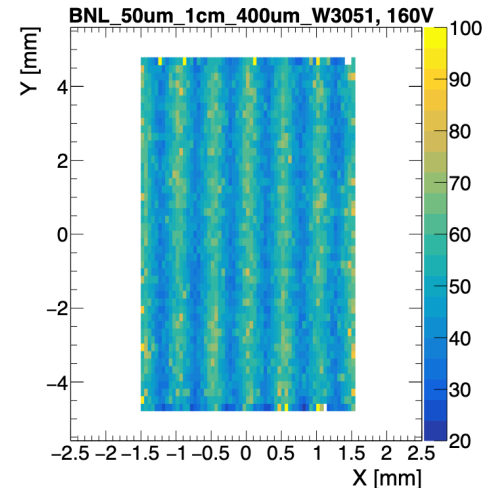
Space-based sensors: power constraints require minimizing number of channels

Gain uniformity over large surfaces

- New challenge with large area sensors: sensitivity to non-uniformity in gain layer
 - Stripe patterns of gain observed in most sensors of the first production
 - High gain regions limit operating voltage \rightarrow other regions remain under-biased



Second round of production

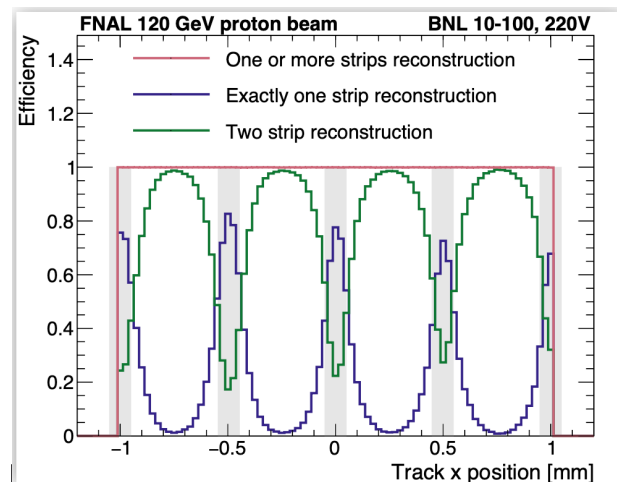


- Improved uniformity in second production
 - Uniform 2x2 cm² LGADs for ATLAS/CMS have been demonstrated

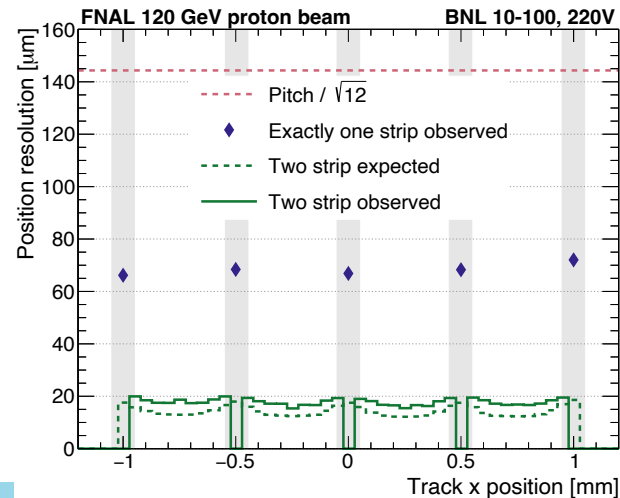
Long AC-LGAD strip sensors performance

- Position reconstruction with ratio of amplitudes
 - Sensor provides 100% efficiency
 - Achieve 15-20 μm resolution for 2-strip events in all 5-10 mm strips
- Time resolution 30-35 ps for 1 cm strips
 - Combining 2 channels & correcting for position-dependent delays
 - High gain regions— achieve 30-35 ps for 5 to 10 mm strips
 - The 2.5 cm long sensor had lower gain \rightarrow improve in next round

Reconstruction efficiency



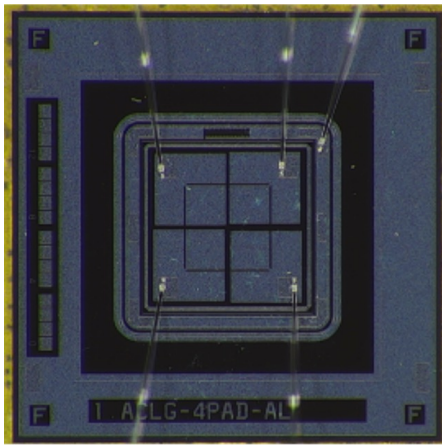
Performance for 1 cm strips, 100 μm metal



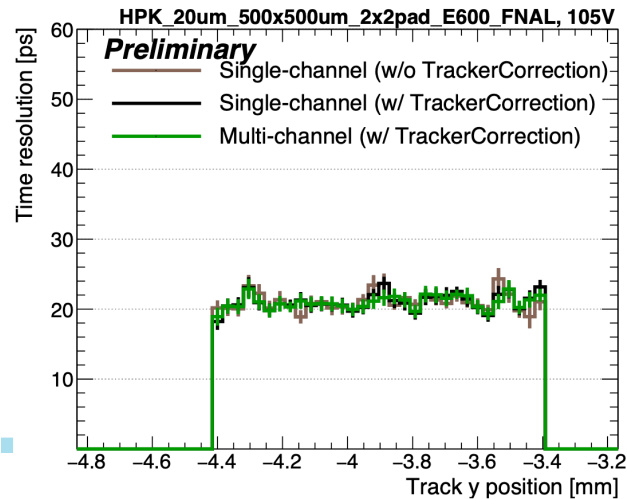
Name Unit	Time resolution
	High gain ps
BNL 5–200	30 ± 1
BNL 10–100	35 ± 1
BNL 10–200	32 ± 1
BNL 10–300	36 ± 1
BNL 25–200	51 ± 1

Towards better time resolution

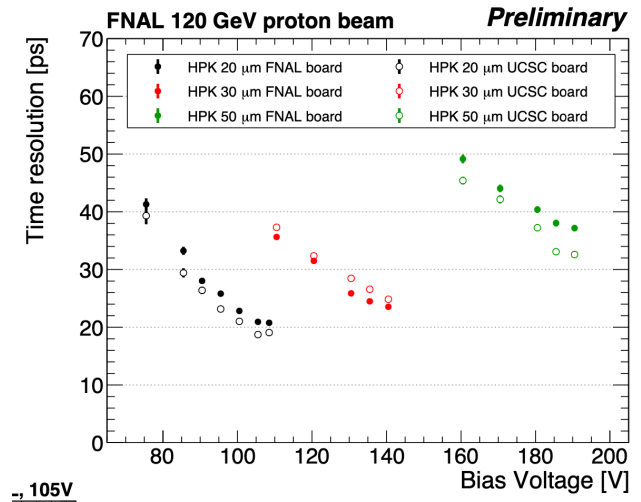
- How do you get better time resolution?
 - Thinner sensors to decrease Landau contribution
- AC-LGAD from HPK with 20, 30, 50 μm thickness
 - Almost fully metallized, optimized for timing performance
 - Can not use signal sharing for position reconstruction
- Uniform time resolution across full sensor area
 - 25 ps for 30 μm thick sensor, 20 ps for 20 μm thick sensor



HPK 2x2, 500x500 μm^2 pixel size



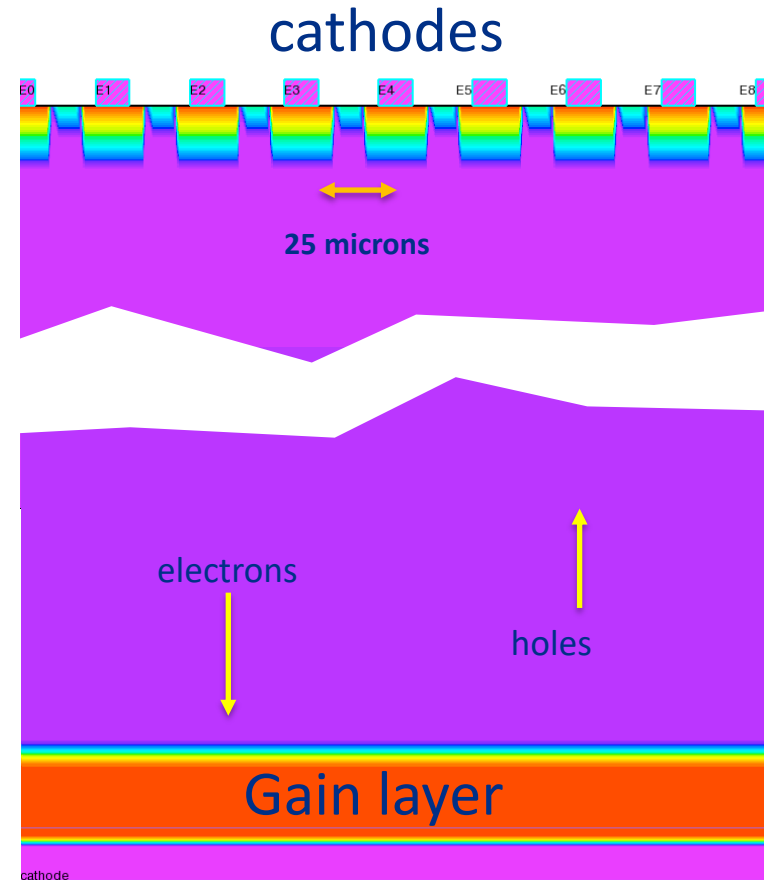
20 ps across full sensor surface



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

Double Sided LGAD

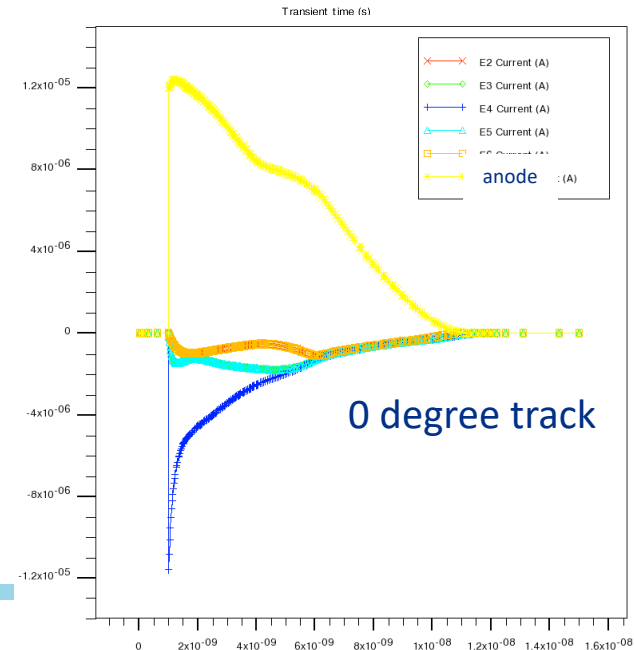
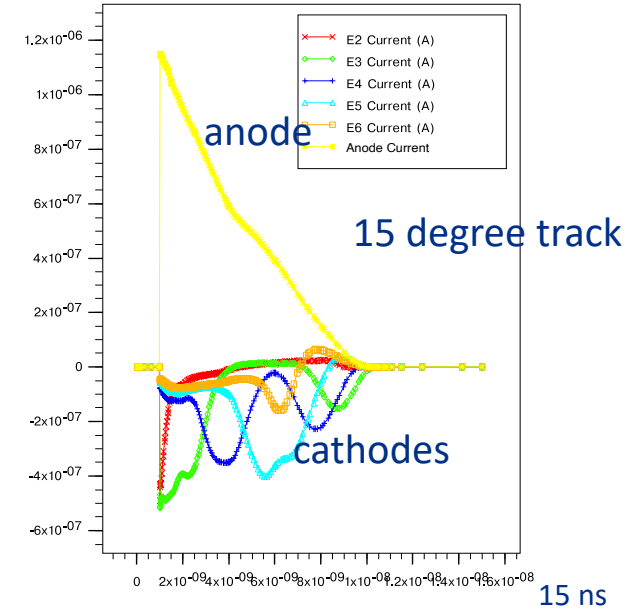
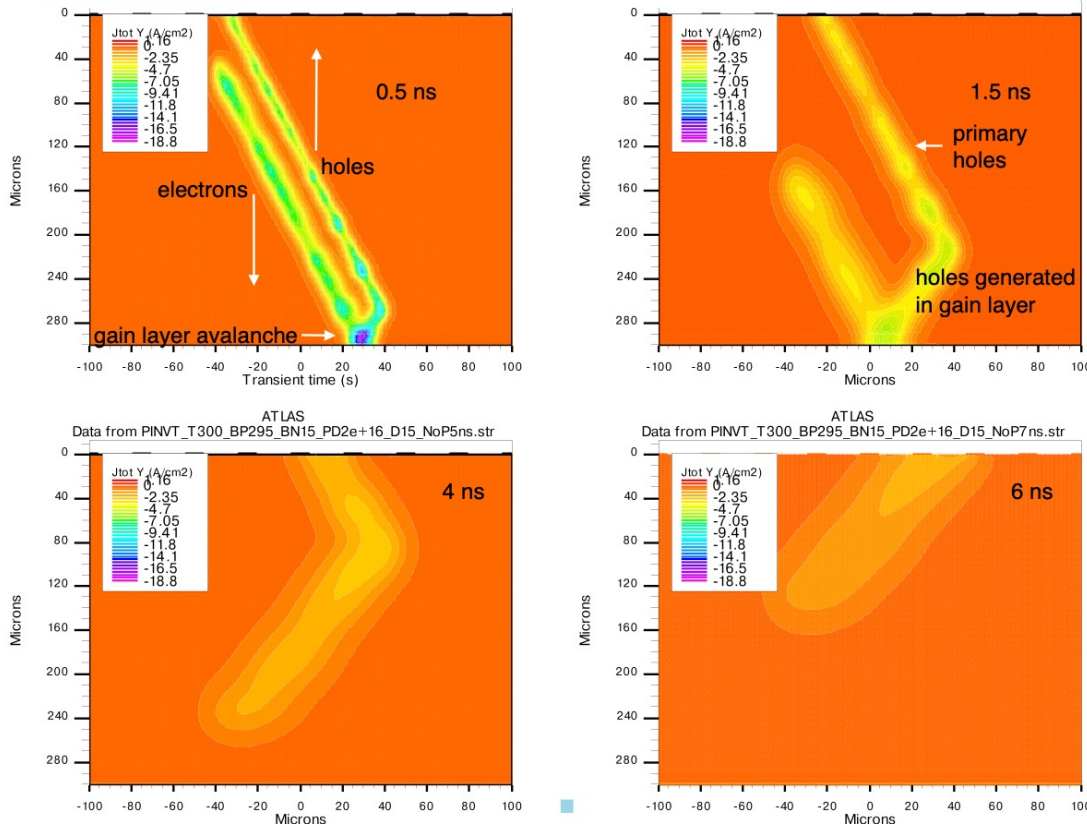
- Low Gain Avalanche Diode with fine pixels on the hole-collecting side
 - Anode can provide timing with coarse pitch
 - Cathode subdivided into small pixels
- Records “primary” hole collection, then holes from gain region – double peak that reflects charge deposition pattern
 - Lower power due to large 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



Double Sided LGAD Simulation

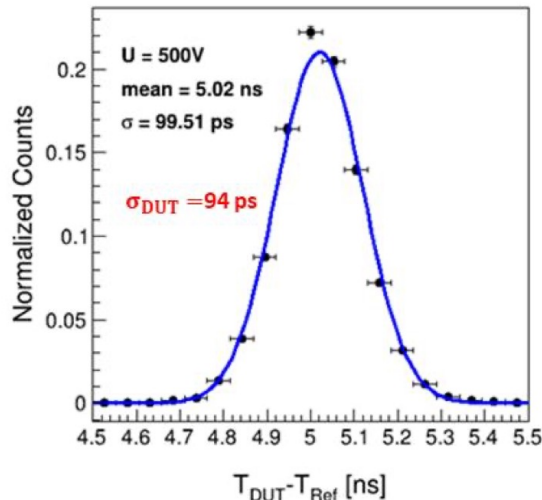
- Use anode for timing, cathodes for pulse shape discrimination

15 degree track detector internal current distributions

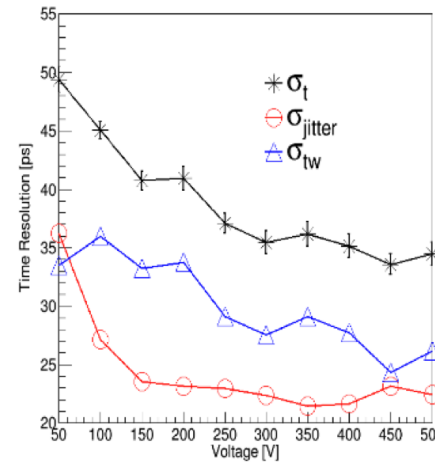


- Wide Band Gap Materials offer potential advantages
 - Enhanced radiation resistance
 - Reduced cooling requirements → reduced detector material mass
 - Increased commercial interest in wide band gap materials for power applications, HEP can benefit from these developments
- Several prototype runs recently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

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



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



doi: [10.3389/fphy.2022.718071](https://doi.org/10.3389/fphy.2022.718071)

doi: [10.3390/mi13010046](https://doi.org/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 $1.3 \times 1.3 \text{ mm}^2$, $\sim 2 \text{ mW/pixel}$
 - Going to small pixels for muon colliders, e.g. $50 \times 50 \text{ }\mu\text{m}^2$: need to reduce power consumption per pixel by $\sim \times 680$ 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

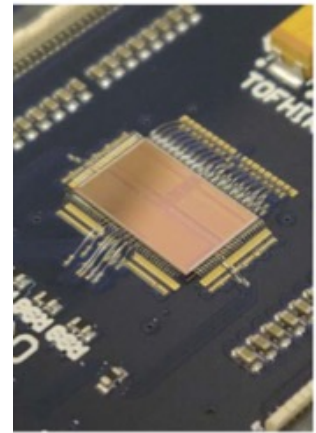
Electronics for MTD and HGTD

• BTL TOFHIR

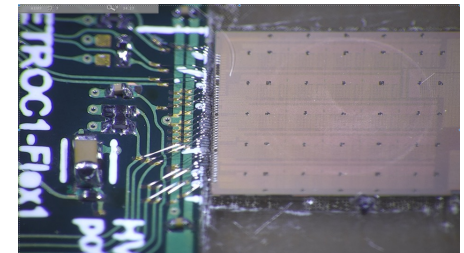
- minimize impact of DCR noise and pileup on time resolution
- cope with very high rate of low energy hits per channel
- Inverted and delayed pulse subtract from the input pulse
 - Restores baseline at the rising edge of the pulse.
- Improves time resolution by about a factor 2 at EOL

• ETROC and ALTIROC

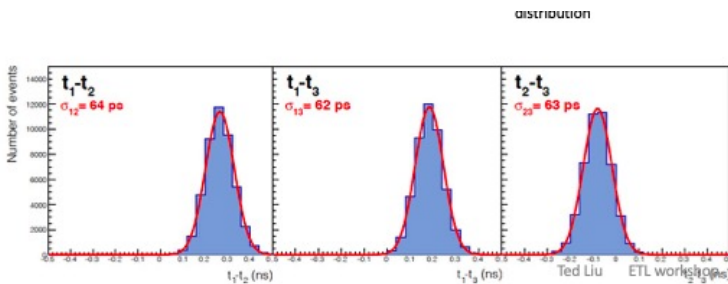
- bump-bonded to LGAD, with 1.3 mm x 1.3 mm pads
- Requirement: ASIC contribution to time resolution < 40ps
- Deal with small signal size (~6fC, at end of operation)
- Power consumption < 1W/chip



TOFHIR for CMS



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:

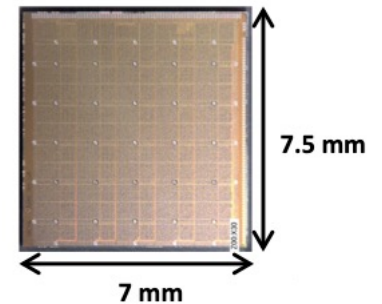
$$\sigma_i = \sqrt{0.5 \cdot (\sigma_{ij}^2 + \sigma_{ik}^2 - \sigma_{jk}^2)} \sim 42 - 46 \text{ ps}$$

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

This measured time resolution includes all four contributions in the table

For more details, see ETROC1 testing results by Zhenyu Ye

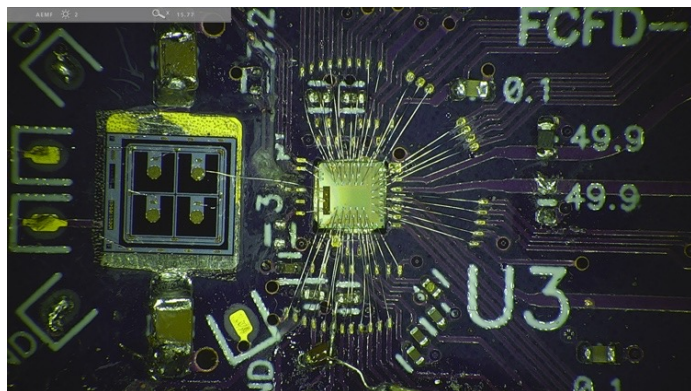
Prototypes performance validated in test beam



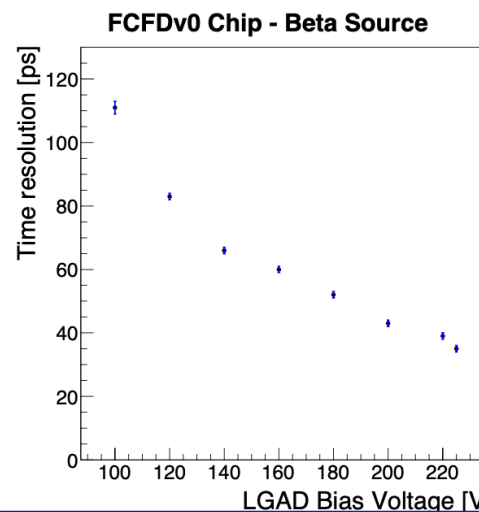
ALTIROC for ATLAS

Timing ASIC with CFD

- A novel ASIC based on CFD for LGAD fast timing readout
 - Expect better performance for low S/N after irradiation, no need for time-walk correction, stability, simplicity of operation,
- The IC form an attenuated and a delayed version of the amplified input pulse
 - These two signals then directly feed a fast differential amplifier.
 - The single-ended output of the differential amplifier feeds a very simple output comparator that compares it to an internal DC threshold voltage



FCFD0 chip mounted to LGAD

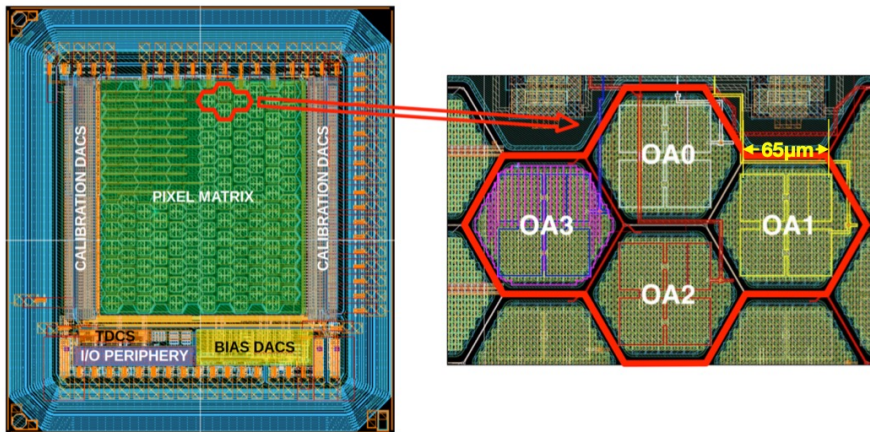


Time resolution with 1.3x1.3 mm² LGAD sensor

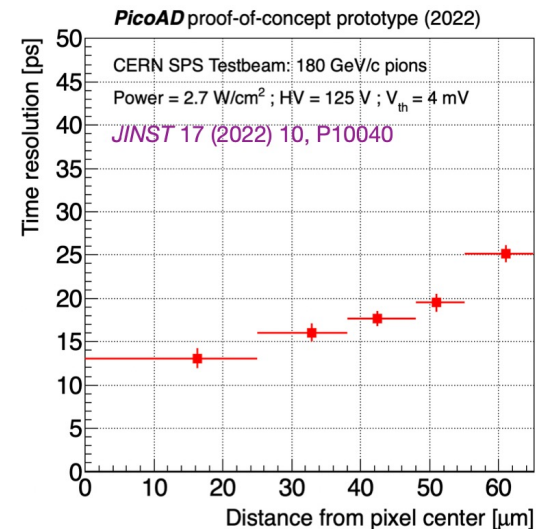
Monolithic sensors

- 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
 - Continuous and deep gain layer, high pixel granularity and full fill factor
 - Time resolution from ~ 13 ps at the center to ~ 25 ps at the edge

PicoAD Proof-Of-Concept Prototype (2021)



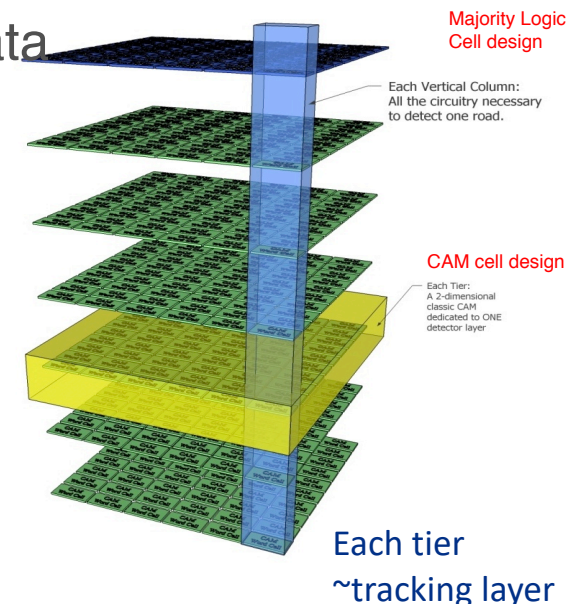
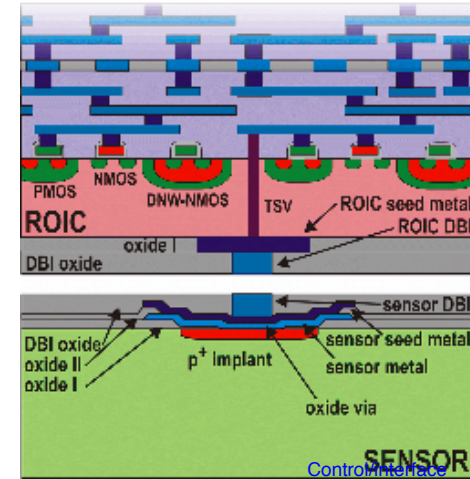
Time resolution



(13.2 ± 0.8) ps at the pixel center 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 chips/layers of trackers to form tracks/stubs/vertices
 - Novel materials to design more power-efficient data 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



Summary

- Timing is an enabling technology for future experiments
 - The last dimension to be used in collider experiments!
 - Will bring improvements in event reconstruction, triggering, and new handles in searches for new physics!
- Future tracking detectors will likely be required to have significant timing precision: both lepton and hadron colliders
 - Timing precision of 20-30 ps achieved with several Si-based technologies
 - Collaborative efforts are a key for the progress in many challenging directions
- Many new disruptive new technologies are emerging