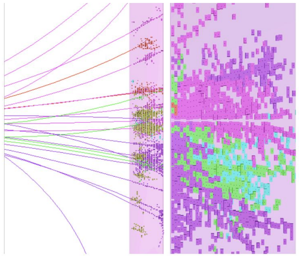
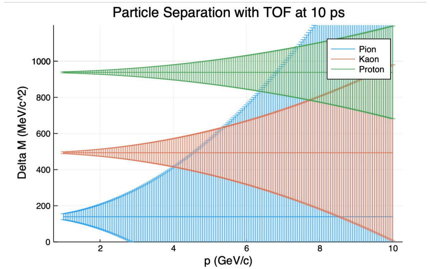
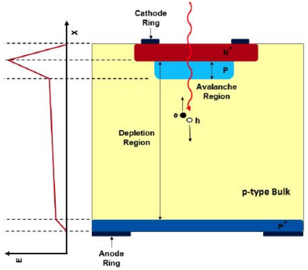
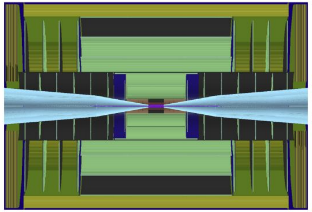
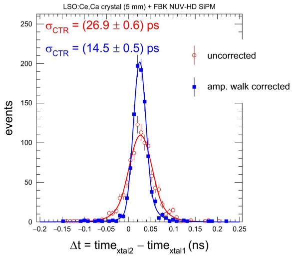







# Fast Timing in Higgs Factory Detectors

**Ariel Schwartzman**
**(SLAC)**

ILC Physics and Detector Meeting
20-Dec-2023

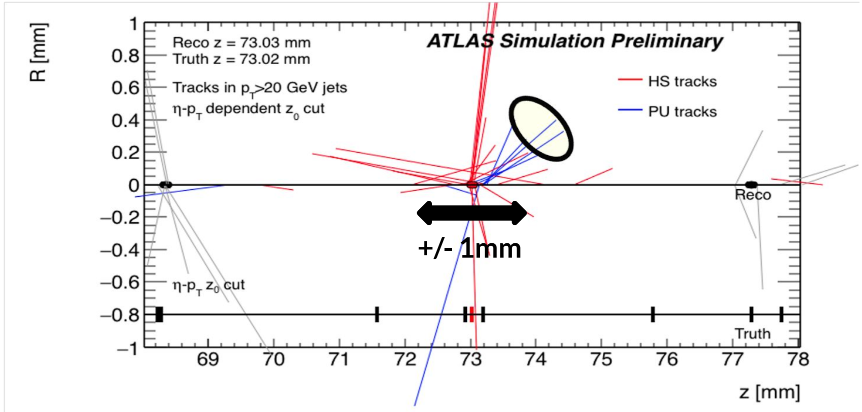
SLAC NATIONAL ACCELERATOR LABORATORY

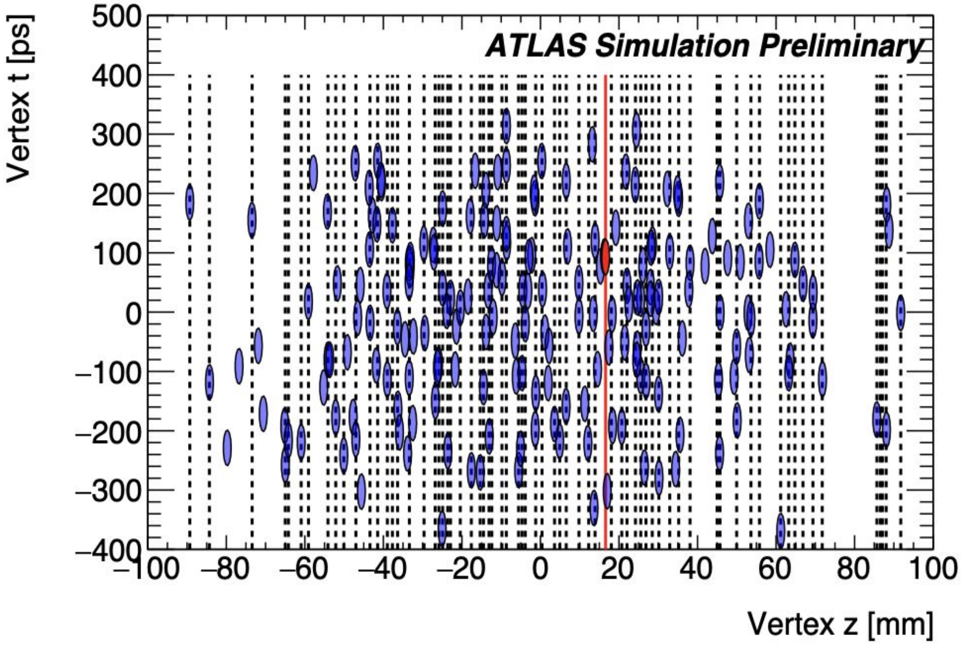
# Introduction

- **While the use of timing in collider detectors has a long history, precision timing at the level of 10-30ps is a new capability for the next generation of particle physics detectors at all future colliders**
  - Address the increasing complexity of events at hadron colliders
    - 4D trackers to resolve vertices at very high pileup densities
  - Identify long-lived particles (LLPs) and expand the reach for new phenomena
  - Enable particle ID capabilities at low momentum
  - Improve calorimetry measurements (PFA and jet energy resolution)
  - Suppress out-of-time beam Induced backgrounds (muon collider)

- **R&D to investigate the full potential of fast timing detectors in future Higgs Factories is an exciting opportunity for the particle physics community**

# Fast Timing at the HL-LHC



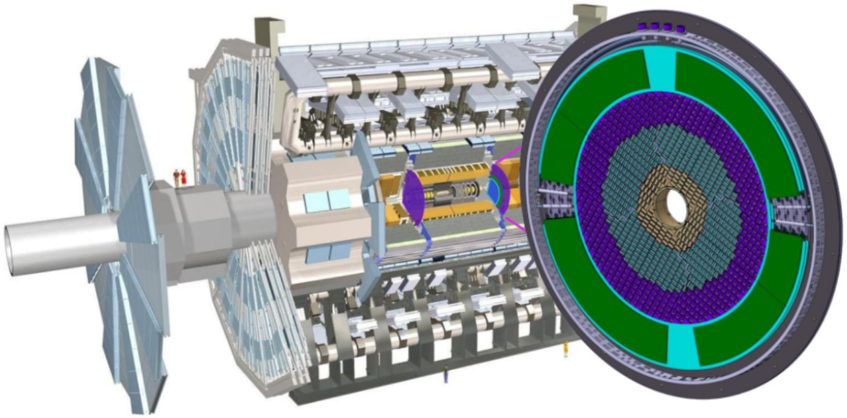

At the HL-LHC, the typical separation between vertices can be comparable to the track longitudinal impact parameter resolution: **the association o tracks to vertices becomes ambiguous**!

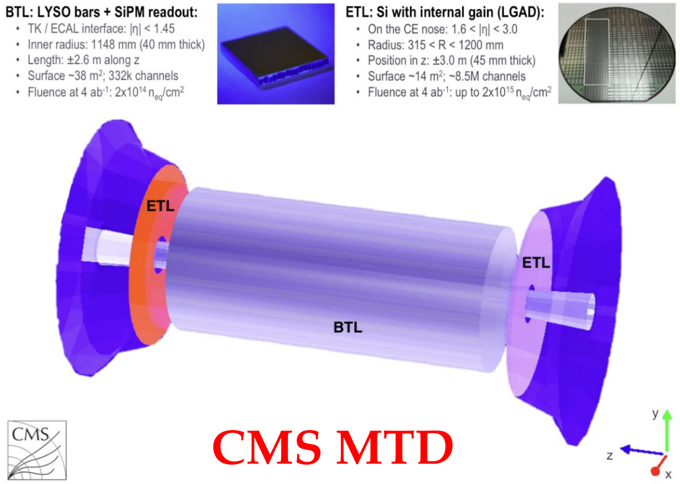
**Exploit the time spread of collisions to reduce pileup contamination**

**Nominal HL-LHC Luminous region $\sigma_t$ = 180ps**
**(30ps detector)** → 30/180 = **6x pile-up rejection**

# ATLAS and CMS

## ALTAS HGTD

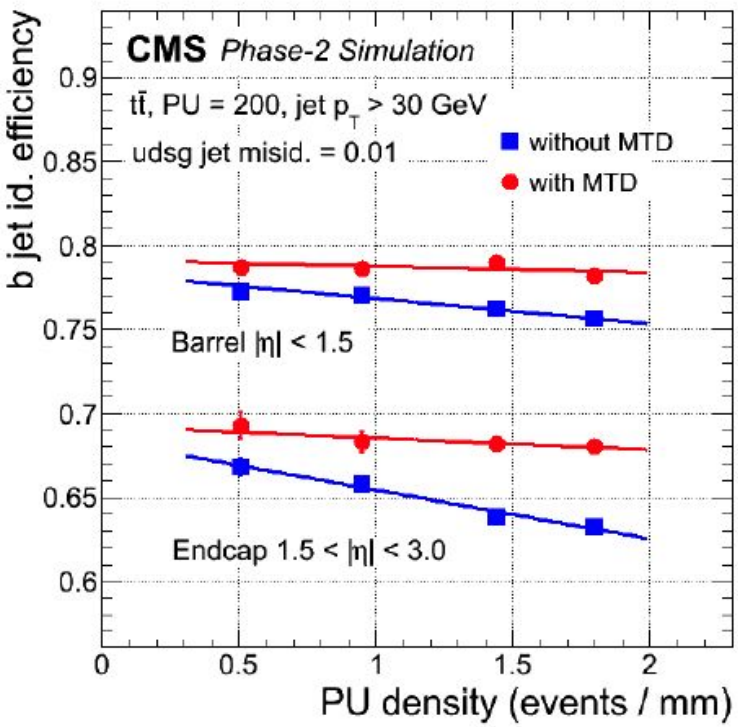


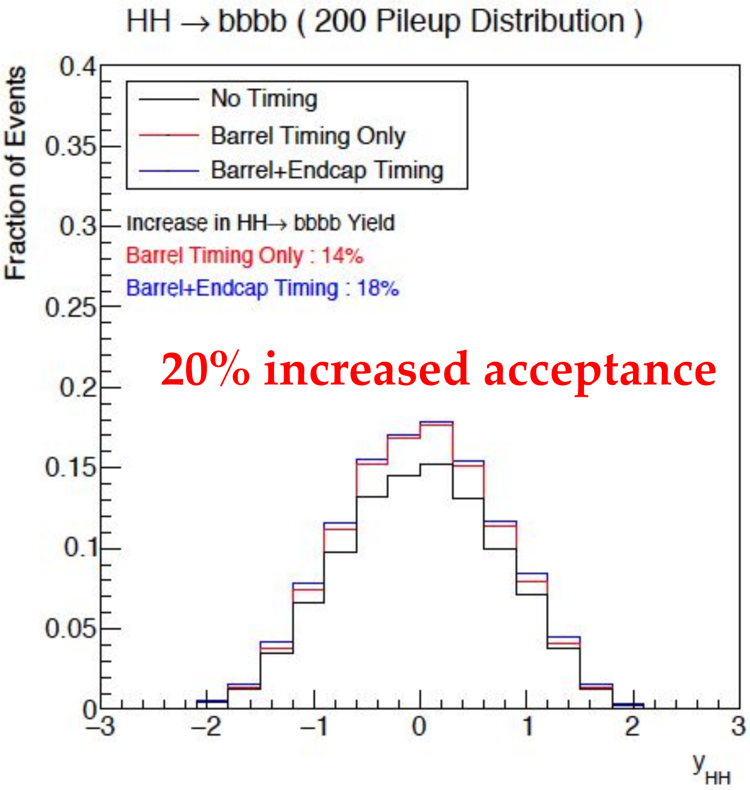



## CMS MTD

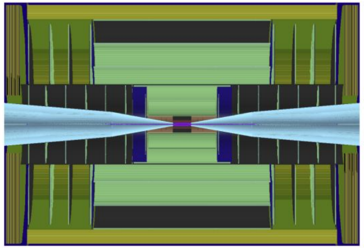
- LGAD sensors in the endcap/forward regions (1.3 x 1.3 $mm^2$)
- Crystals and SiPM readout in the barrel central region
- ~30ps time resolution per track
- ATLAS improves forward VBF final states (pileup suppression, lepton isolation)
- CMS hermetic coverage improves b-tagging, LLP, and provides PID capabilities
- **Precursors to future timing layers in collider experiments**

# Physics impact: Di-Higgs



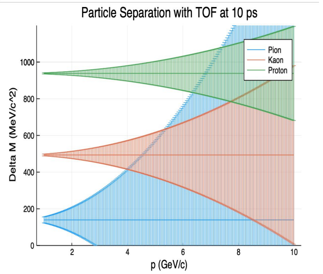



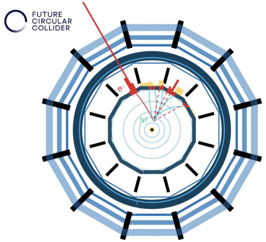
# Fast timing in Higgs Factories



Suppression of beam induced backgrounds at muon colliders

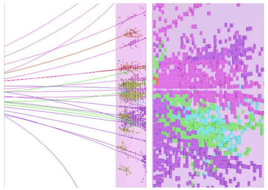
**Full 4D tracking**

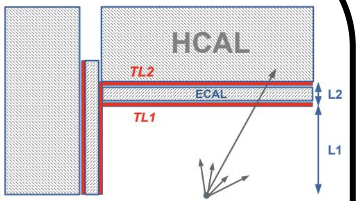



Time of Flight for Particle ID at low momentum and Long Lived particles

**Timing layers**



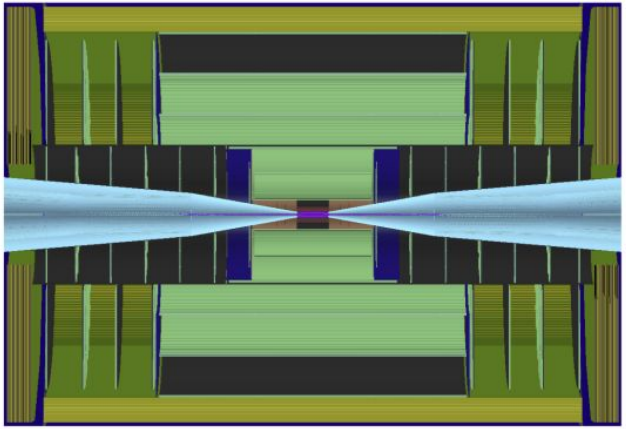


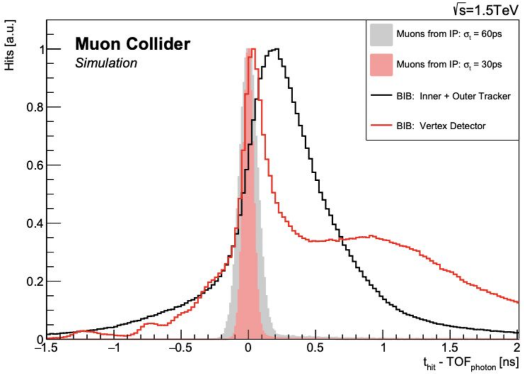

Exploit the time structure of hadronic showers to enhance PFA and improve jet energy resolution

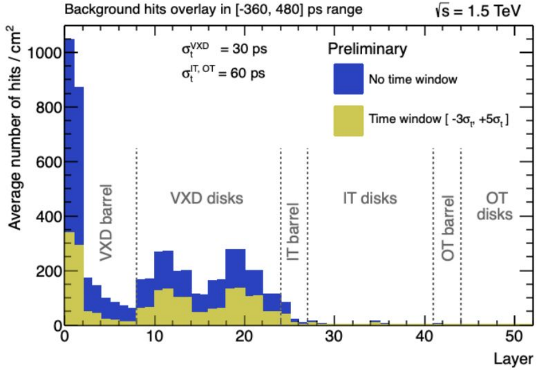
**5D Calorimetry**

Timing layers or volumetric timing

# Muon Collider: 4D Tracking






**Full 4D tracking design to address the challenge of Beam Induced Backgrounds**

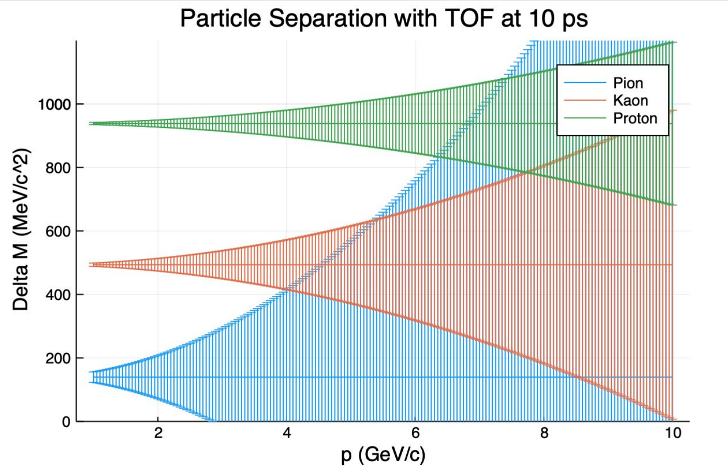
- **Picosecond timing plays a key role reducing the hit densities from BIB** (10 x HL-LHC!)
- Large number of hit combinations create a challenge for tracking pattern recognition
- **Timing information reduces hit densities by a factor of 2**

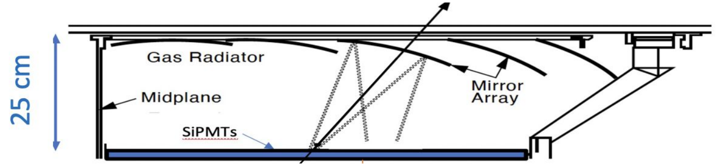
| | Vertex Detector | Inner Tracker | Outer Tracker |
|---|---|---|---|
| Cell type | pixels | macropixels | microstrips |
| Cell Size | $25\mu m \times 25\mu m$ | $50\mu m \times 1mm$ | $50\mu m \times 10mm$ |
| Sensor Thickness | $50\mu m$ | $100\mu m$ | $100\mu m$ |
| Time Resolution | 30ps | 60ps | 60ps |
| Spatial Resolution | $5\mu m \times 5\mu m$ | $7\mu m \times 90\mu m$ | $7\mu m \times 90\mu m$ |

# ToF: Particle ID

Updating the SiD Detector concept [Breidenbach, et. al.]

- Large-radius timing layers in the in front of the calorimeter can provide **Time-of-Flight (ToF) for PID**
  - Flavour physics
- Need 10ps resolution for K/pi separation at low momentum (up to ~3-4 GeV)
- **Complements other PID sub-detectors in the low momentum region**
  - RICH detector for high (10-50 GeV) momentum
    - Strange tagging for H→ss
    - Fast-timing (~100ps) for background suppression




Strange quark as a probe for new physics in the Higgs sector, J. Va'vra, et.al.

A gaseous RICH detector for SiD or ILD

# ToF: Long Lived Particles

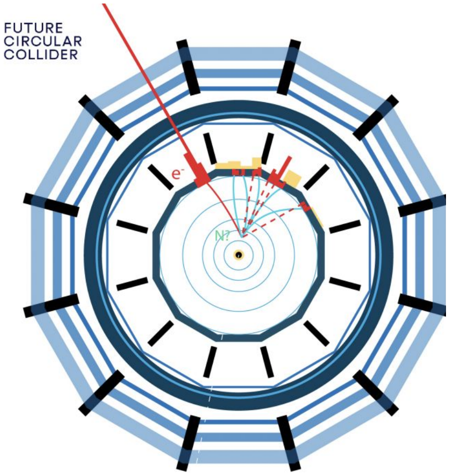
**Exploit high luminosity Z run of FCC-ee to search for LLP:**

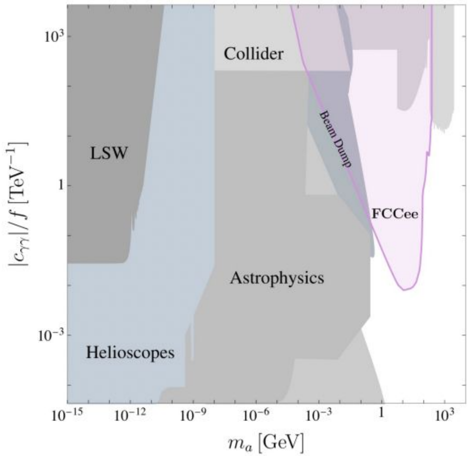
- Heavy Neutral Leptons
- Axion-like particles
- Exotic Higgs decays

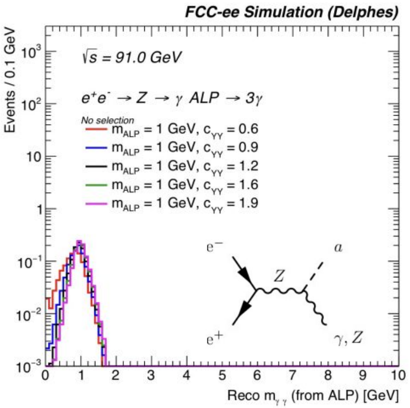
**Timing information:**

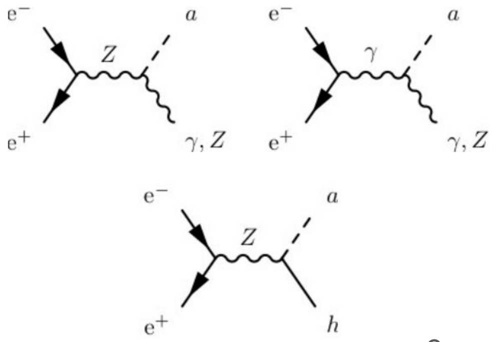
- Simultaneous determination of mass and proper decay time combining decay path and ToF
- Combine with displaced vertex reconstruction for enhanced performance

FUTURE CIRCULAR COLLIDER



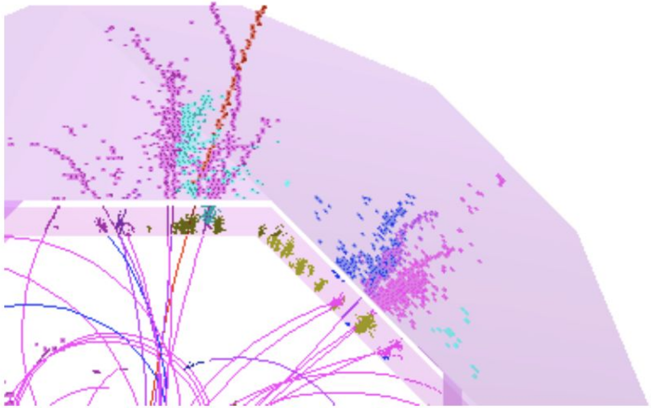




Searches for Long-Lived Particles at the Future FCC-ee

# 5D Calorimetry

Precision timing for collider-experiment-based calorimetry [Chekanov, et. al.]

- **Performance of particle flow reconstruction depends on the ability to associate showers to particles**
  - Challenging when showers overlap in space
- **Precision timing information can help resolve close-by particles, exploiting the full space-time structure of showers**, improving the jet energy resolution
  - separate delayed shower components from neutron induced processes
  - resolve track-cluster associations following shower development cell-to-cell (PFA pattern recognition)

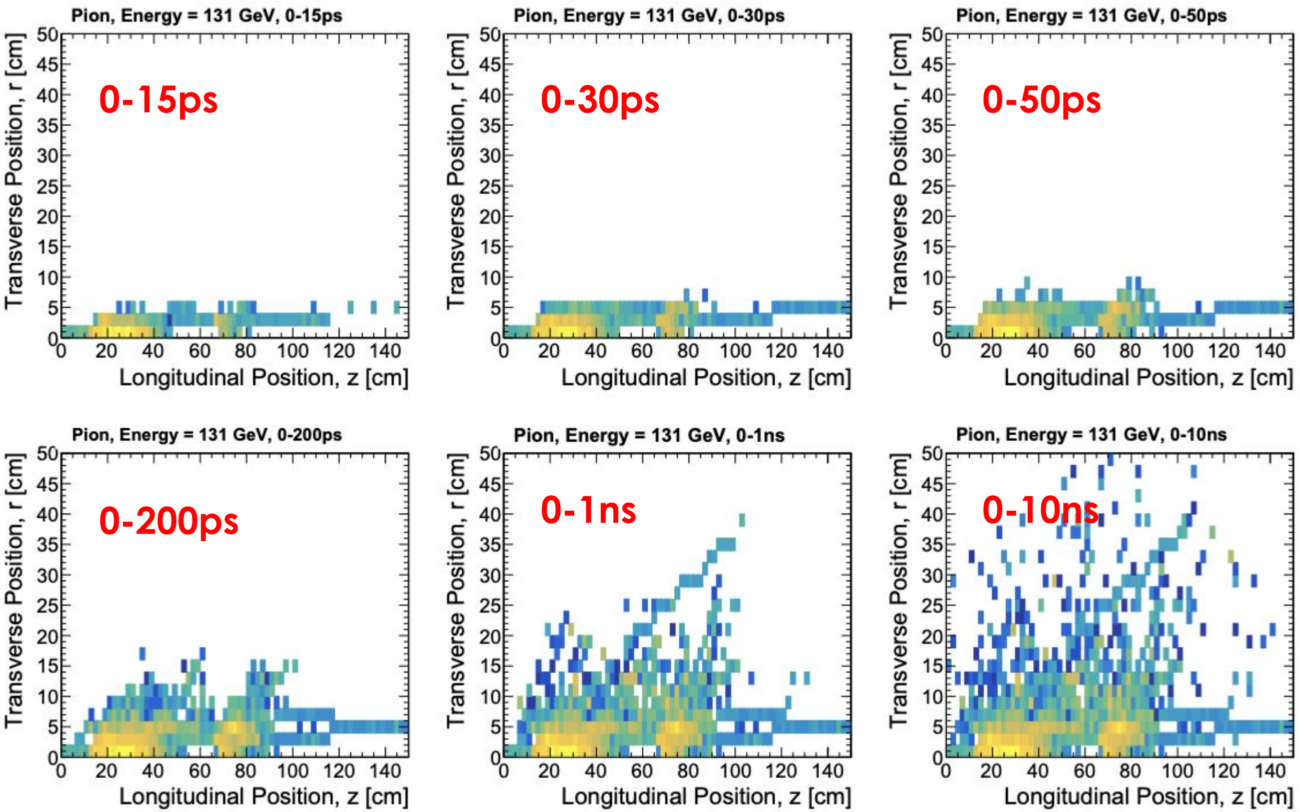


**Different approaches:**

- Volume (cell-level) timing
- Dedicated timing cells
- Timing layers within the calorimeter

# 5D Calorimetry

On the Use of Neural Networks for Energy Reconstruction in High-granularity Calorimeters [Akchurin, et. al.]



# Time-assisted software compensation

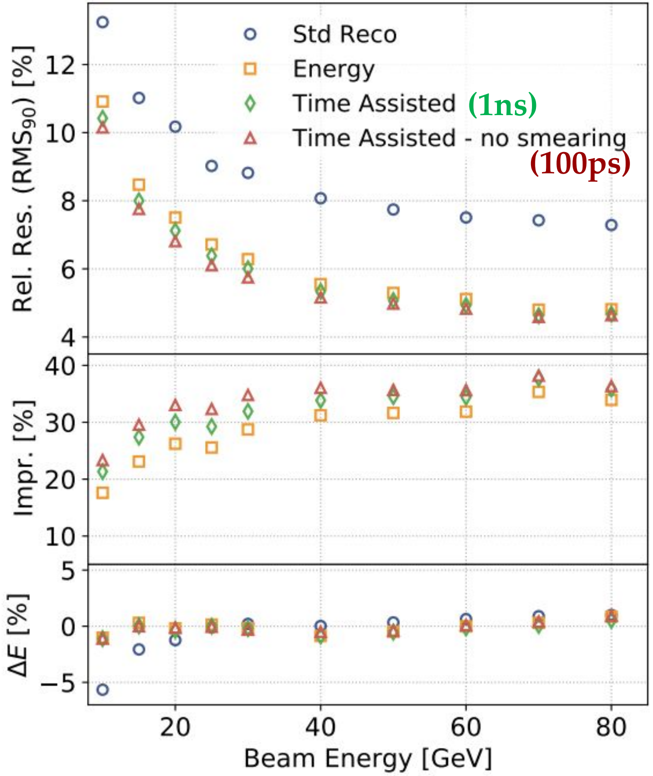
Time-assisted energy reconstruction in a highly-granular hadronic calorimeter Christian [Graf, Simon]

- CALICE AHCAL LTP
  - **cell-by-cell time measurement for full 5D reconstruction of particle showers**
- Local software compensation incorporating time:

$$E^{local}_{reco} = \sum e_j\, w(e_j, E_{std})$$

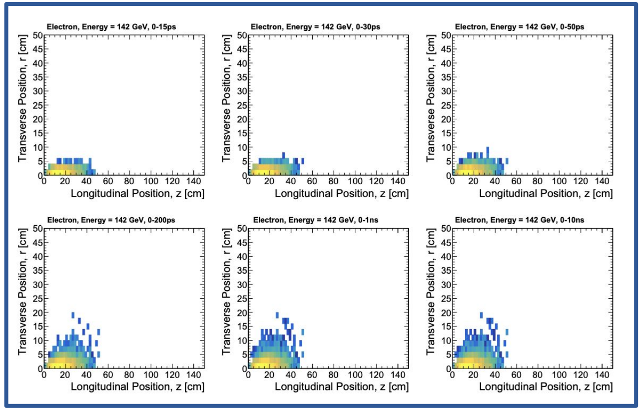
split 14 energy bins in $t$ < 3ns and $t$ > 3ns

- **Use of (local) timing information in highly-granular hadronic calorimeters improves the energy resolution**
- Simple algorithm: expect Machine Learning techniques exploiting full 5D reconstruction will enable further improvements

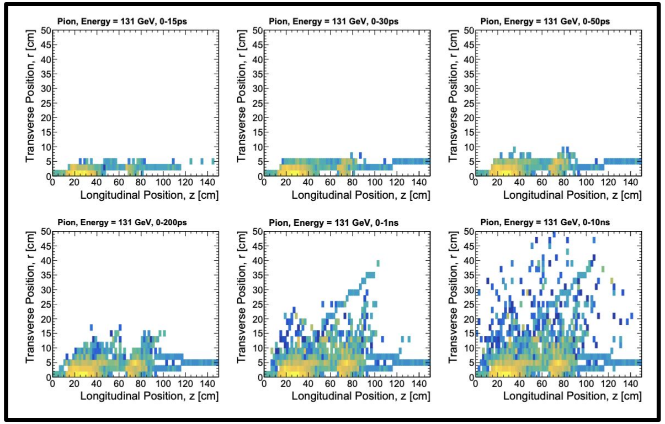


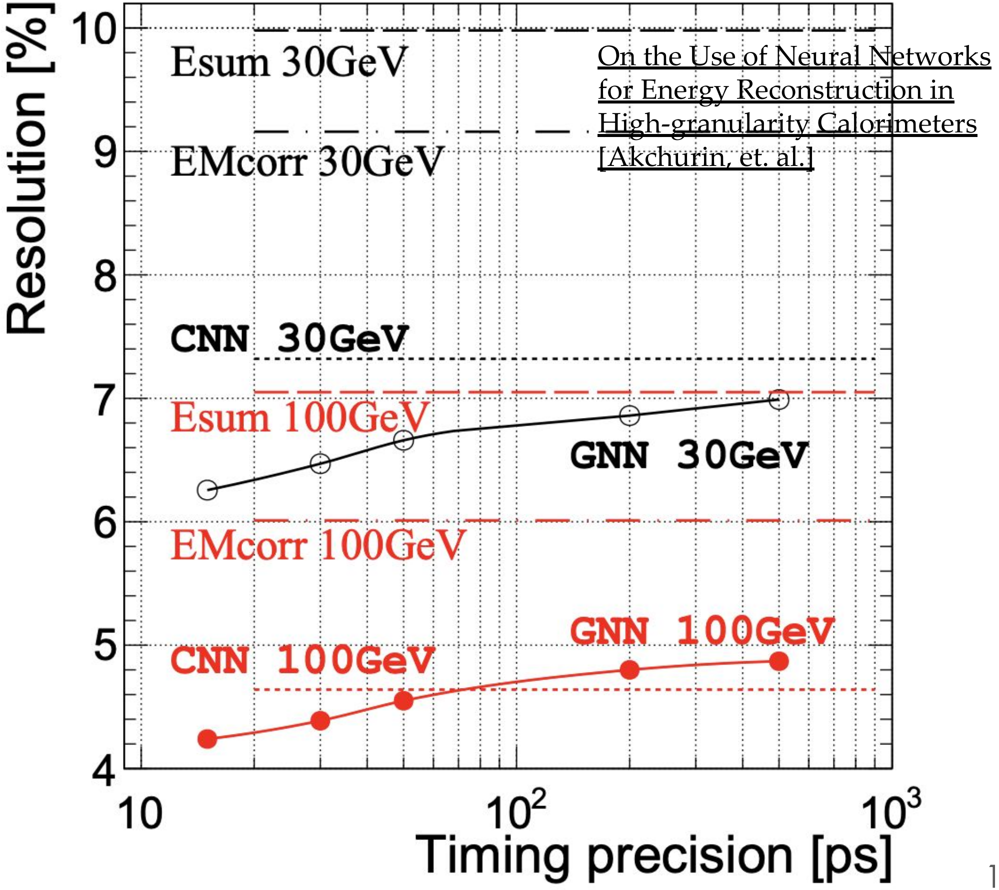
# Graph Neural Network

electron

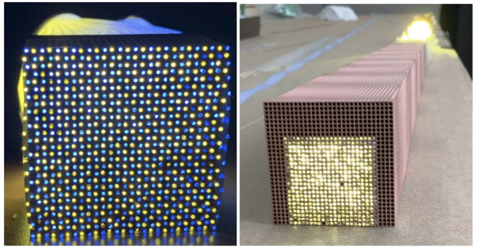



charged pion

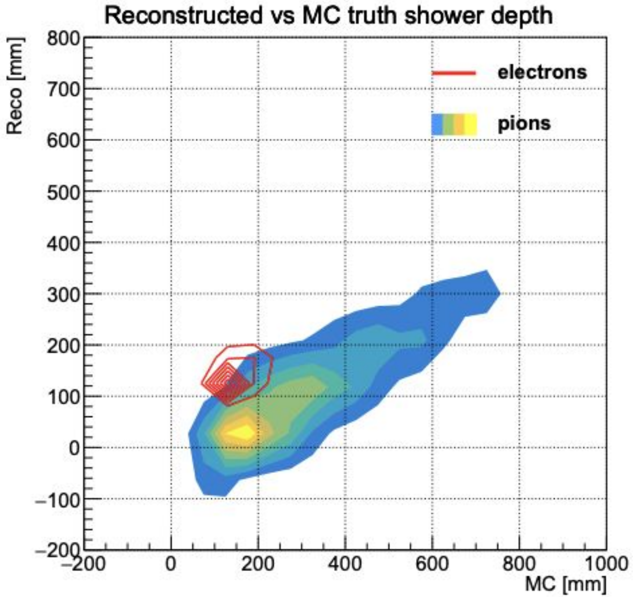


# Longitudinal segmentation by timing in dual-readout fiber calorimeters



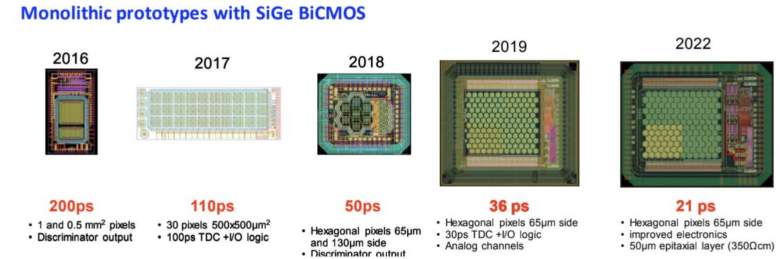
- Optical fibers inserted longitudinally and attached to SiPMs a the rear end
  - Energy deposits closer to the readout lead to shorter propagation times
- Utilize the entire timing structure of the electronic pulse with digital processing methods
- **Timing information at the level of 10ps can effectively segment longitudinally fiber calorimeters, providing new capabilities for shower shape reconstruction**

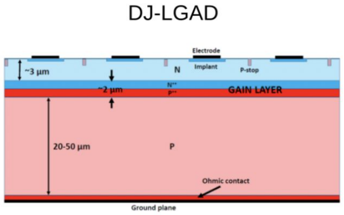


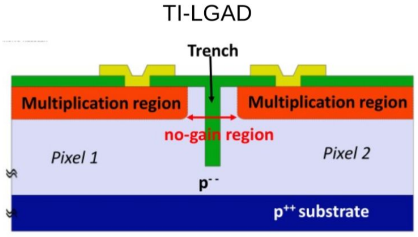

Reconstruction of 3D Shower Shape with the Dual-Readout Calorimeter, Sanghyun Ko, Hwidong Yoo, Seungkyu Ha

# Detector Technologies

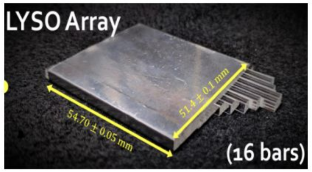
- **Timing layers / 4D tracking:**
  - (LYSO) Crystals + SiMPS (timing layers)
  - Silicon sensors (timing layers / 4D tracking)
    - **Advanced LGADs** with O(10ps) and O(10um) resolution
      - AC-LGAD, TI-LGAD, DJ-LGAD, Buried LGAD, DS-LGAD
    - **Monolithic CMOS**
      - LGAD MAPS, miniCACTUS, PicoAD, Monolith, HV-CMOS, DMAPS
    - Silicon Carbide LGADs
    - 3D silicon sensors

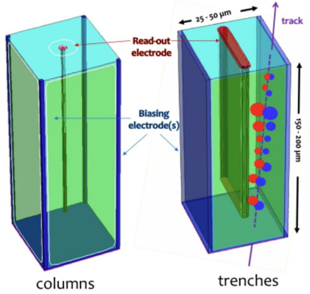



- **Volume calorimeter timing:**
  - LGAD or Silicon pads in Si+W calorimeter (CMS HGCAL)
  - Highly granular crystals
  - Plastic scintillator tiles or strips + SiPMs
  - RPC can cover large active areas for digital hadronic calorimeters (SDHCAL CALICE)

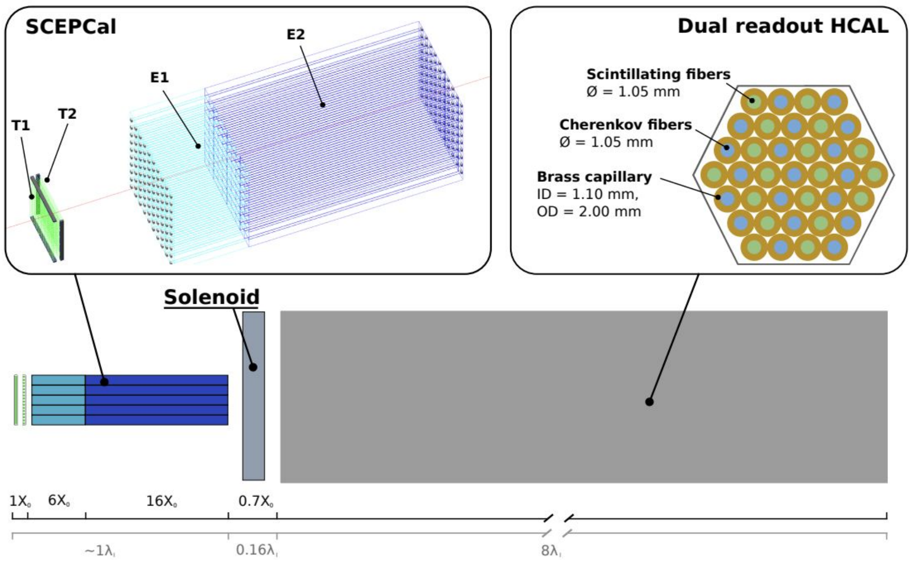


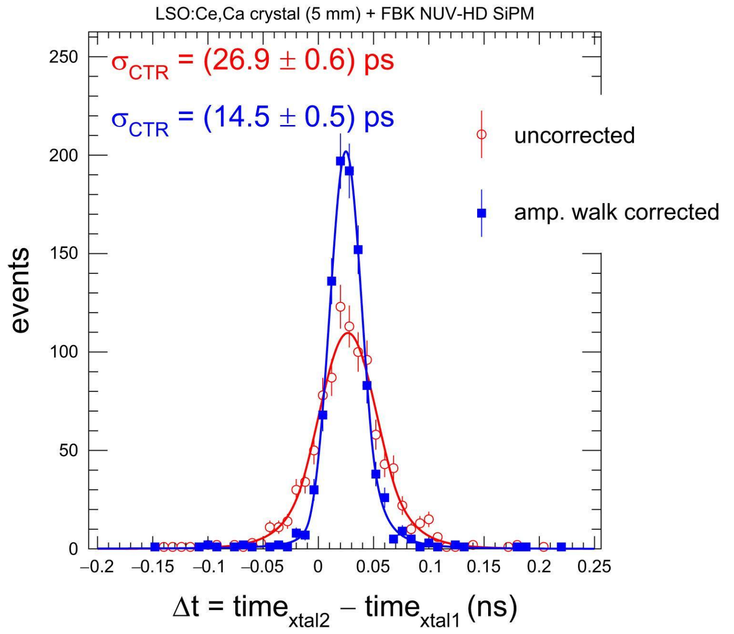




4-Dimensional Trackers [Berry, et. al]

# Timing layers: Crystals

New perspectives on segmented crystal calorimeters for future colliders [Lucchini, et. al.]

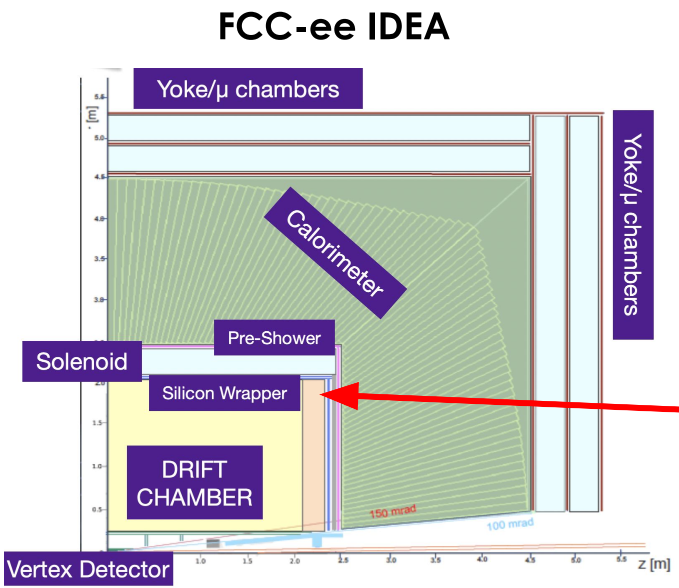


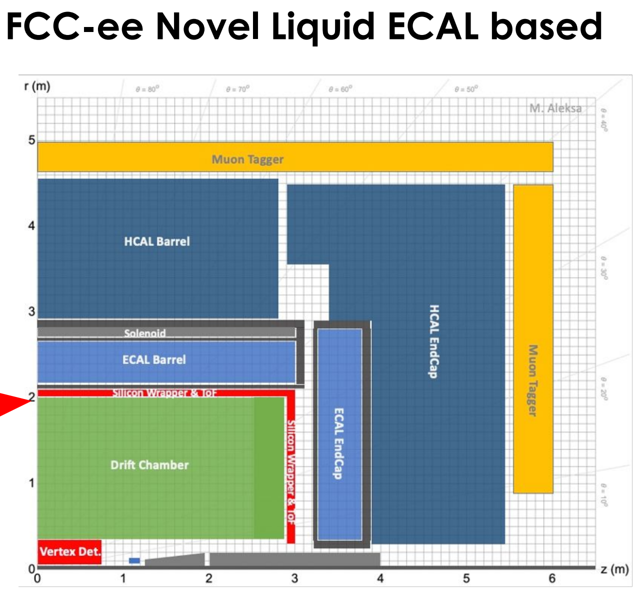

Detection of high energy muons with sub-20 ps timing resolution using L(Y)SO crystals and SiPM readout [Benaglia, et. al.]

- **Hybrid segmented dual-readout calorimeter**
  - Two thin timing layers in front of EM calorimeter to measure **MIPs with 20ps resolution**
  - Provides ToF particle ID at low momentum
  - Timing layers integrated within calorimeter

# Timing layers: Silicon



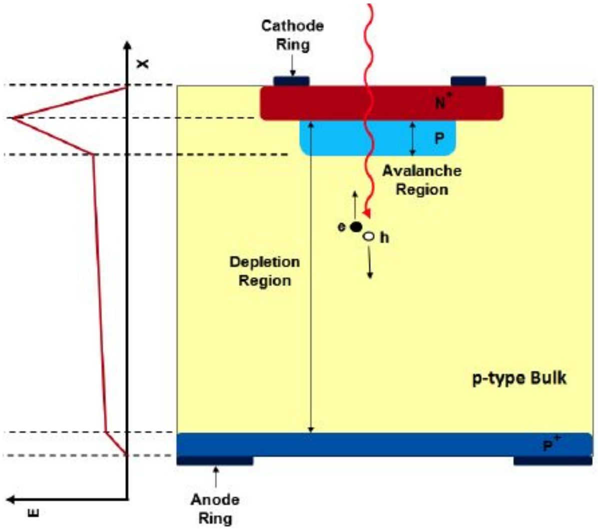


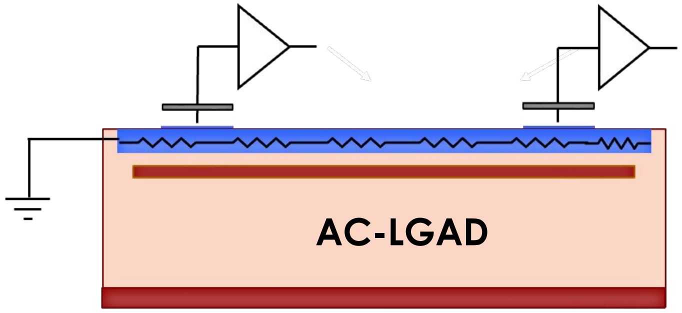



- **Silicon Wrapper detectors in FCC-ee detector concepts**
  - ToF particle ID, LLP
  - Several silicon sensor options being explored

# LGAD sensors

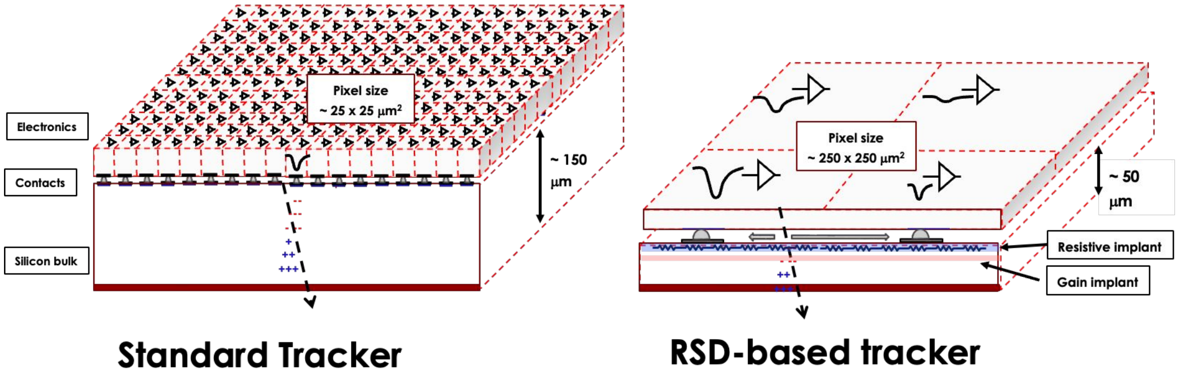
- **Thin silicon sensors with modest intrinsic gain (5-50) provided by a doped p+ multiplication layer**
  - thin: reduces Landau fluctuations
  - high S/B from internal gain
  - short rise time minimizes jitter
  - 30ps resolution sensors used in ATLAS and CMS HL-LHC endcap timing layer upgrades
- Standard LGADs require mm-size pads and require junction termination extensions to interrupt the gain between channels introducing inactive regions
- **Advanced LGAD designs**
  - Resistive silicon detector (AC-LGAD), Trench-isolated, Deep junction, Buried layers, …

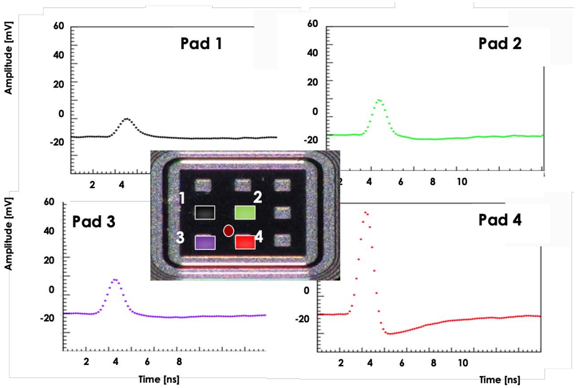


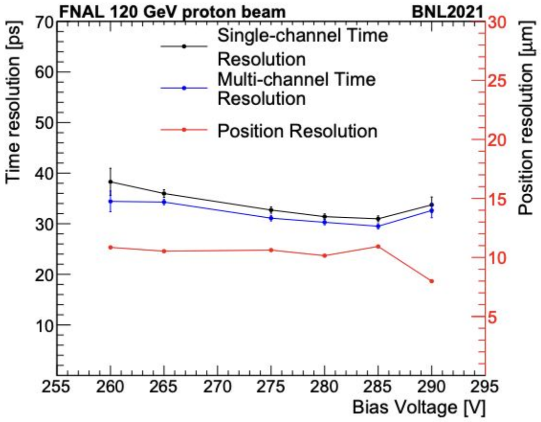
4D Tracking: Present Status and Perspective

# AC-LGAD




- Replace many p-n diodes by a single one
- The n-doped implant is resistive and acts as a signal divider (**100% fill factor**)
- Charge sharing enables **precise position resolution** (5-10μm)
- For the same spatial resolution, the **number of pixels is reduced** by 50-100
    - **<u>Much lower power consumption</u>**: could be air-cooled (0.1W/cm$^2$)depending on electronics




Characterization of BNL and HPK AC-LGAD sensors with a 120 GeV proton beam [Heller, et. al.]

# Electronics and System Design

- **The development of fast electronics is a critical element for realizing large-scale detectors**
  - impacts cooling and mechanics which can deteriorate performance in space/time
- HL-LHC timing ASICs are a revolutionary step forward to bring ps timing to collider experiments, applying similar techniques at Higgs Factories present **many challenges**:
  - High granularity → **ASICs with smaller pixel sizes**, maintaining power consumption
  - Including the required electronics for timing extraction (TDCs and memories) in pixel pitches of O(10um) → **adoption of deeper low power and fast nodes beyond 65nm**
  - The entire pixel electronics will need to be designed with **low power techniques and novel timing extraction architectures**
  - **Clock distribution**

Electronics for Fast Timing [Braga, et. al.]

- **System design:**
  - The fine spatial resolution demands towards low material budget and low power may require a mix of layers with different balance of spatial and time resolutions or a combination of 3D + 1D timing layers
  - Full-scale calorimeters with 10ps resolution in each cell can be very challenging. Alternatives include dedicated time-cells, or timing layers within the calorimeter

| Name | Sensor | Node [nm] | Pixel size [$\mu m^2$] | Temporal precision [ps] | Power [W/cm$^2$] |
|---|---|---|---|---|---|
| ETROC | LGAD | 65 | 1300x1300 | ~ 40 | 0.3 |
| ALTIROC | LGAD | 130 | 1300x1300 | ~ 40 | 0.4 |
| TDCpix | PIN | 130 | 300x300 | ~ 120 | 0.32 matrix + 4.8 periphery |
| TIMEPIX4 | PIN, 3D | 65 | 55x55 | ~ 200 | 0.4 analog + 0.3 digital |
| TimeSpot1 | 3D | 28 | 55x55 | ~ 30 ps | 3-5 |
| FASTPIX | MAPS | 180 | 20x20 | ~ 130 | 5-10 |
| miniCACTUS | MAPS | 150 | 500x1000 | ~ 90 | 0.15 – 0.3 |
| MonPicoAD | MAPS | 130 SiGe | 100x100 | ~ 36 | 1.8 |
| Monolith | Multi Junct. MAPS | 130 SiGe | 100x100 | ~ 25 | 0.9 |

4D Tracking: Present Status and Perspective, N. Cartiglia, et. al.

# Summary

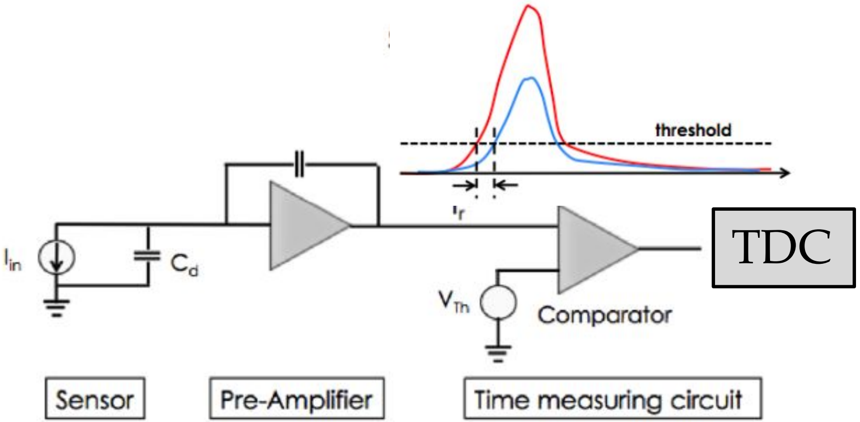
- **Fast timing capabilities present an exciting opportunity for the next generation of detectors at Higgs Factories**
  - **4D Tracking** will be crucial to suppress BIB at Muon Colliders
  - **Timing layers** can enhance particle identification and long lived particle searches
  - **5D Calorimetry** can improve Particle Flow reconstruction and jet energy resolution

- **Many technologies exist and new are under active development, but significant R&D is required to address the multiple challenges of integrating fast timing in realistic detector concepts**
  - Electronics (power consumption, granularity, novel timing extraction architectures), clock distribution, and system design

# Backup

# Time resolution

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




- Time walk
  - Variable threshold (CFD)
  - Correction based on TOT

$$\sigma_{jitter} = \frac{N}{dV/dt} \propto \frac{t_{rise}}{S/N}$$

- TDC quantization error (bin size)
  - ATLAS/CMS 20-30ps ToA
  - ATLAS/CMS 40-100ps TOT
  - $\sigma_{TDC} = {}^{binsize}/_{\sqrt{12}} \sim 7ps$

**Key to precision timing**: Large signal with short rise time and low noise (reduce jitter), limited thickness (reduce Landau), and small TDC bin size (reduce TDC component)