Developments of 4D-trackers for future colliders

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13th workshop on picosecond timing detectors, Elba

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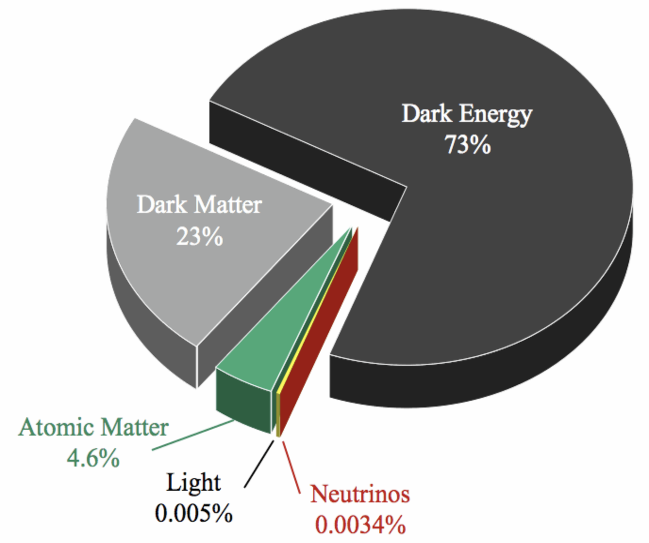
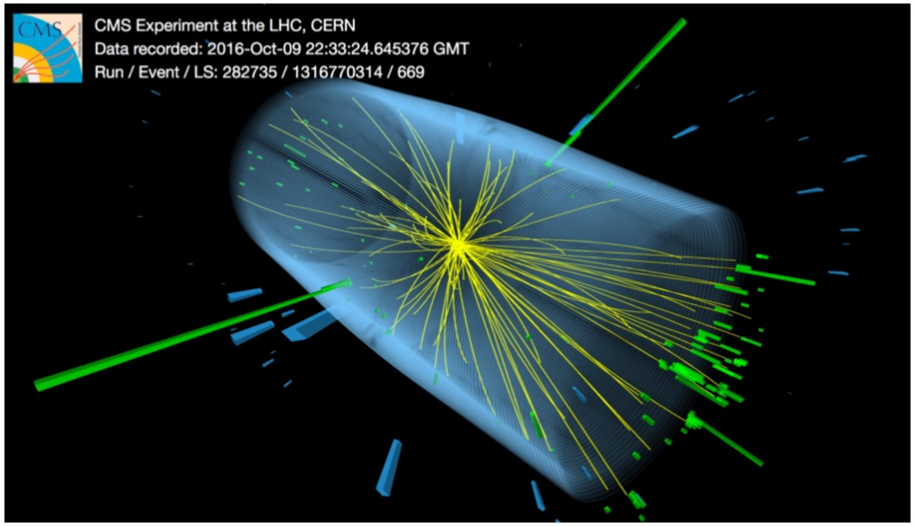
The grand challenges

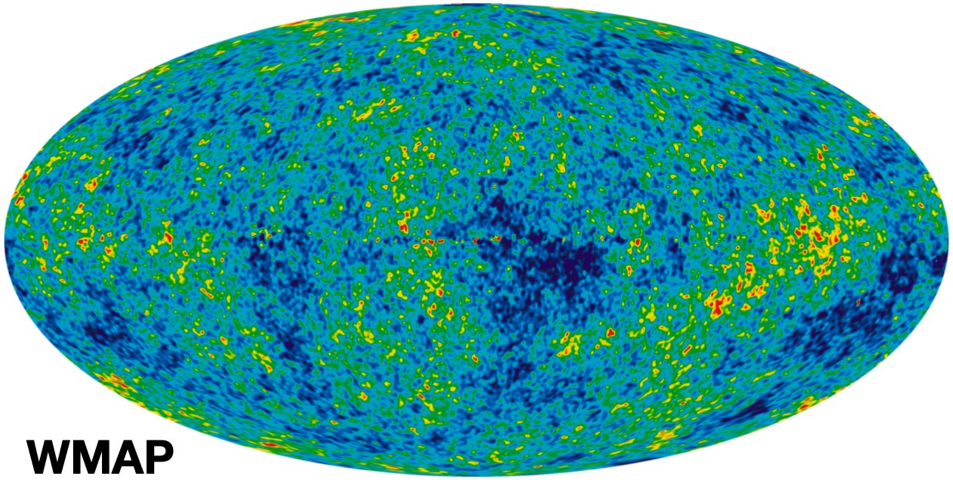
- Many fundamental questions remain in SM
  - Higgs boson: ”unnatural” mass
  - Dark matter: no candidate particle
  - Non-zero neutrino masses
  - Origins of the dark energy
  - Baryon asymmetry

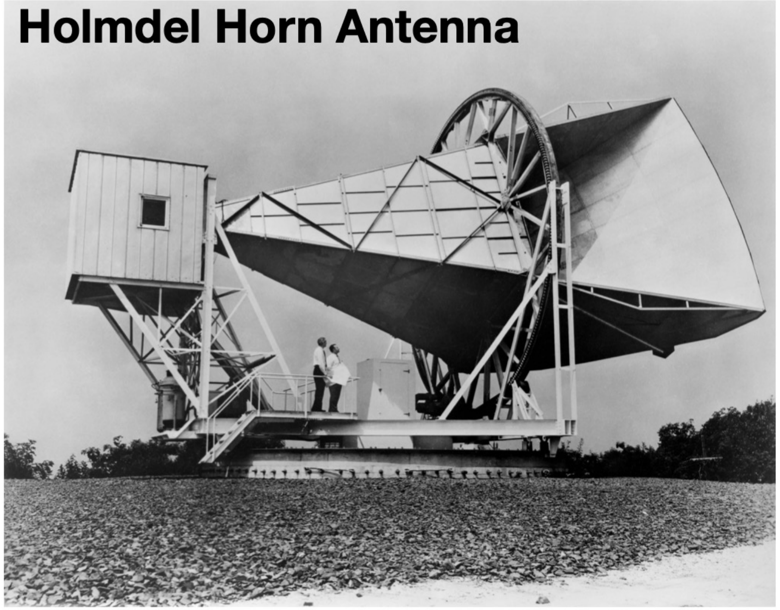




Transformative Physics Discoveries

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



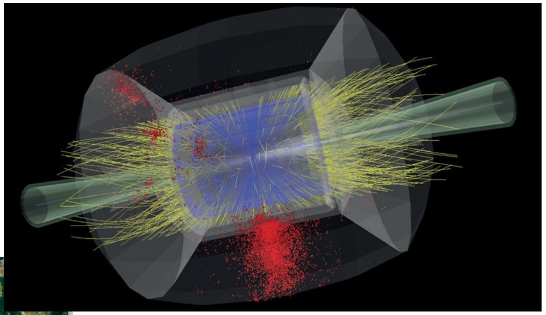


Future trackers need timing

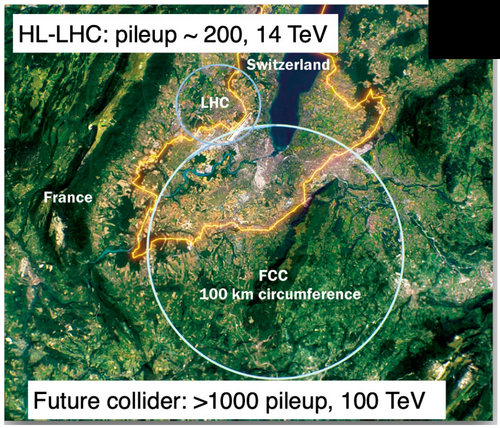
- 4D-trackers will play a key role at future machines
  - Reduce backgrounds, track reconstruction, Level-1 triggering
  - New capabilities: PID and LLP reconstruction
  - All of these pose unique challenges and opportunities to detector design

Measurement	Technical requirement
Tracking for e^+e^-	Granularity: 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]



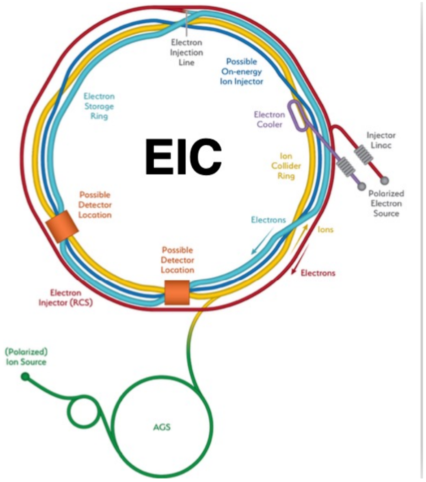
Muon collider



HL-LHC: pileup ~ 200, 14 TeV

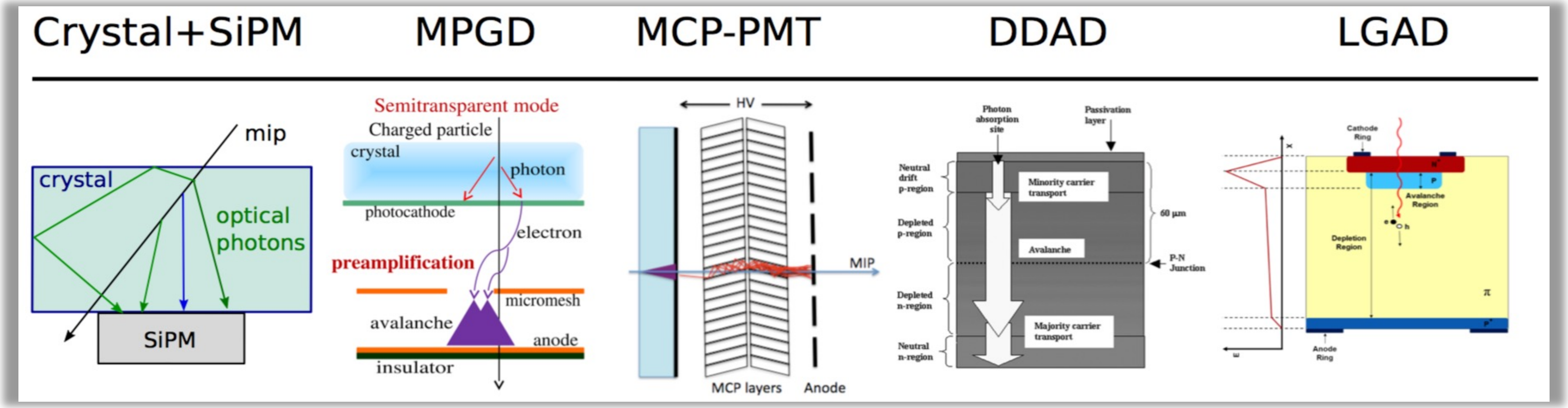
Future collider: >1000 pileup, 100 TeV

FCC



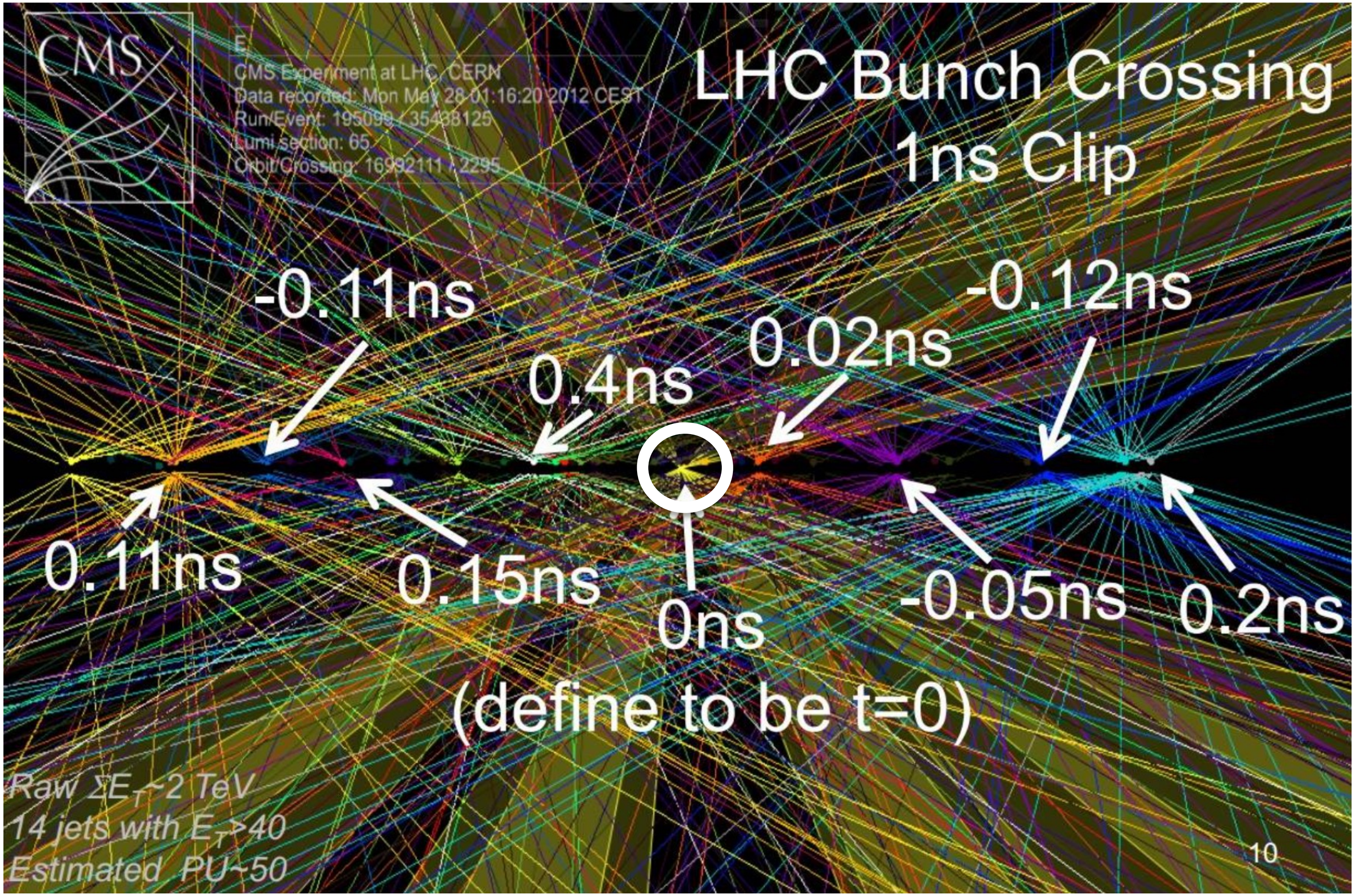
Technologies for precision timing detectors

- 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



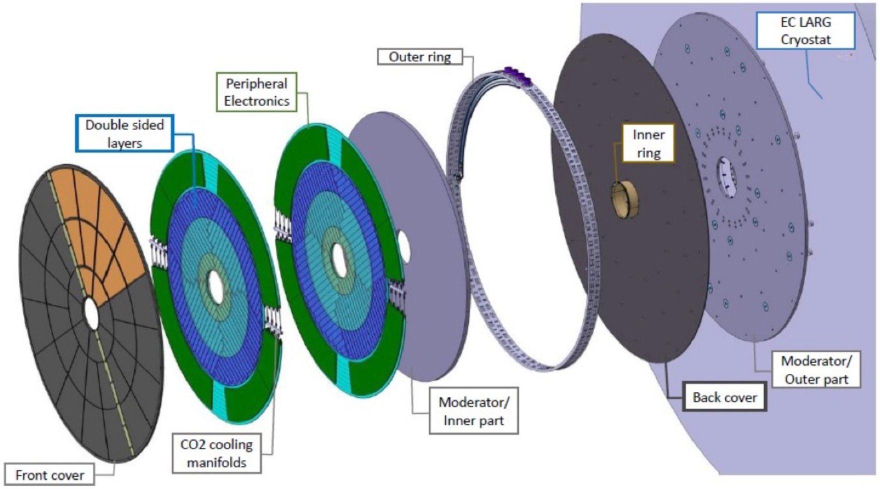
A common challenge in future experiments

More collision → **More confusion**

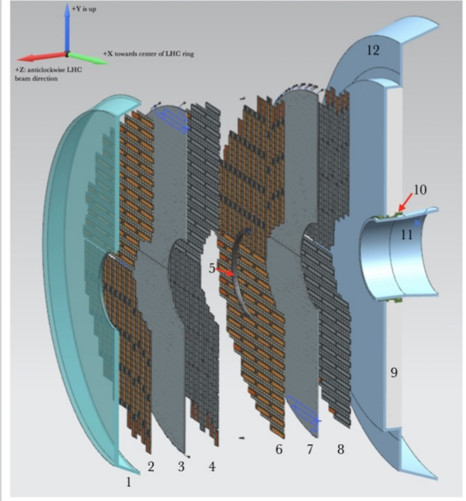


Precision timing

- 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



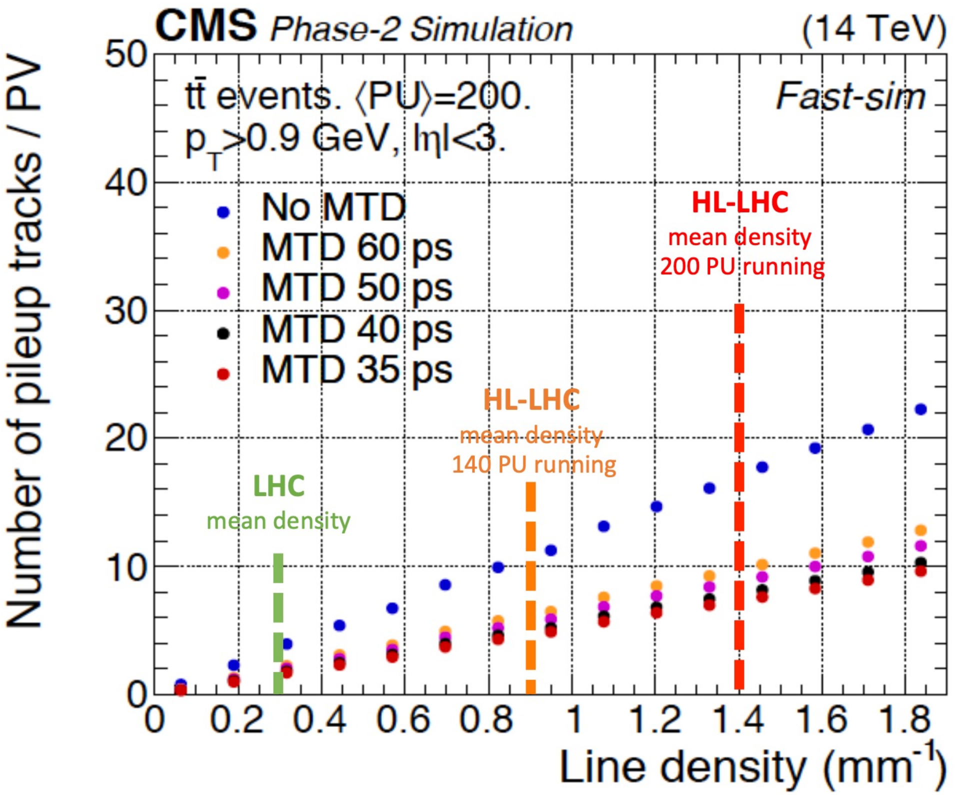
ATLAS timing detector

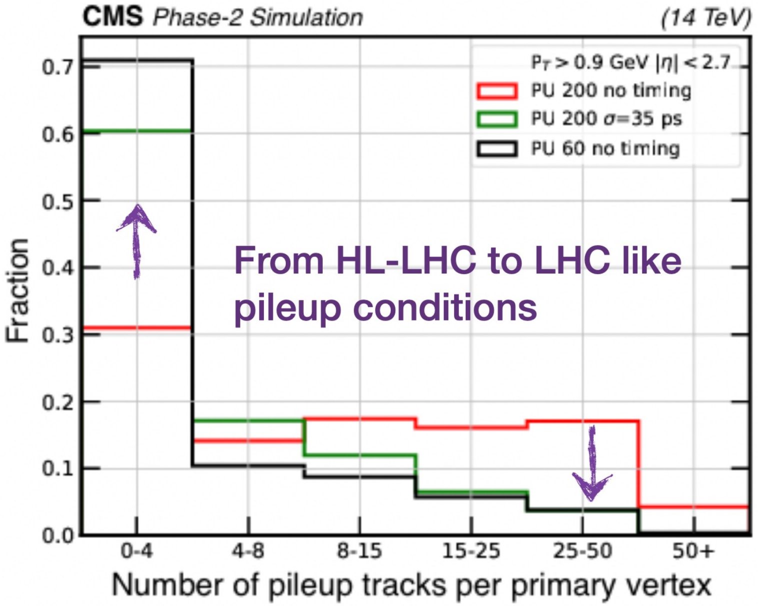


1: ETL Thermal Screen
2: Disk 1, Face 1
3: Disk 1 Support Plate
4: Disk 1, Face 2
5: ETL Mounting Bracket
6: Disk 2, Face 1
7: Disk 2 Support Plate
8: Disk 2, Face 2
9: HGCal Neutron Moderator
10: ETL Support Cone
11: Support cone insulation
12: HGCal Thermal Screen

CMS timing detector

Pileup rejection





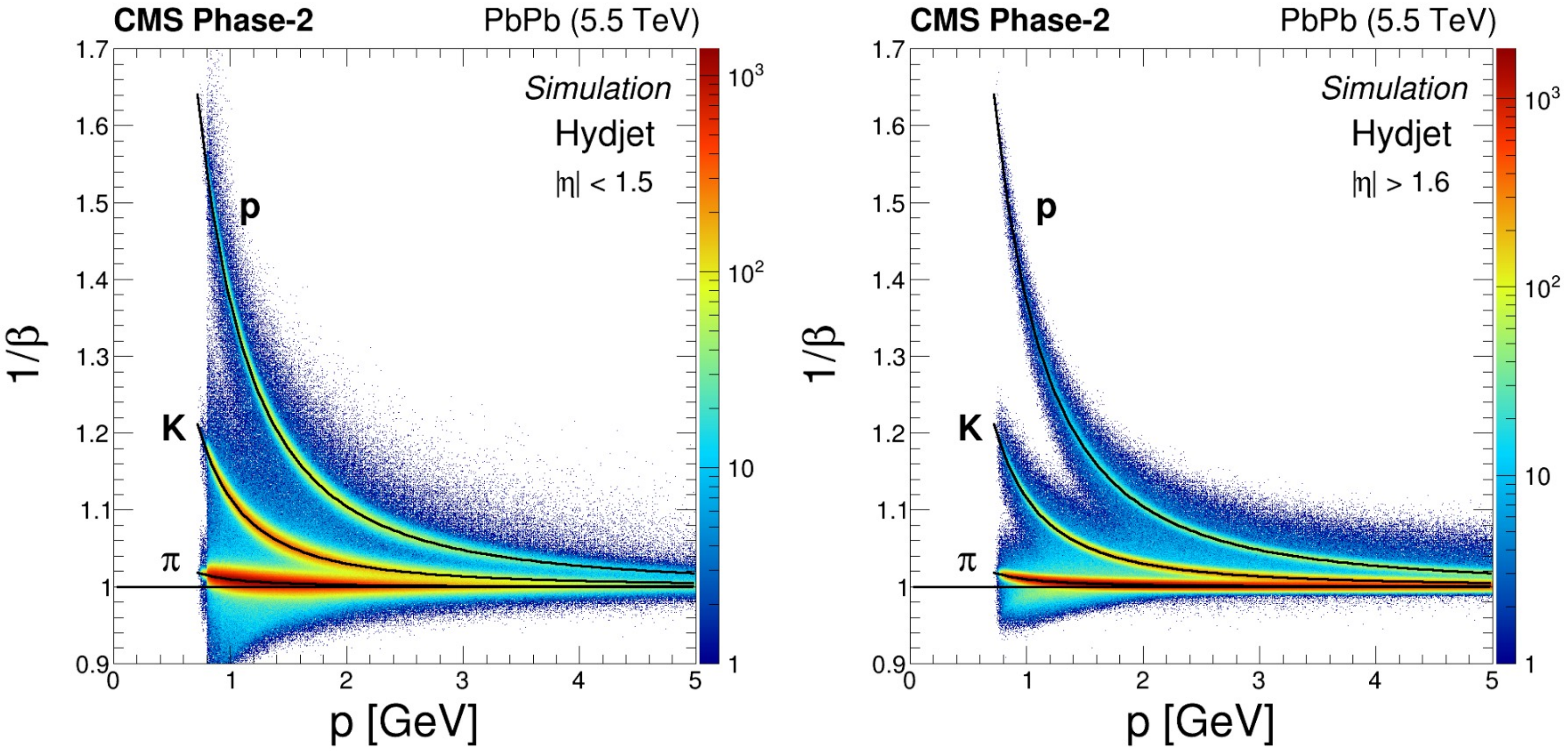
From HL-LHC to LHC like pileup conditions

- 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→200 PU running
  - Brings per-vertex track purity close to typical current LHC running conditions

Time-of-flight Particle ID

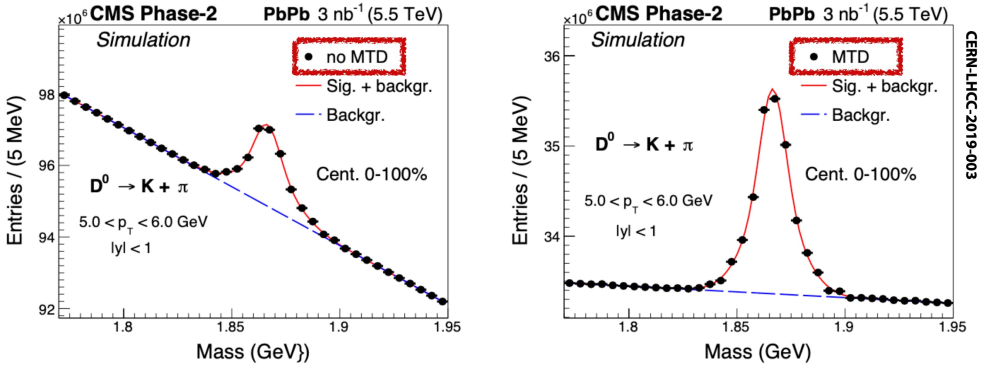
- Time-of-flight particle identification: 2σ **π**/K separation up to p~2 GeV and K/p up to p~4 GeV
  - New handle for CMS for heavy flavor physics

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

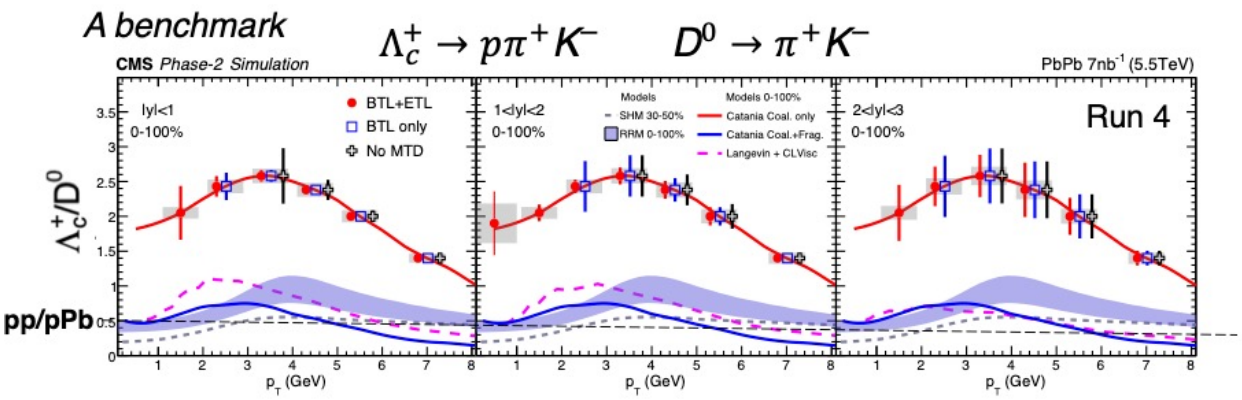


Physics impact: TOF Particle ID

- 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



CERN-LHCC-2019-003



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.

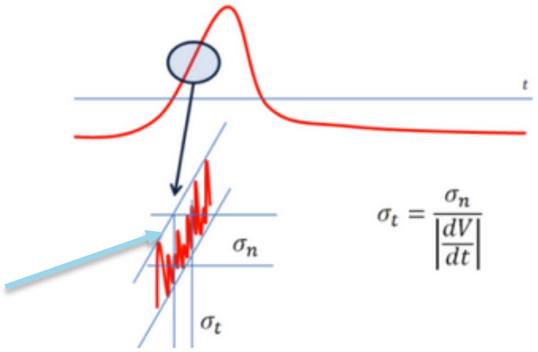
Technologies for precision timing detectors

- 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?

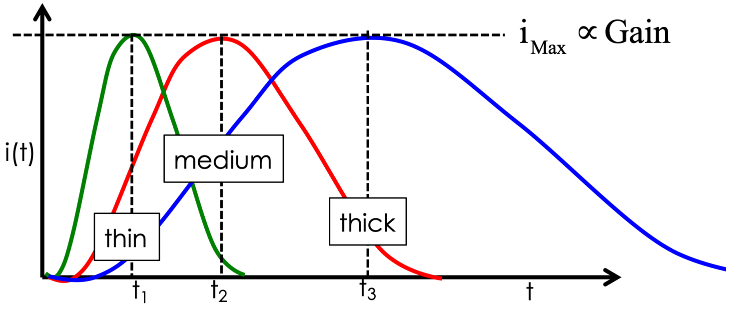
$$\sigma_t = \frac{\sigma_V}{\frac{dV}{dt}} = \frac{N}{\frac{S}{t_r}} = \frac{t_r}{S/N}$$



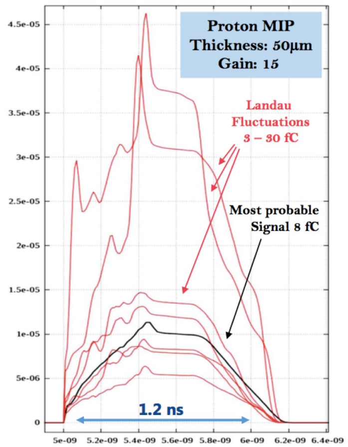
$$\sigma_t = \frac{\sigma_n}{\left|\frac{dV}{dt}\right|}$$

jitter

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



Rise time dependance on Si thickness



Landau fluctuations

Timing resolution

- Putting together various components

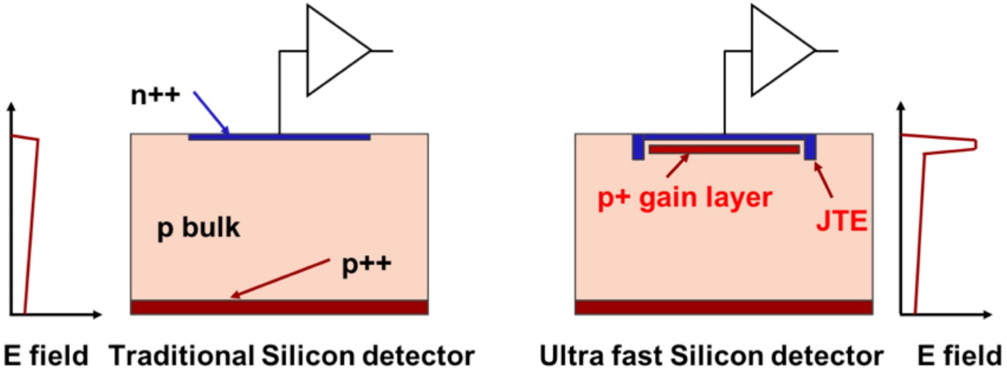
$$\sigma_t^2 = \sigma_{Landau}^2 + \sigma_{timewalk}^2 + \sigma_{jitter}^2 + \sigma_{TDC}^2 + \sigma_{clock}^2$$

- 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

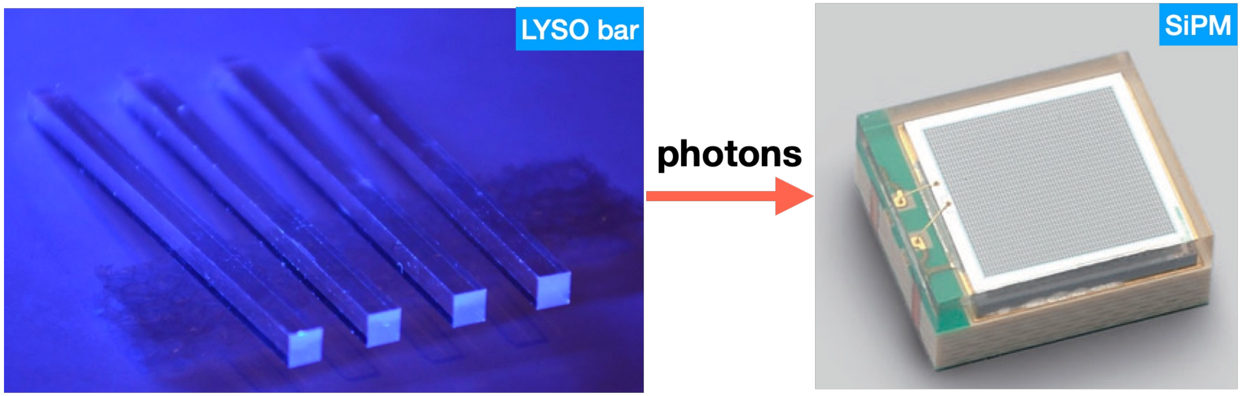
Low Gain Avalanche Diode (LGAD) detectors

- 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 → high signal → faster rise → smaller "jitter"



Crystals + Fast PMT

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

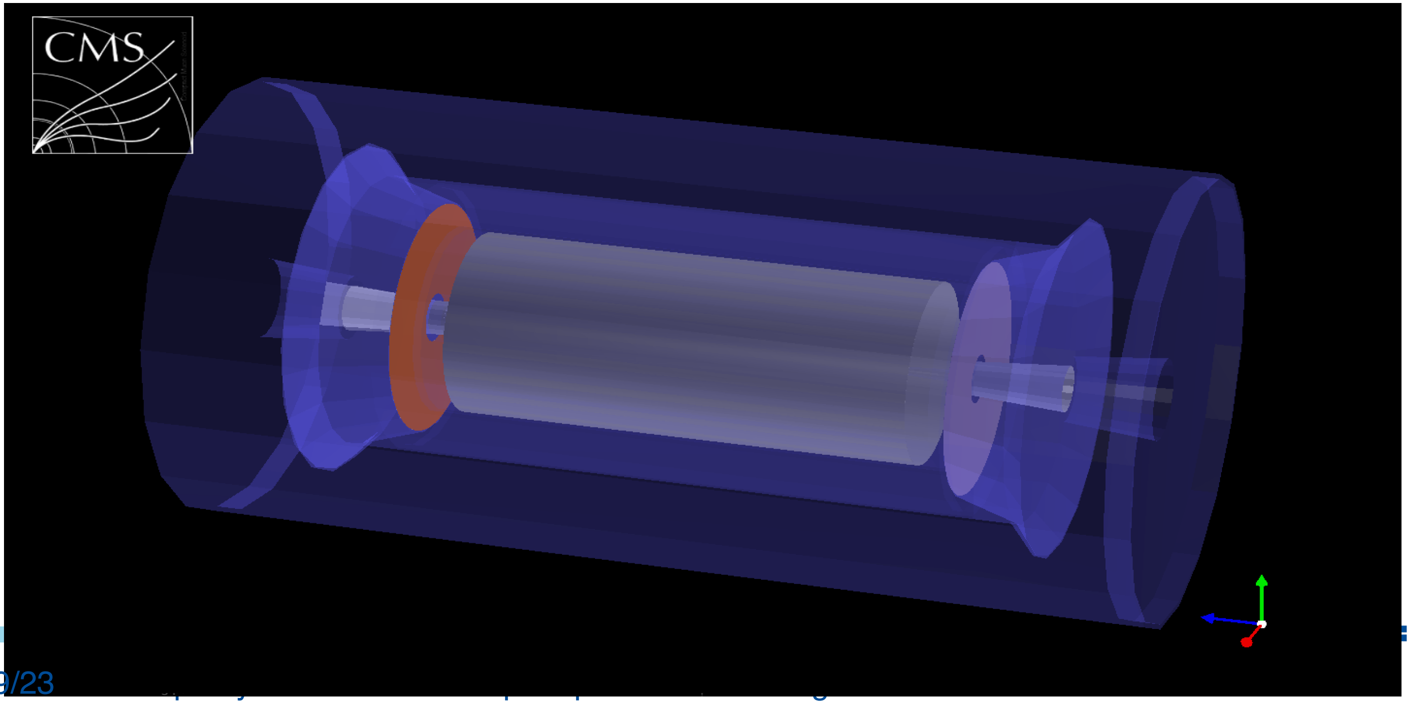


radiation-hard bright scintillator

solid state photon detector

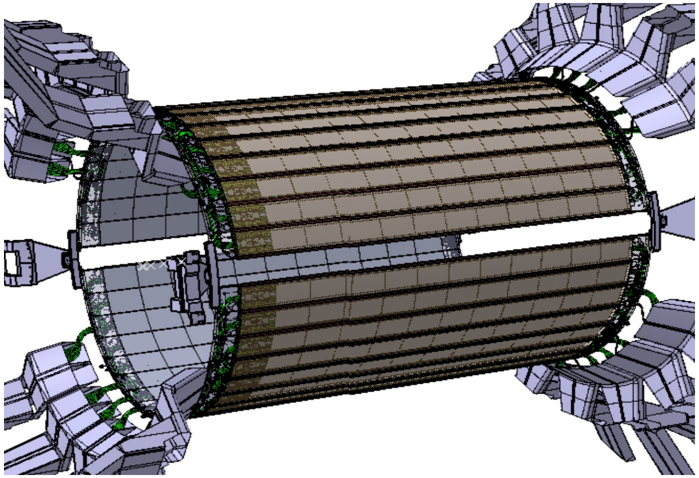
Precision timing for CMS in HL-LHC

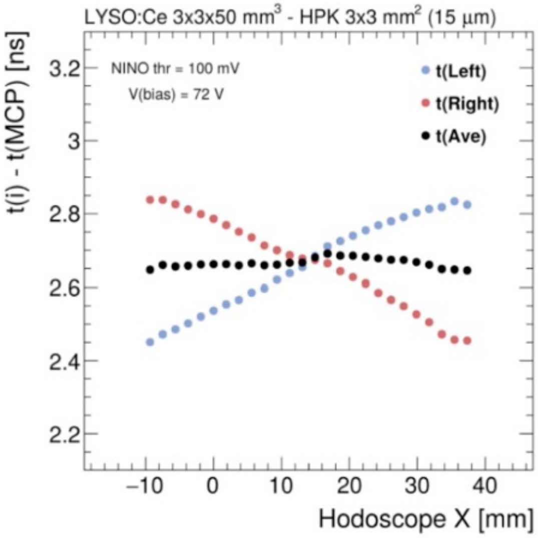
- CMS Phase 2 upgrade aims to achieve high precision timing measurements
  - **In ECAL barrel**: new electronics to achieve ~30 ps resolution for photon/electron
  - **In HGCal**: design to achieve ~50 ps timing resolution per layer in EM showers, multiple layers can be combined
  - **MIP timing detector:** cover up to |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



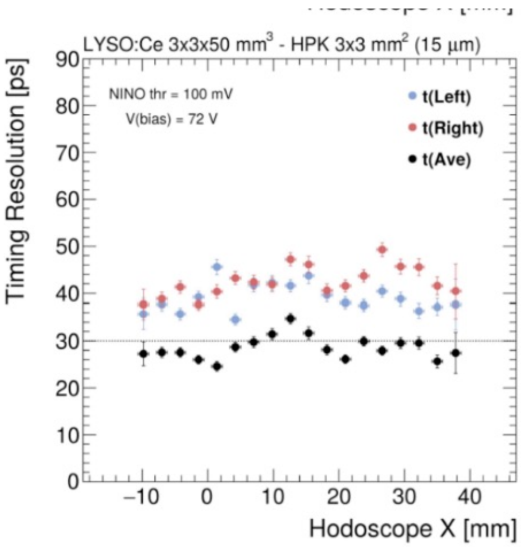
Barrel Timing Layer (BTL) design

- 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.





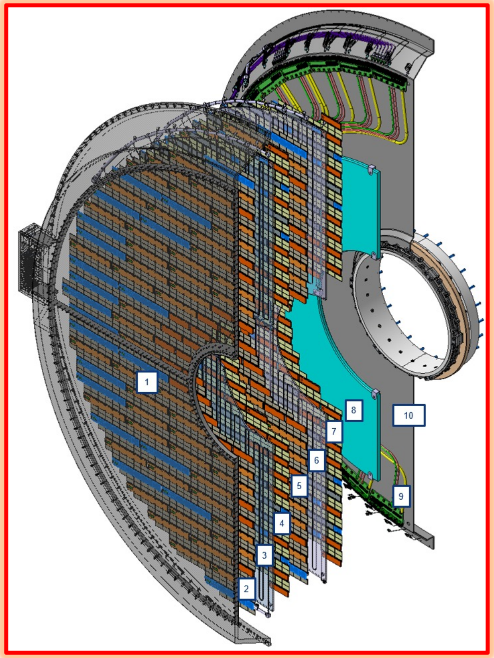
Time resolution per SiPM



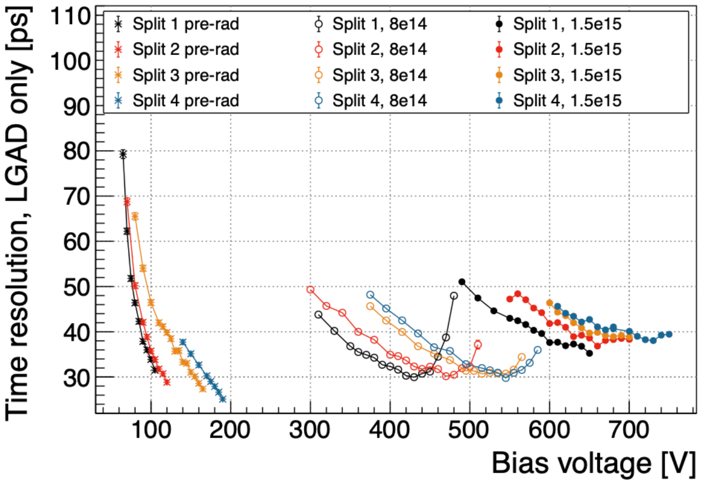
Combined time resolution

Endcap Timing Layer (ETL) design

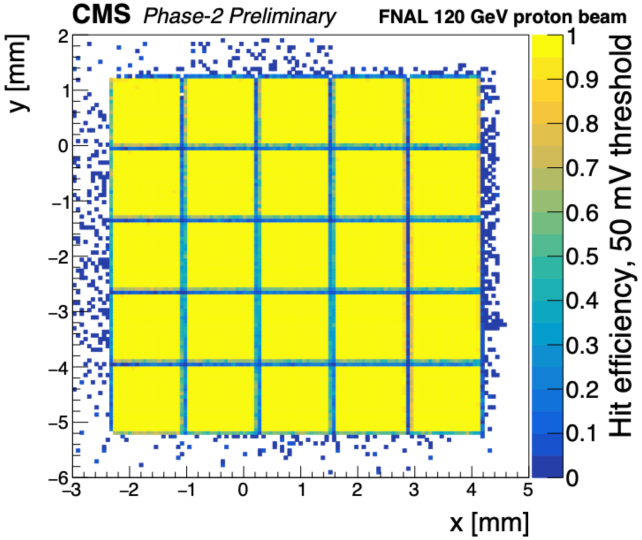
- Sensitive element are LGAD sensors
- Time resolution 30 ps at the beginning of life, 40 ps by the end
- Total silicon surface area of ~14 m^2 for the two Z-sides
  - Two hits for most tracks to improve per track efficiency and resolution



CMS Endcap Timing Layer



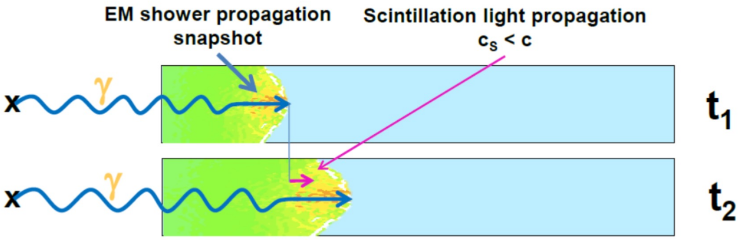
Time resolution for different fluences

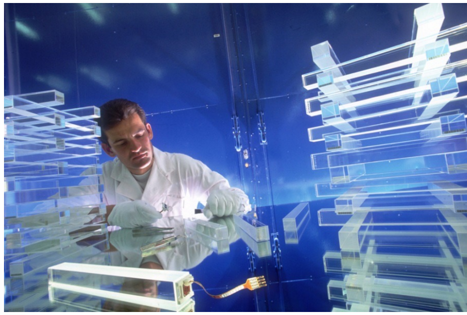


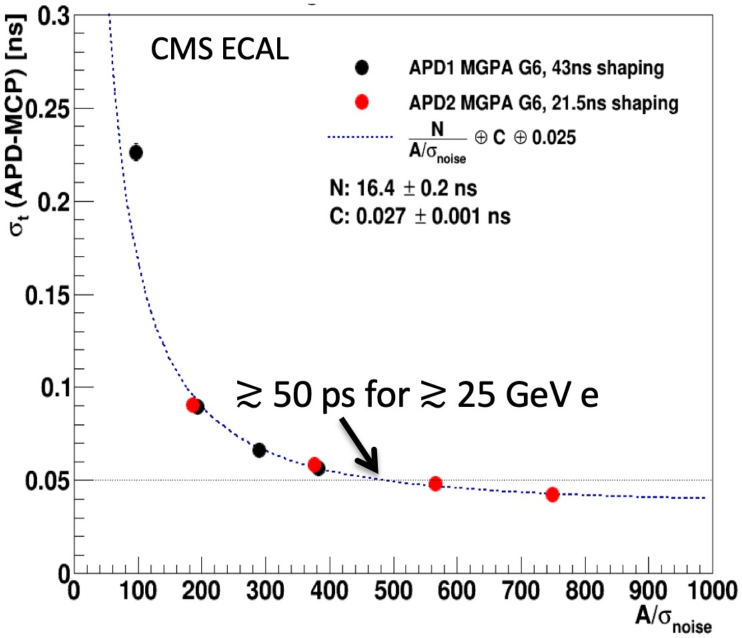
Hit efficiency across sensor area

Calorimeters with timing

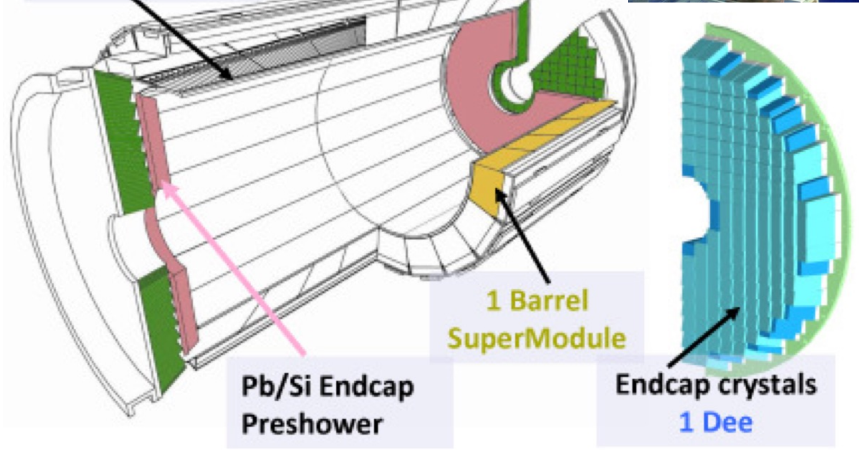
- ECAL with $PbWO_4$
  - High Light Yield ~100 photons MeV
  - Readout by fast APD
  - New electronics for HL-LHC to take advantage of the fast signals to achieve <50 ps time resolution





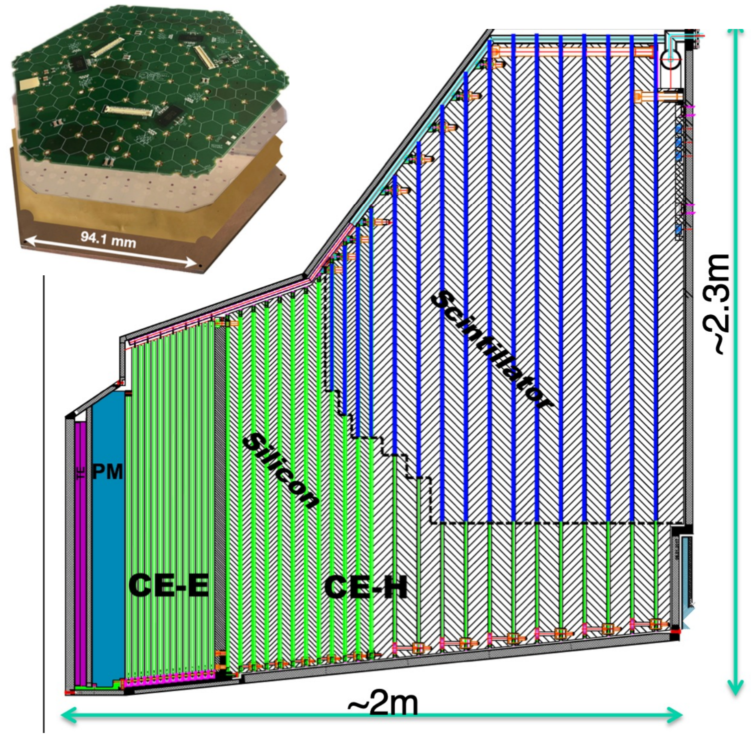


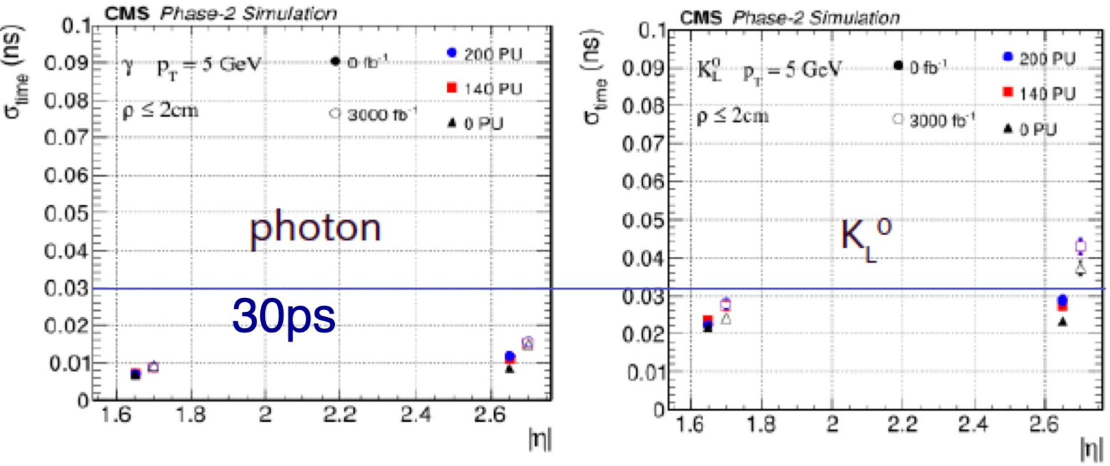
$\gtrsim$ 50 ps for $\gtrsim$ 25 GeV e



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

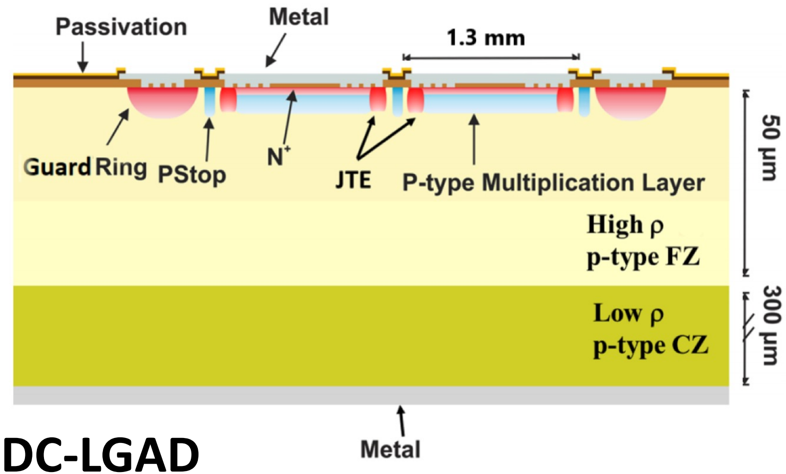




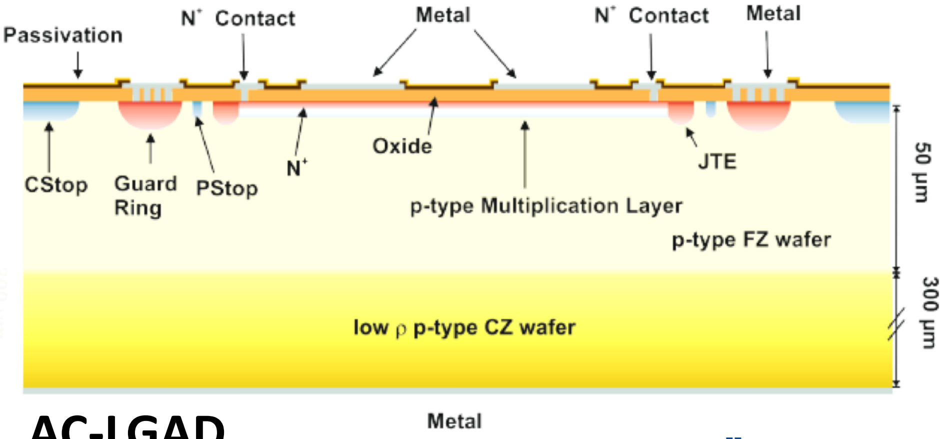
AC-coupled LGADs

- **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



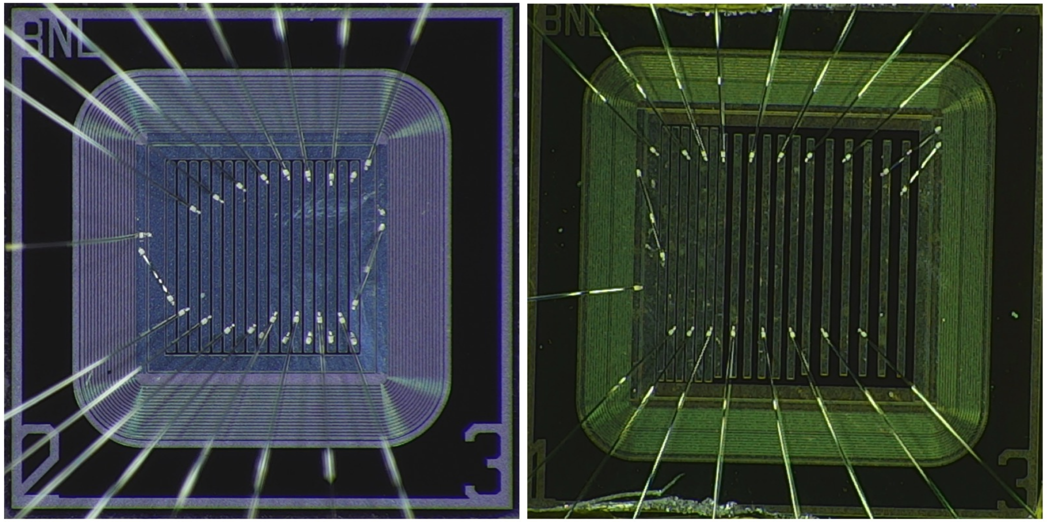
DC-LGAD



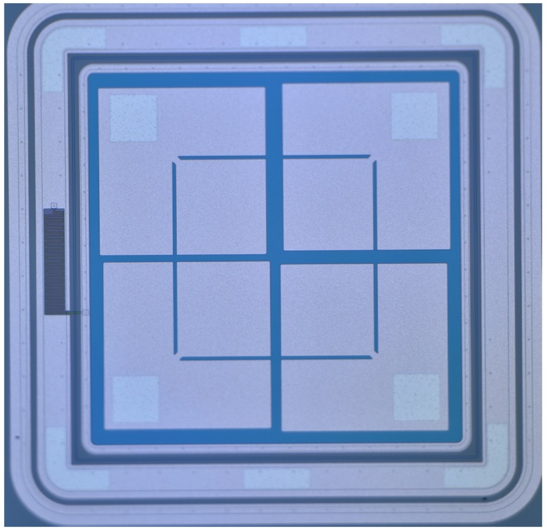
AC-LGAD

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

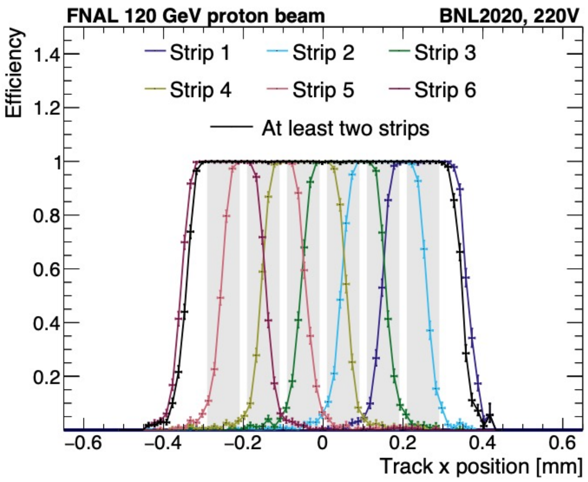


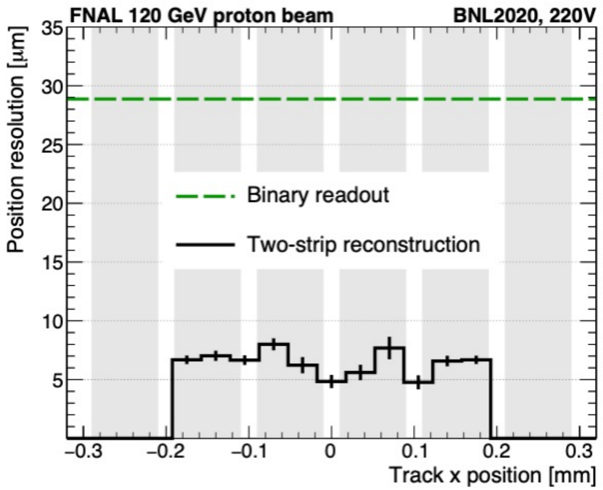
HPK pads AC-LGAD

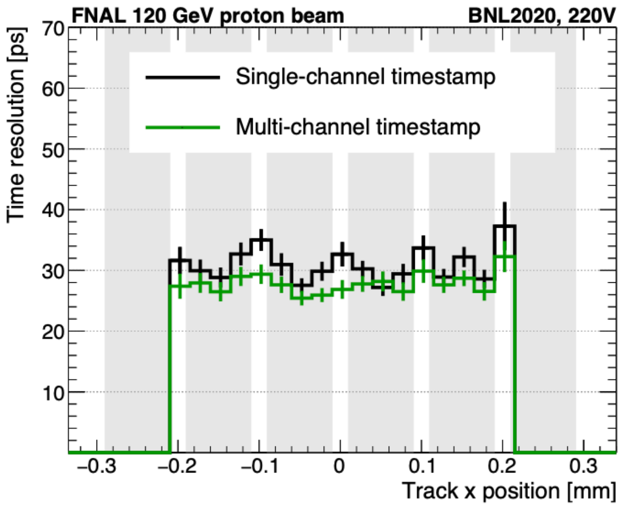
Strip-sensor AC-LGADs (short sensors)

JINST 17 (2022) P05001

- 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 → uniform 5-10 μm resolution



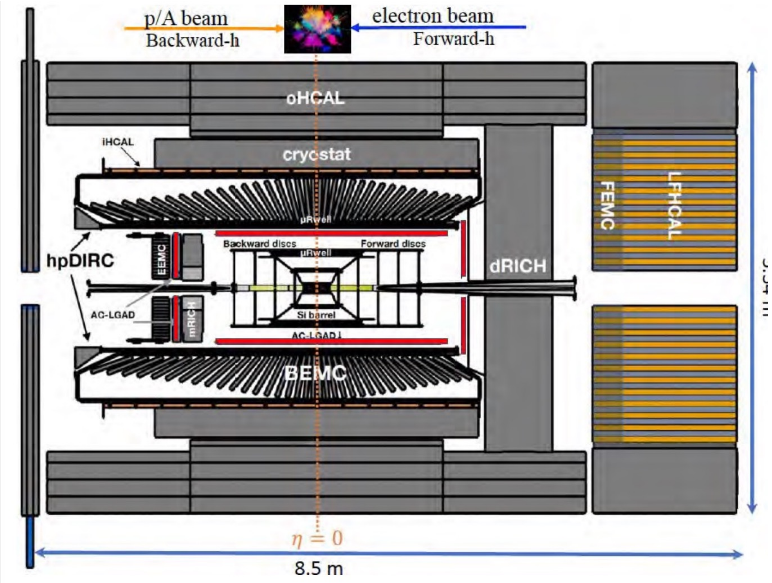




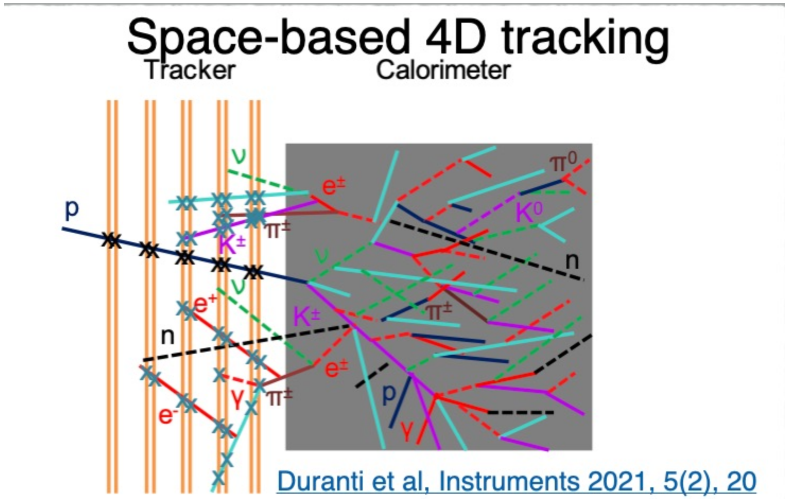
- **First demonstration of simultaneous ~5 μm, ~30 ps resolutions in a test beam: technology for 4D-trackers!**

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

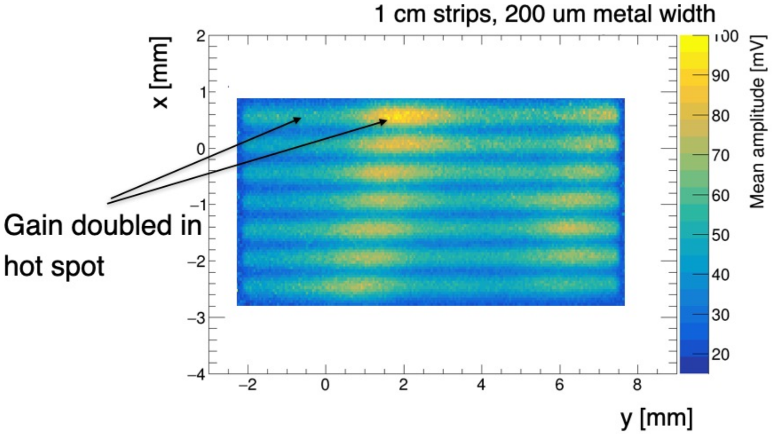


Duranti et al, Instruments 2021, 5(2), 20

Space-based sensors: power constraints require minimizing number of channels arXiv:2211.09698

Gain uniformity over large surfaces

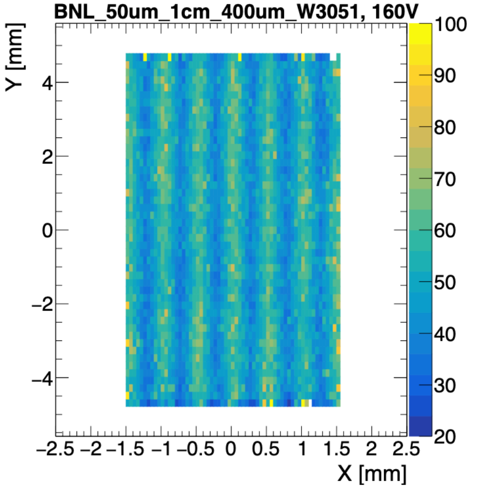
- New challenge with large area sensors: sensitivity to non-uniformity in gain layer
  - Stripe patterns of gain observed in most sensors of the first production
  - High gain regions limit operating voltage → other regions remain under-biased



1 cm strips, 200 um metal width

Gain doubled in hot spot

Second round of production



BNL_50um_1cm_400um_W3051, 160V

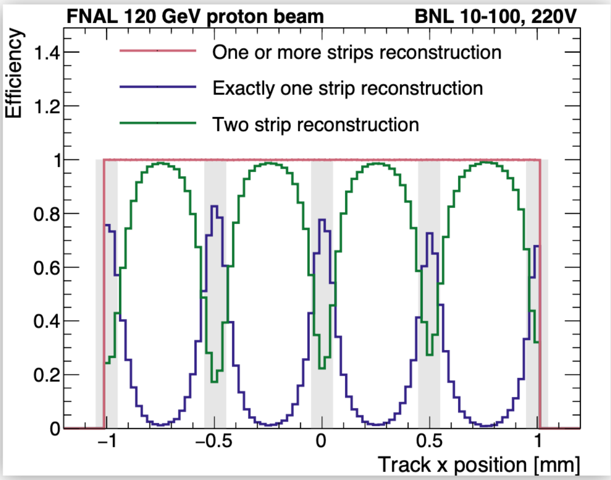
- Improved uniformity in second production
  - Uniform 2x2 cm^2 LGADs for ATLAS/CMS have been demonstrated

arXiv:2211.09698

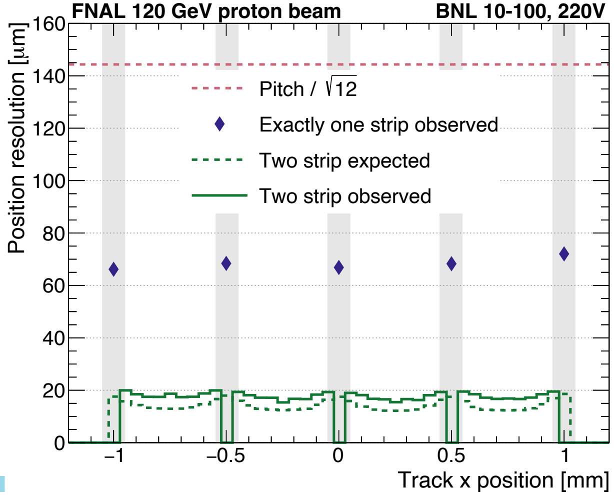
Long AC-LGAD strip sensors performance

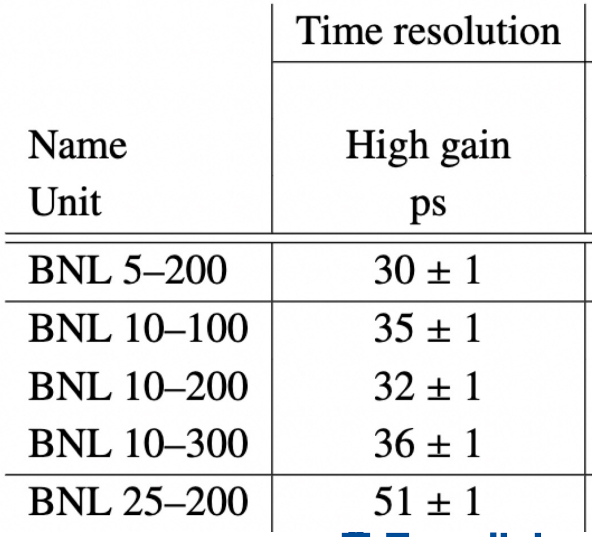
- Position reconstruction with ratio of amplitudes
  - Sensor provides 100% efficiency
  - Achieve 15-20 µm resolution for 2-strip events in all 5-10 mm strips
- Time resolution 30-35 ps for 1 cm strips
  - Combining 2 channels & correcting for position-dependent delays
  - High gain regions— achieve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

Reconstruction efficiency



Performance for 1 cm strips, 100 um metal



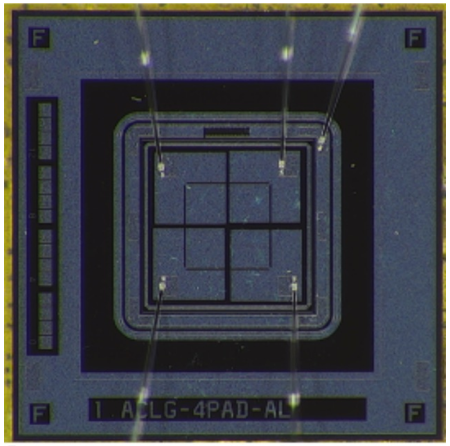


	Time resolution
Name Unit	High gain ps
BNL 5–200	30 ± 1
BNL 10–100	35 ± 1
BNL 10–200	32 ± 1
BNL 10–300	36 ± 1
BNL 25–200	51 ± 1

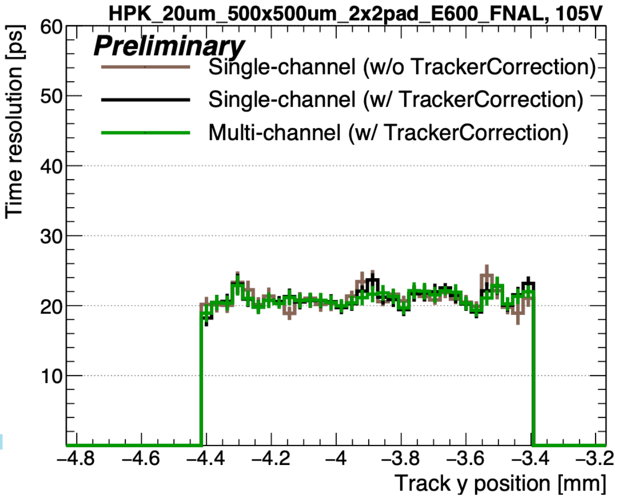
C. Madrid in TREDI 2023

Towards better time resolution

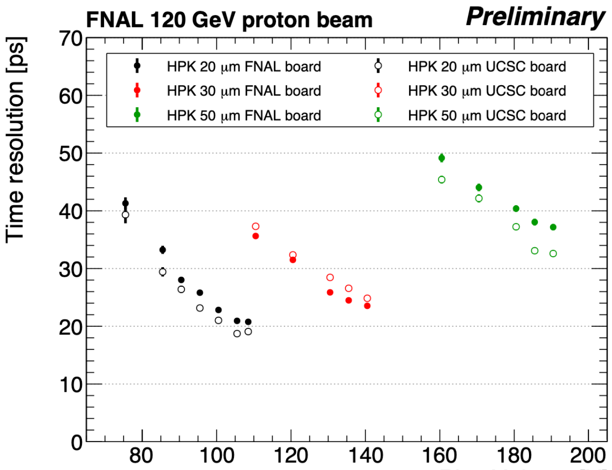
- How do you get better time resolution?
  - Thinner sensors to decrease Landau contribution
- AC-LGAD from HPK with 20, 30, 50 µm thickness
  - Almost fully metallized, optimized for timing performance
  - Can not use signal sharing for position reconstruction
- Uniform time resolution across full sensor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



HPK 2x2, 500x500 µm² pixel size



20 ps across full sensor surface

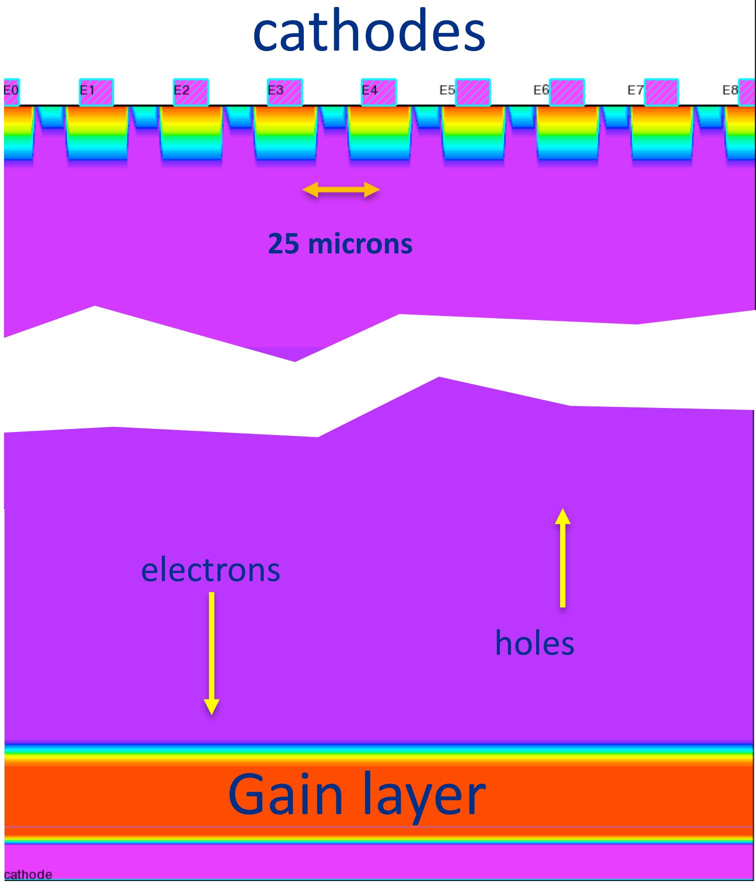


–, 105V

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

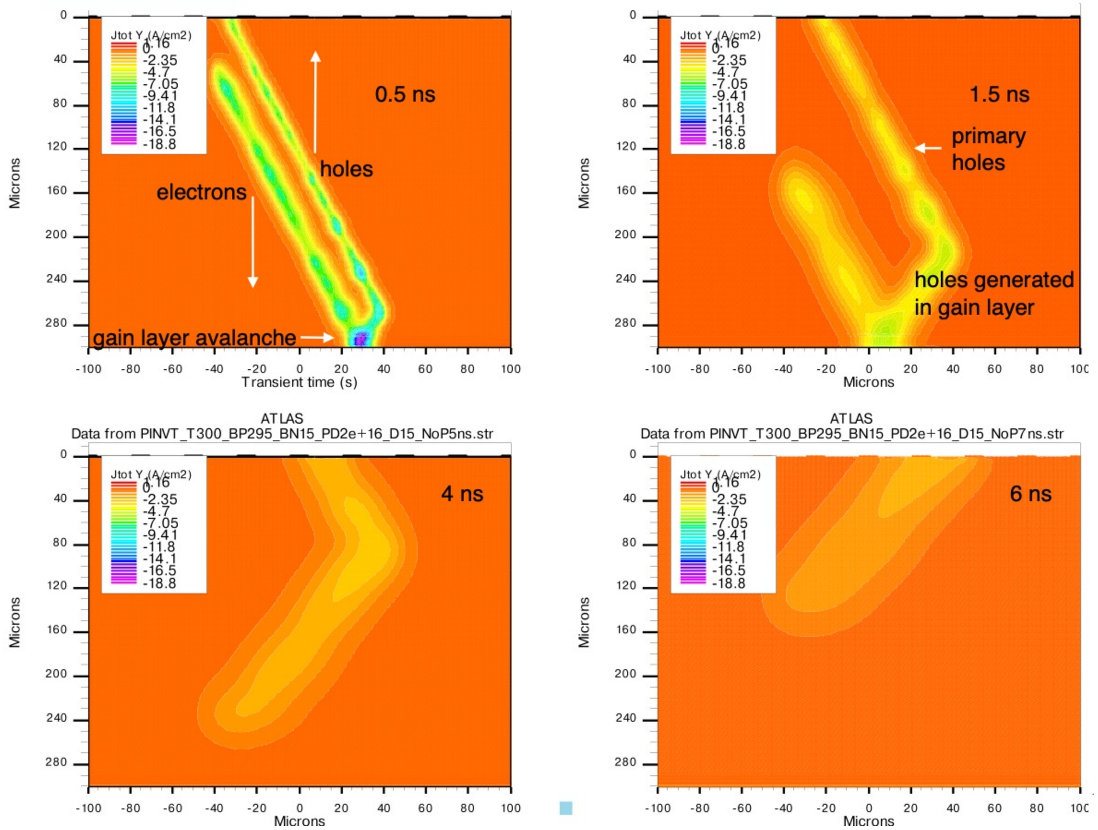


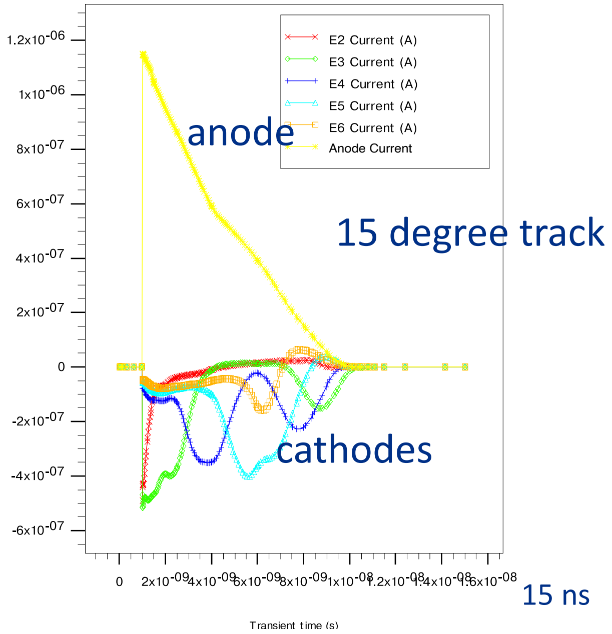
R. Lipton, Snowmass 2021

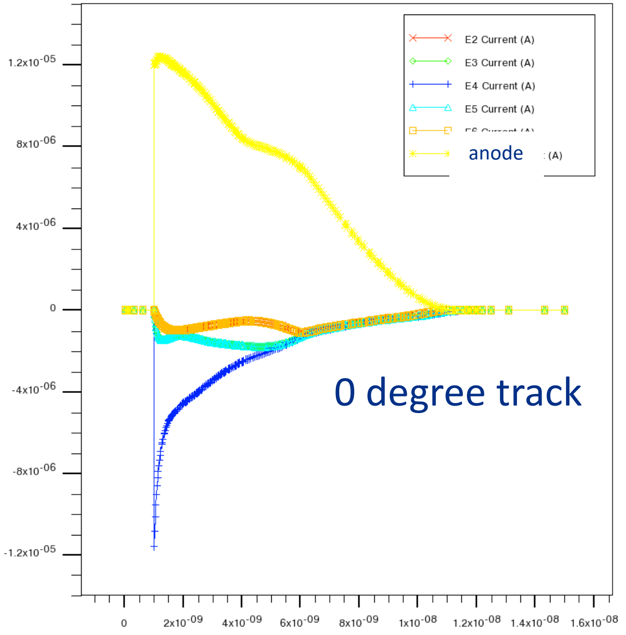
Double Sided LGAD Simulation

- Use anode for timing, cathodes for pulse shape discrimination

15 degree track detector internal current distributions





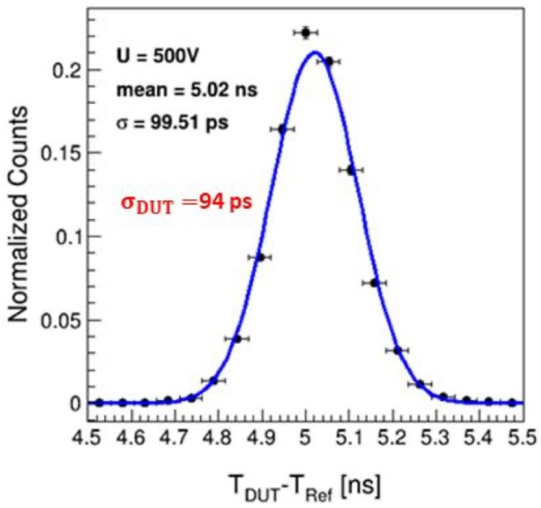


LGADs with SiC sensors

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

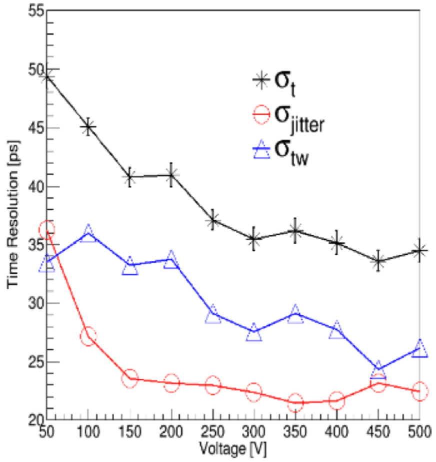
- Wide Band Gap Materials offer potential advantages
  - Enhanced radiation resistance
  - Reduced cooling requirements → reduced detector material mass
  - Increased commercial interest in wide band gap materials for power applications, HEP can benefit from these developments
- Several prototype runs 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

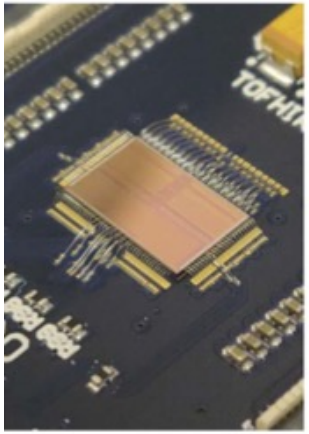
Electronics needs

- 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.

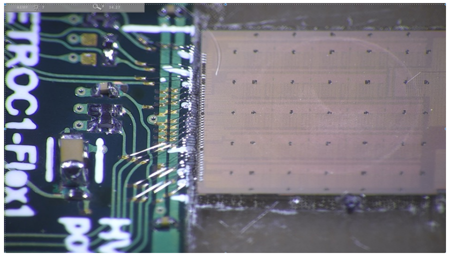
- Significant advancements will be needed:
  - More power/cooling budget,
  - Larger pixel size: AC-LGAD is one potential way to get precision position resolution with relatively large pixel sizes
  - Advanced detector concepts, new materials, AI/ML processing on chip
  - Advanced technology nodes (e.g.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

Electronics for MTD and HGTD

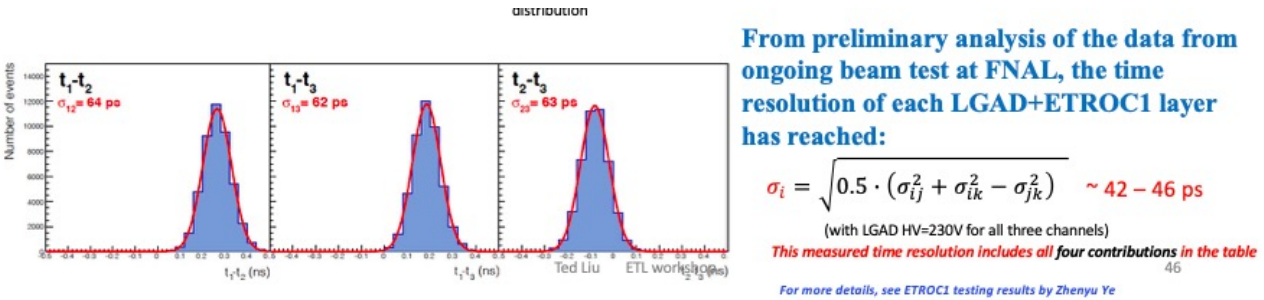
- BTL TOFHIR
  - minimize impact of DCR noise and pileup on time resolution
  - cope with very high rate of low energy hits per channel
  - Inverted and delayed pulse subtract from the input pulse
    - Restores baseline at the rising edge of the pulse.
  - Improves time resolution by about a factor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

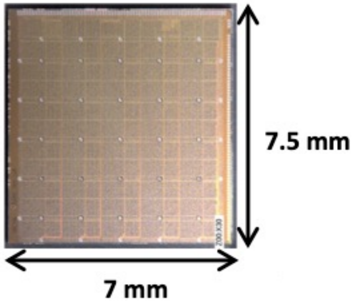
$$\sigma_i = \sqrt{0.5 \cdot (\sigma_{ij}^2 + \sigma_{ik}^2 - \sigma_{jk}^2)} \quad \text{~ 42 – 46 ps}$$

(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

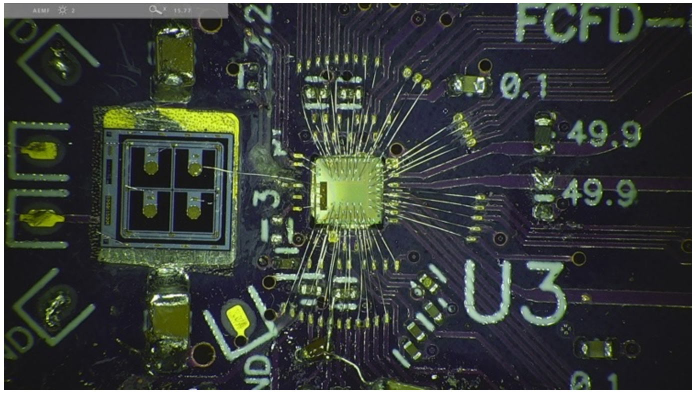
Prototypes performance validated in test beam



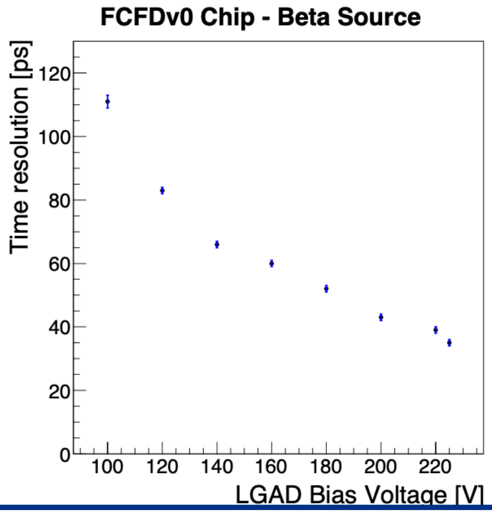
ALTIROC for ATLAS

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



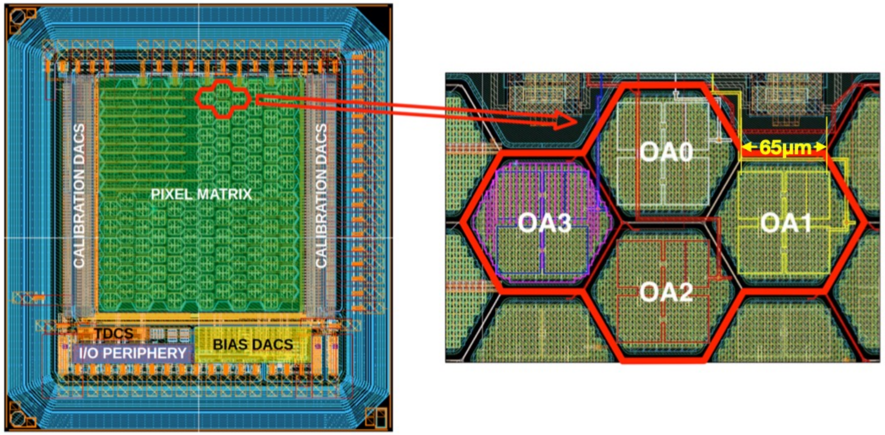
Time resolution with 1.3x1.3 mm^2 LGAD sensor

Monolithic sensors

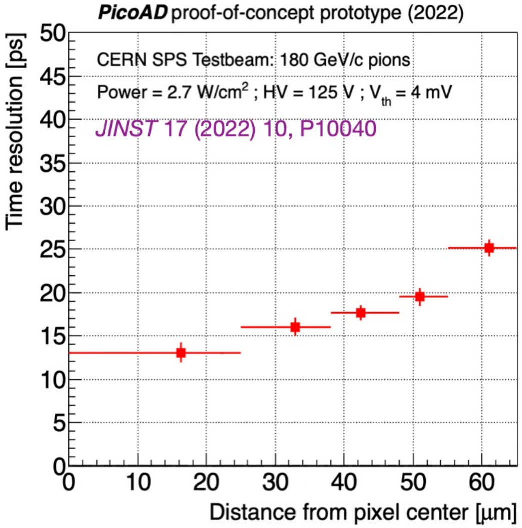
JINST 17 (2022) P10040

- 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)



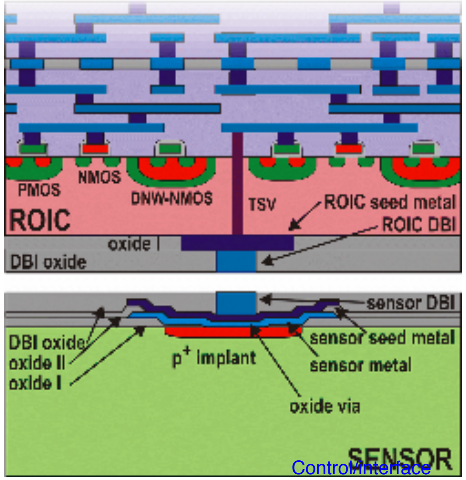
Time resolution

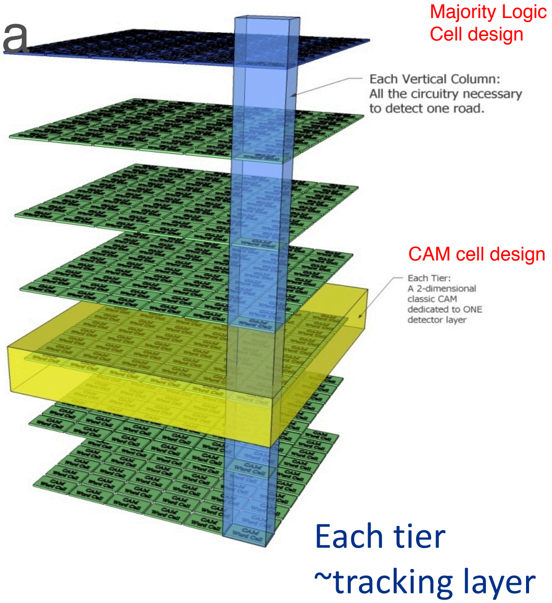


(13.2 ± 0.8) ps at the pixel center

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