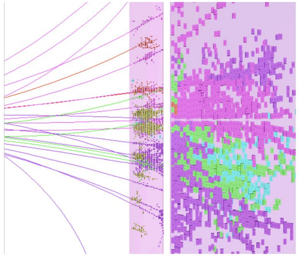
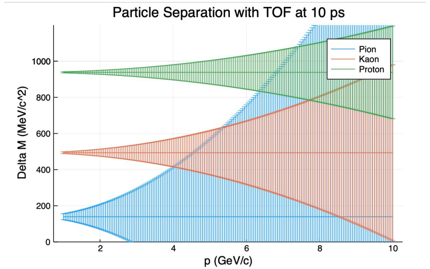
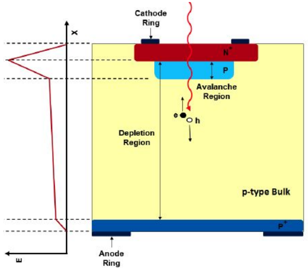
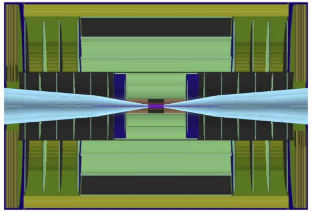
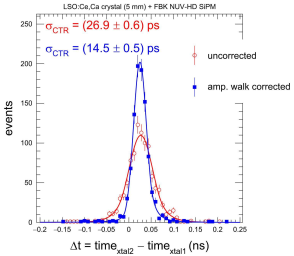










Fast Timing in Higgs Factory Detectors

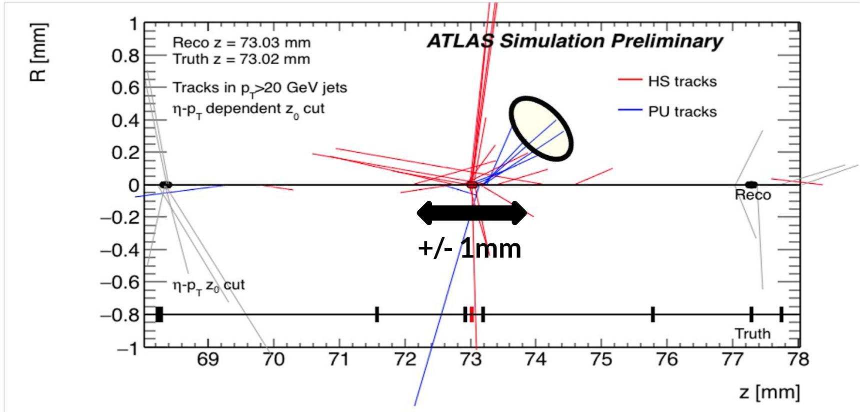
Ariel Schwartzman
(SLAC)

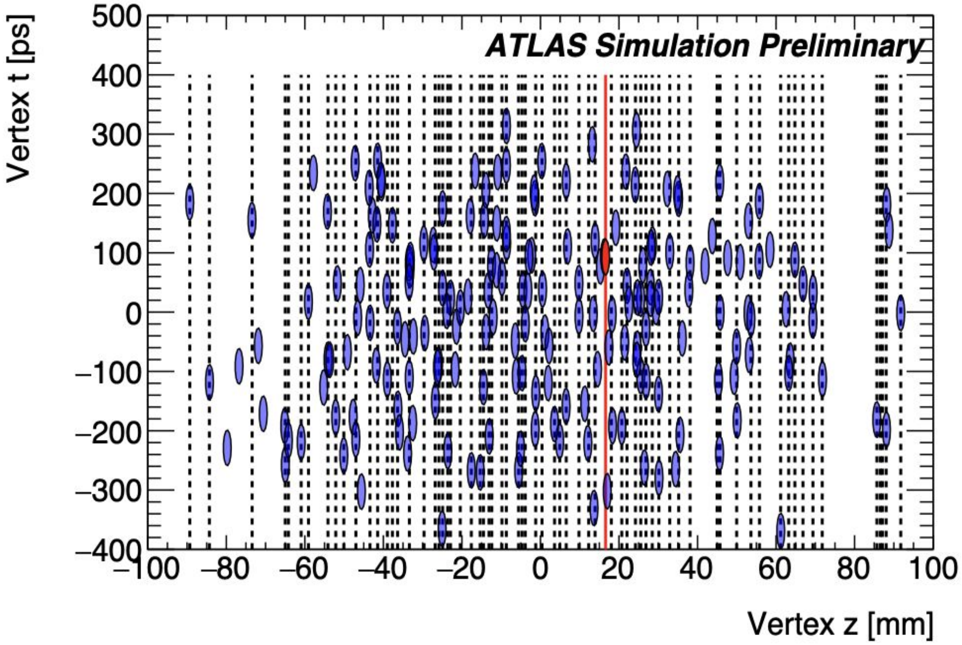
LCWS 2023 Workshop
15-May-2023

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)
- **Coarse timing at the ns-level can complement picosecond timing detectors for enhanced overall 4D tracking and 5D calorimetry**
- **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





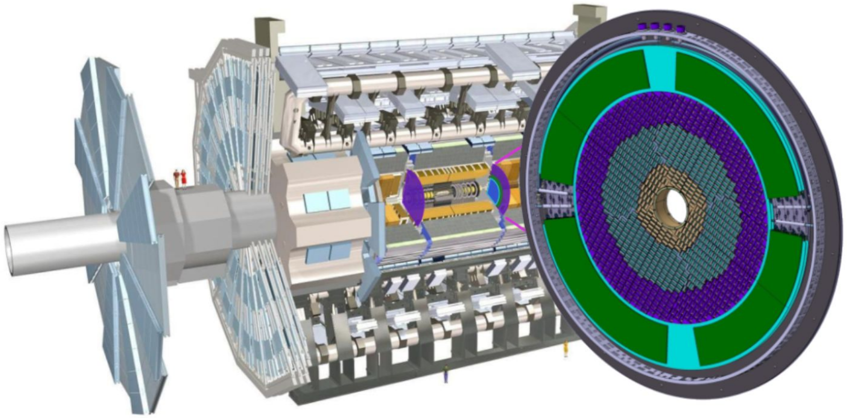
At the HL-LHC, the typical separation between vertices can be comparable to the track longitudinal impact parameter resolution: **the association o tracks to vertices becomes ambiguous**!

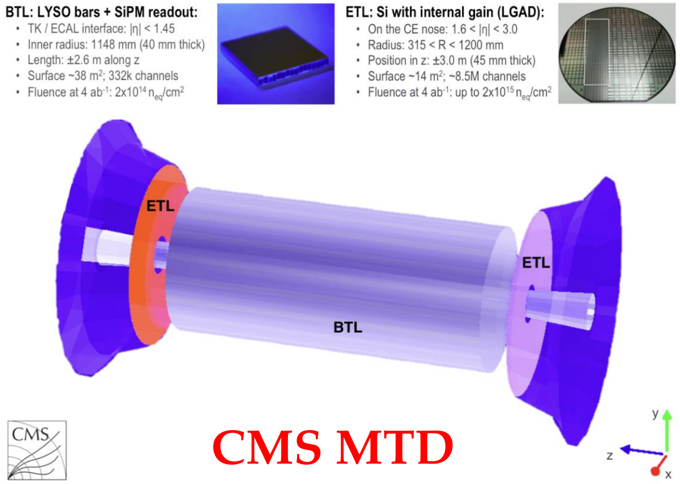
Exploit the time spread of collisions to reduce pileup contamination

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

ATLAS and CMS

ALTAS HGTD

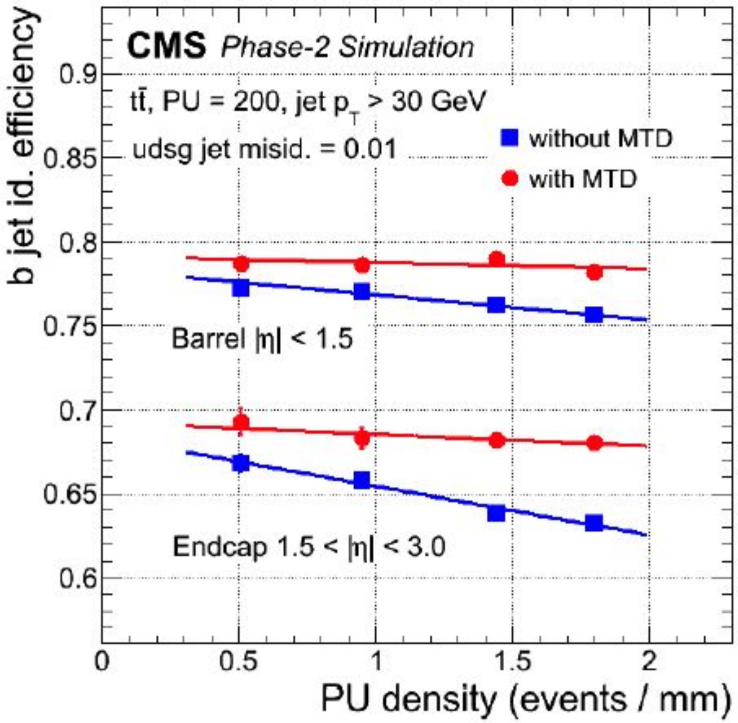


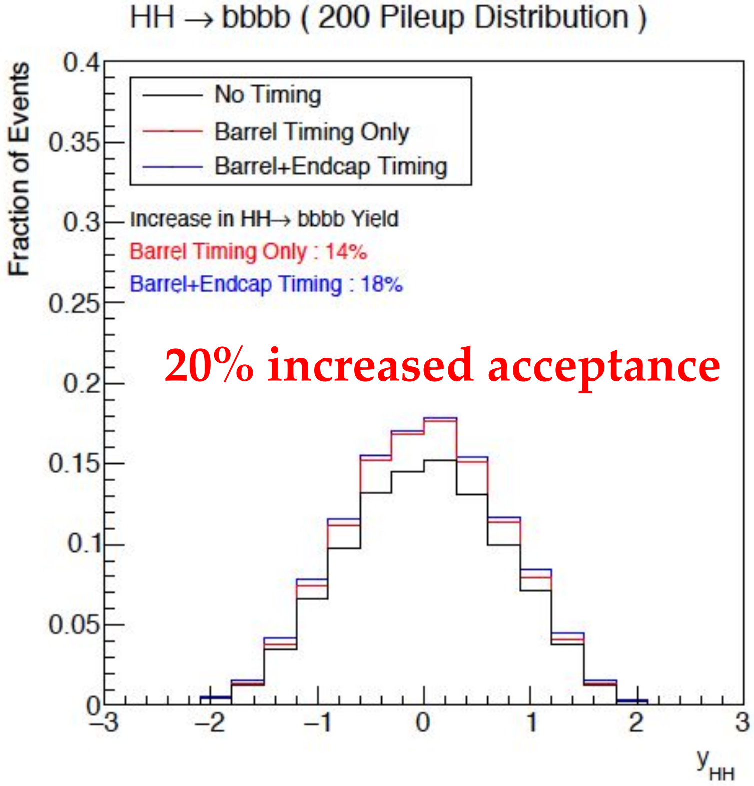


CMS MTD

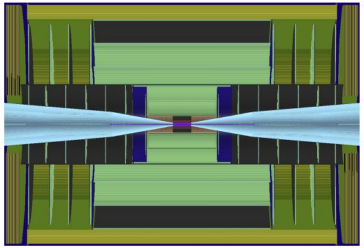
- LGAD sensors in the endcap/forward regions (1.3 x 1.3 mm^2)
- Crystals and SiPM readout in the barrel central region
- ~30ps time resolution per track
- ATLAS improves forward VBF final states (pileup suppression, lepton isolation)
- CMS hermetic coverage improves b-tagging, LLP, and provides PID capabilities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

Physics impact: Di-Higgs



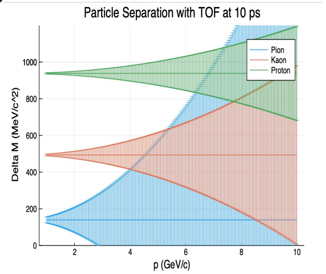


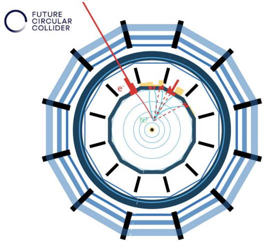
Fast timing in Higgs Factories



Suppression of beam induced backgrounds at muon colliders

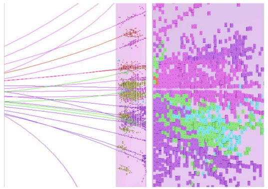
Full 4D tracking

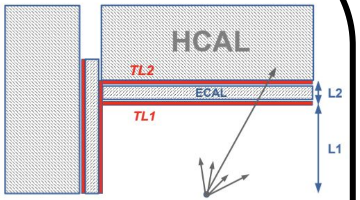




Time of Flight for Particle ID at low momentum and Long Lived particles

Timing layers



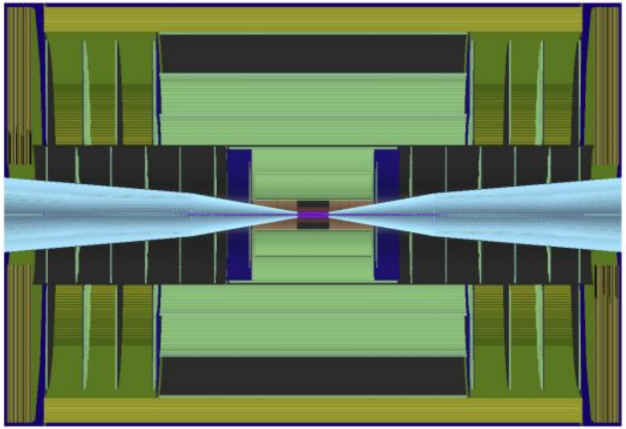


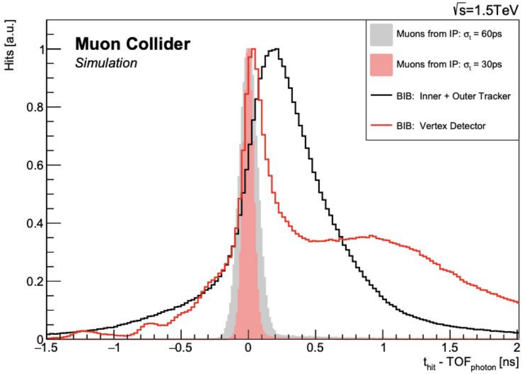
Exploit the time structure of hadronic showers to enhance PFA and improve jet energy resolution

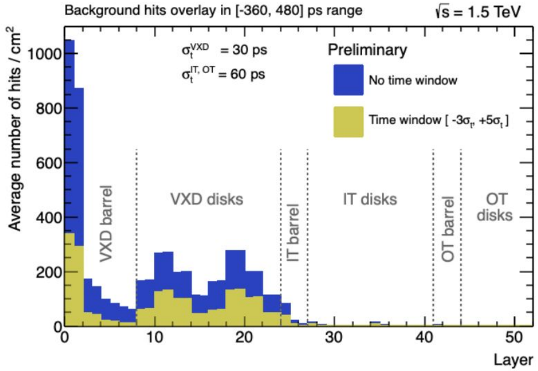
5D Calorimetry

Timing layers or volumetric timing

Muon collider: 4D Tracking







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

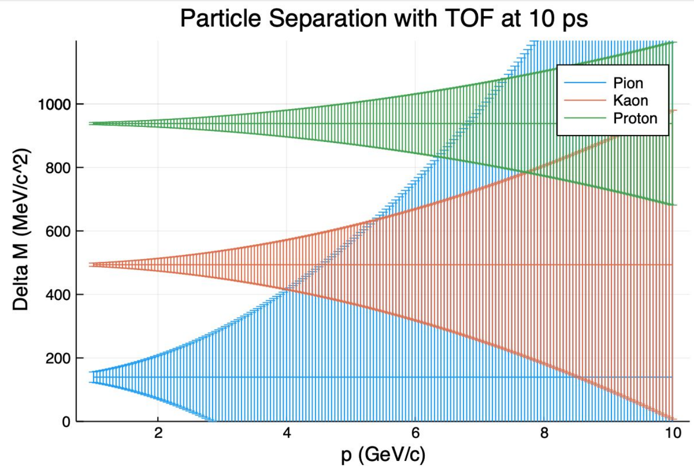
- **Picosecond timing plays a key role reducing the hit densities from BIB** (10 x HL-LHC!)
- Large number of hit combinations create a challenge for tracking pattern recognition
- **Timing information reduces hit densities by a factor of 2**

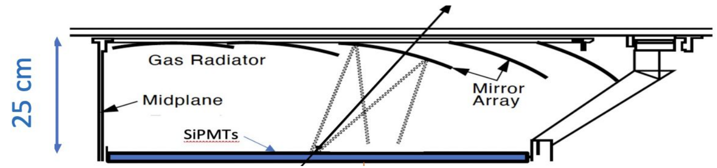
	Vertex Detector	Inner Tracker	Outer Tracker
Cell type	pixels	macropixels	microstrips
Cell Size	$25\mu m \times 25\mu m$	$50\mu m \times 1mm$	$50\mu m \times 10mm$
Sensor Thickness	$50\mu m$	$100\mu m$	$100\mu m$
Time Resolution	30ps	60ps	60ps
Spatial Resolution	$5\mu m \times 5\mu m$	$7\mu m\times 90\mu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

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.

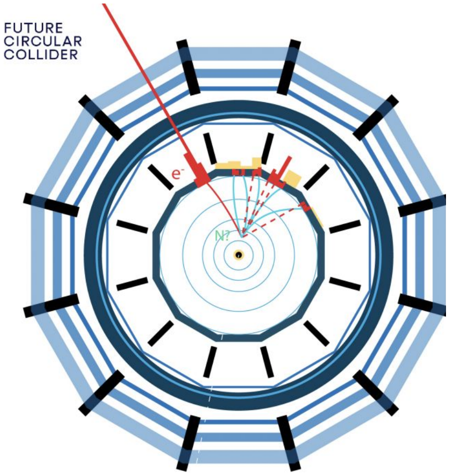
ToF: Long Lived Particles

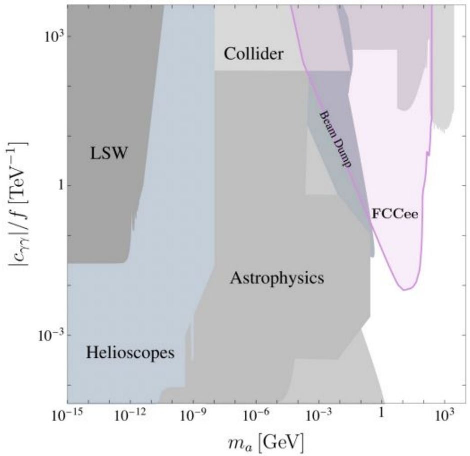
Exploit high luminosity Z run of FCC-ee to search for LLP:

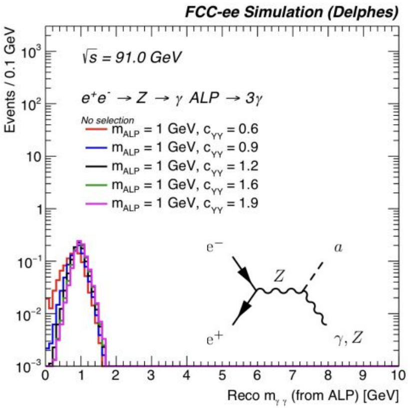
- Heavy Neutral Leptons
- Axion-like particles
- Exotic Higgs decays

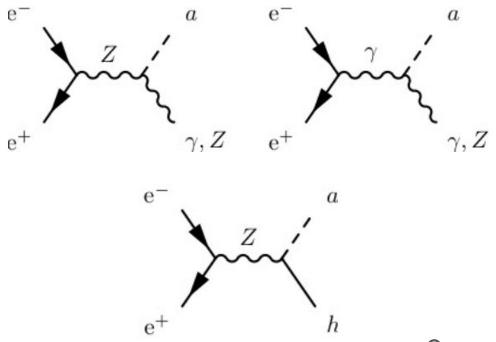
Timing information:

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







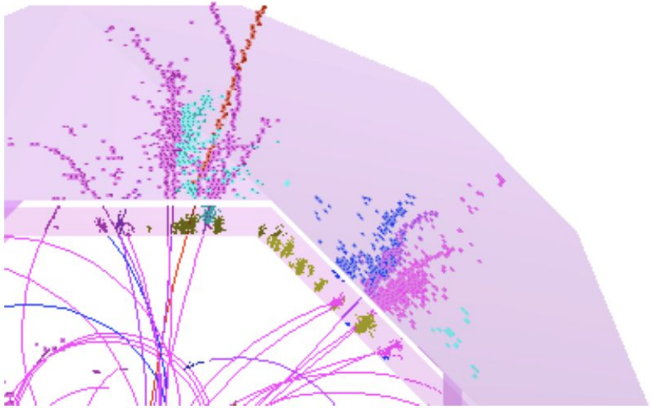


[Searches for Long-Lived Particles at the Future FCC-ee](#)

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)

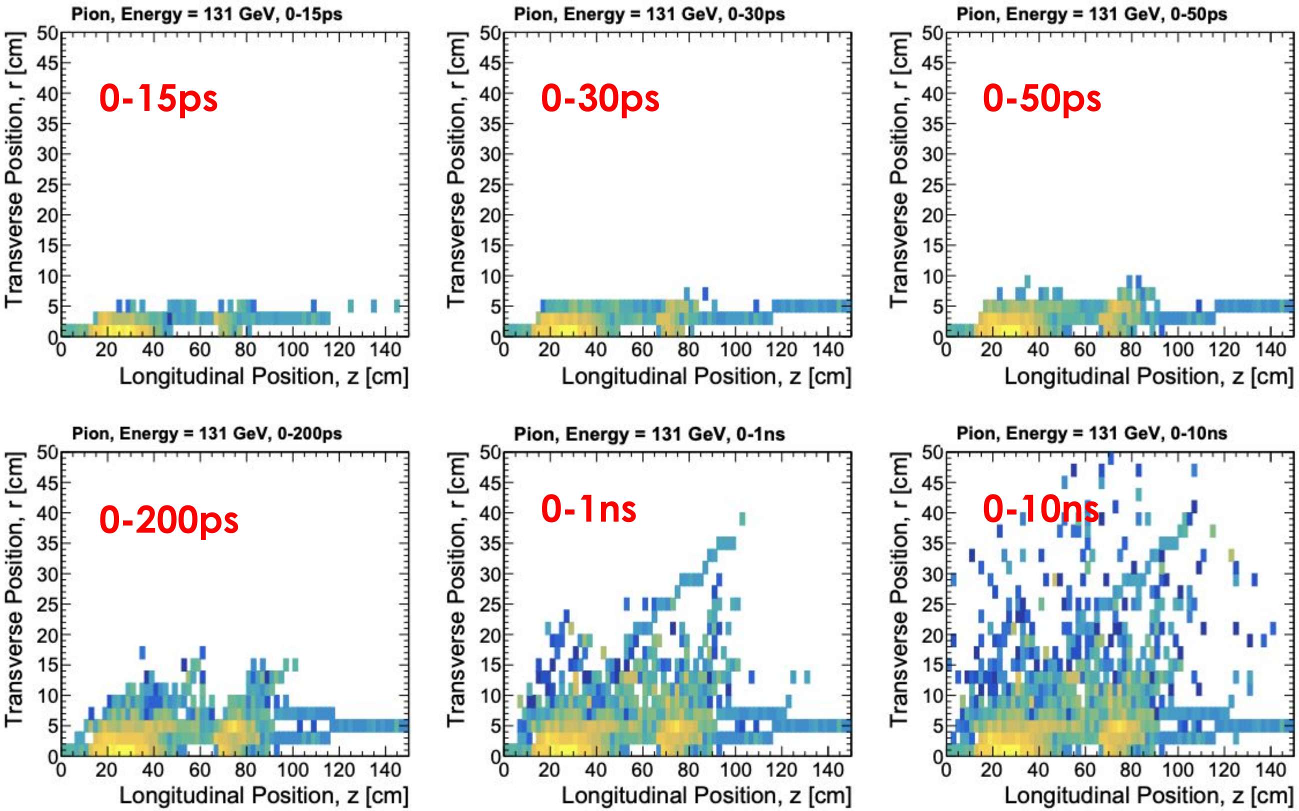


Different approaches:

- "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

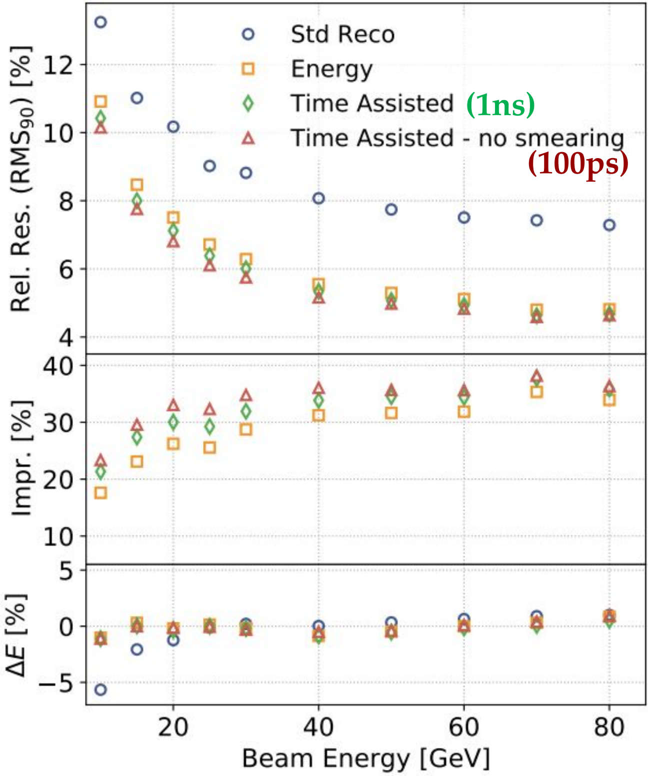
Time-assisted energy reconstruction in a highly-granular hadronic calorimeter Christian [Graf, Simon]

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

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

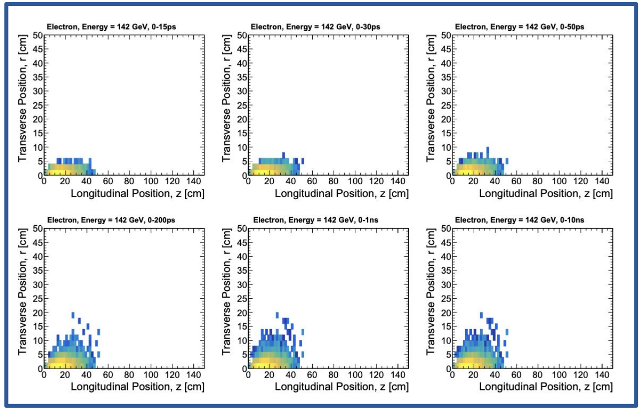
split 14 energy bins in t<3ns and t>3ns

- **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

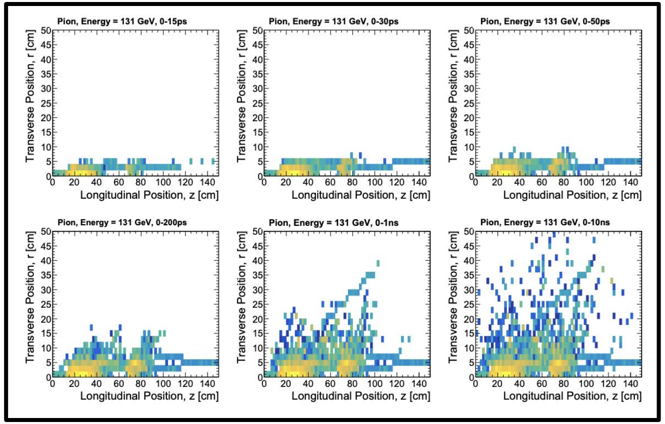


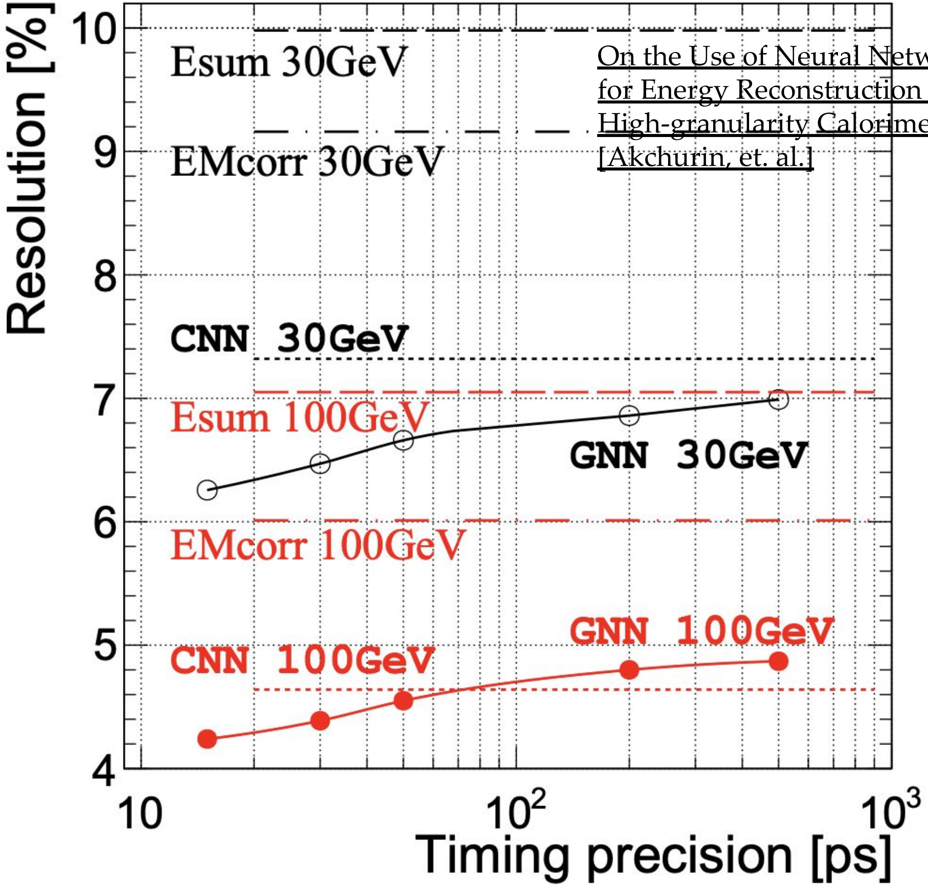
Graph Neural Network

electron



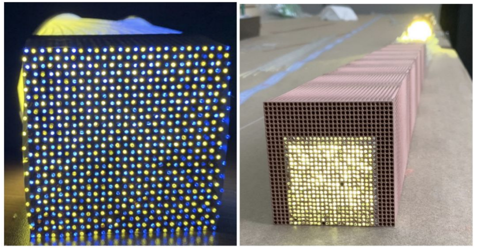
charged pion



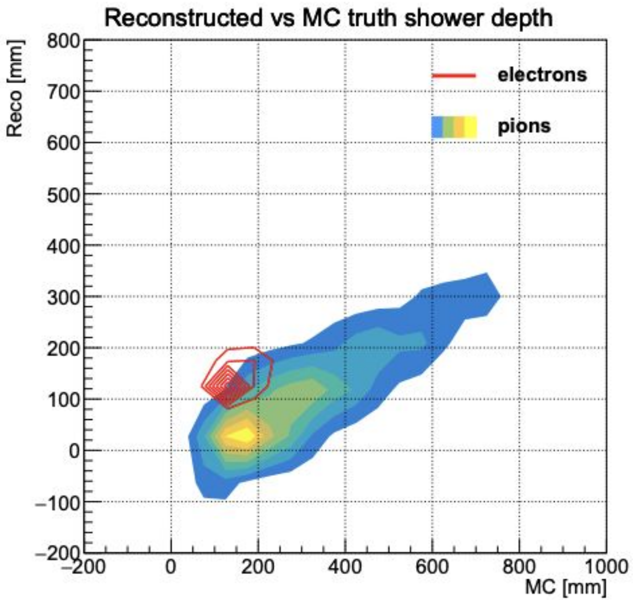


On the Use of Neural Networks for Energy Reconstruction in High-granularity Calorimeters [Akchurin, et. al.]

Longitudinal segmentation by timing in dual-readout fiber calorimeters



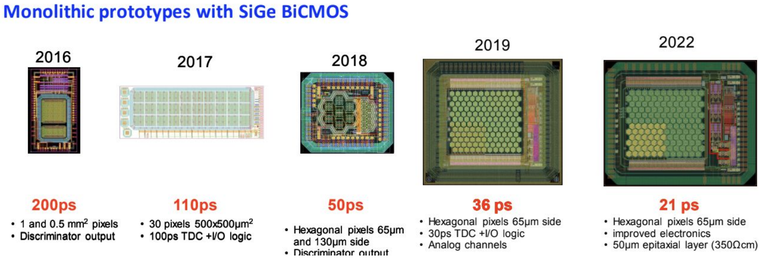
- Optical fibers inserted longitudinally and attached to SiPMs a the rear end
  - Energy deposits closer to the readout lead to shorter propagation times
- Utilize the entire timing structure of the electronic pulse with digital processing methods
- **Timing information at the level of 10ps can effectively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

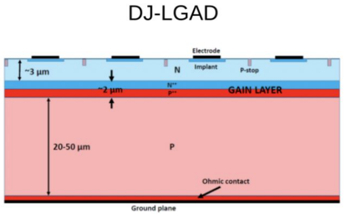


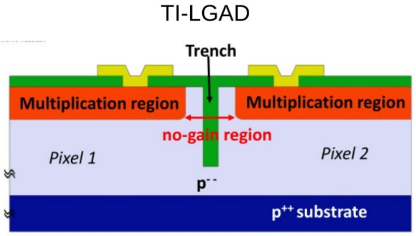
[Reconstruction of 3D Shower Shape with the Dual-Readout Calorimeter, Sanghyun Ko, Hwidong Yoo, Seungkyu Ha]

Detector Technologies

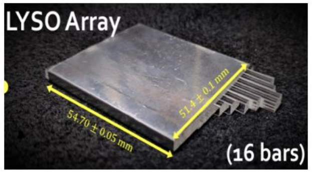
- **Timing layers / 4D tracking:**
  - (LYSO) Crystals + SiMPS (timing layers)
  - Silicon sensors (timing layers / 4D tracking)
    - **Advanced LGADs** with O(10ps) and O(10um) resolution
      - AC-LGAD, TI-LGAD, DJ-LGAD, Buried LGAD, DS-LGAD
    - **Monolithic CMOS**
      - LGAD MAPS, miniCACTUS,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

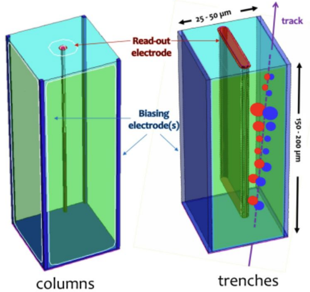






- **Volume calorimeter timing:**
  - LGAD or Silicon pads in Si+W calorimeter (CMS HGCAL)
  - Highly granular crystals
  - Plastic scintillator tiles or strips + SiPMs
  - RPC can cover large active areas for digital hadronic calorimeters (SDHCAL CALICE)

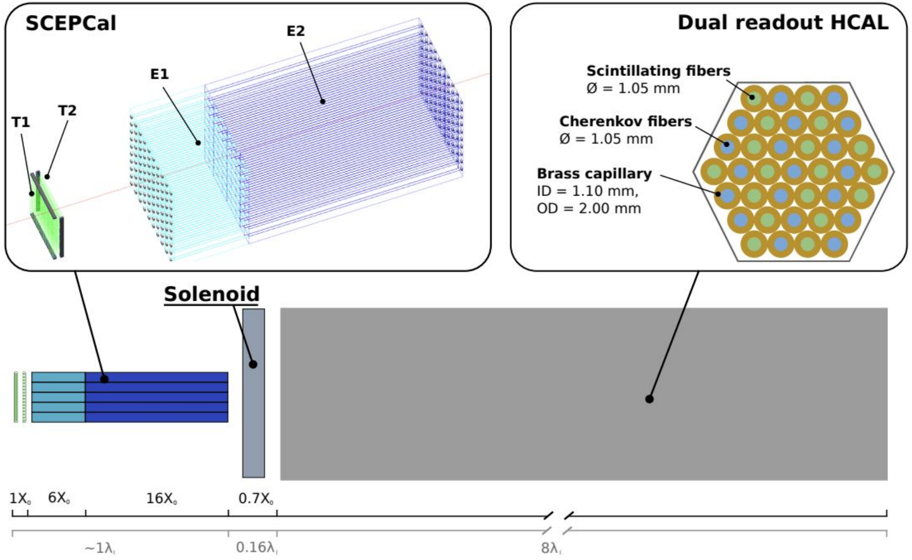


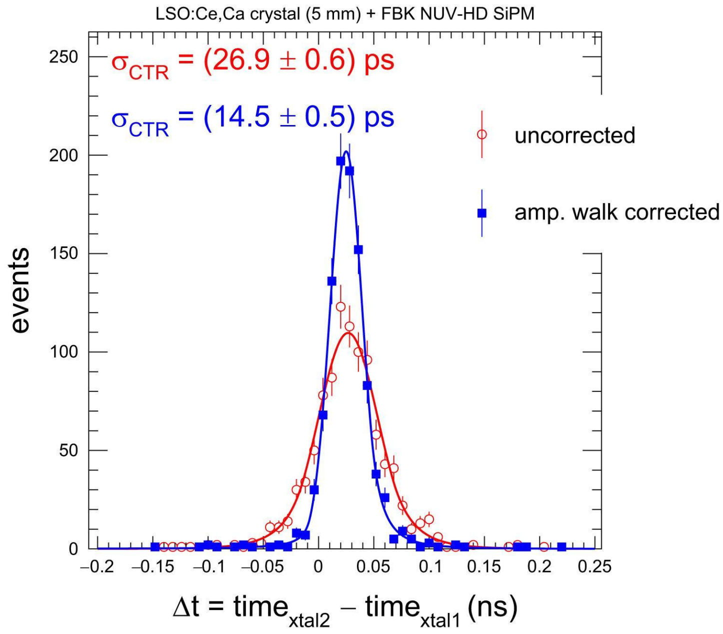


4-Dimensional Trackers [Berry, et. al]

Timing layers: Crystals

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





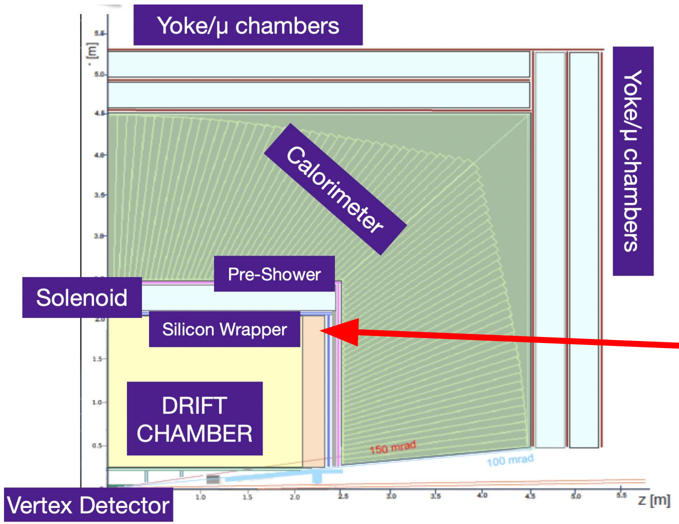
Detection of high energy muons with sub-20 ps timing resolution using L(Y)SO crystals and SiPM readout [Benaglia, et. al.]

- **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

FCC-ee IDEA

FCC-ee Novel Liquid ECAL based

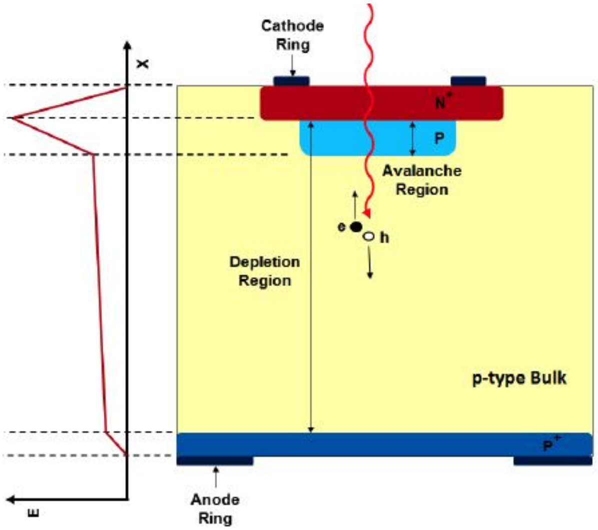


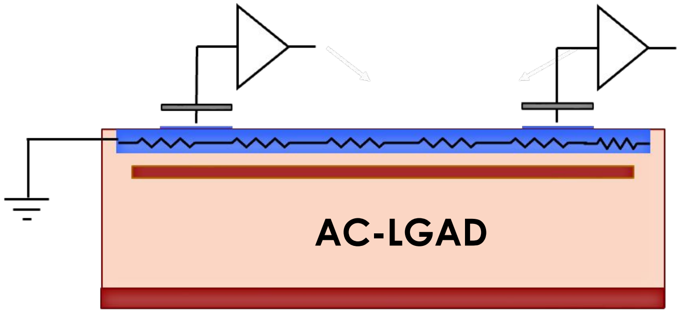
Silicon Wrapper

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

LGAD sensors

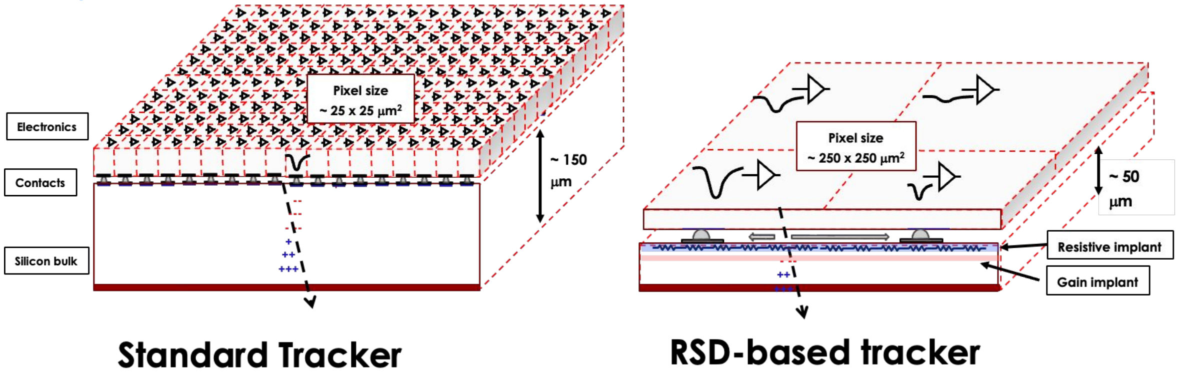
- **Thin silicon sensors with modest intrinsic gain (5-50) provided by a doped p+ multiplication layer**
  - thin: reduces Landau fluctuations
  - high S/B from internal gain
  - short rise time minimizes jitter
  - 30ps resolution sensors used in ATLAS and CMS HL-LHC endcap timing layer upgrades
- Standard 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, …

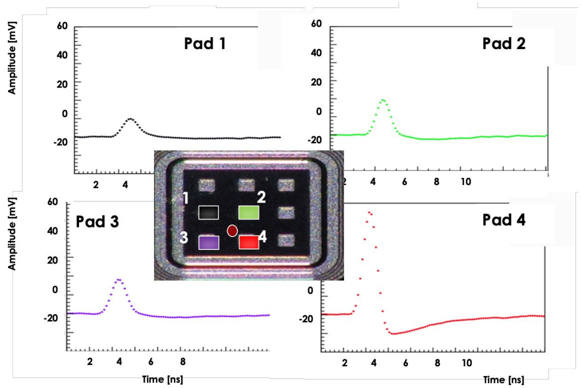


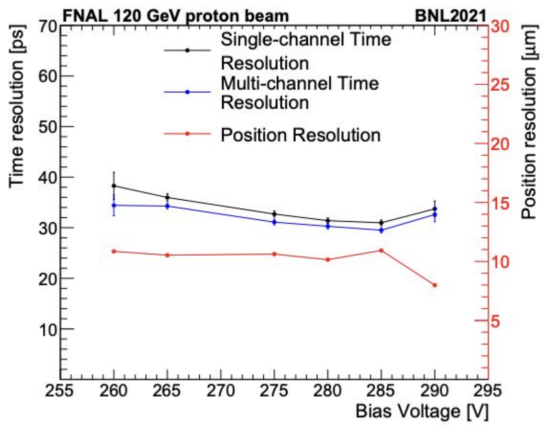


AC-LGAD

[The power of gaining and sharing: introducing internal gain and built-in charge sharing in silicon sensors, N. Cartiglia]







- 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
  - **Much lower power consumption**: 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 [μm^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

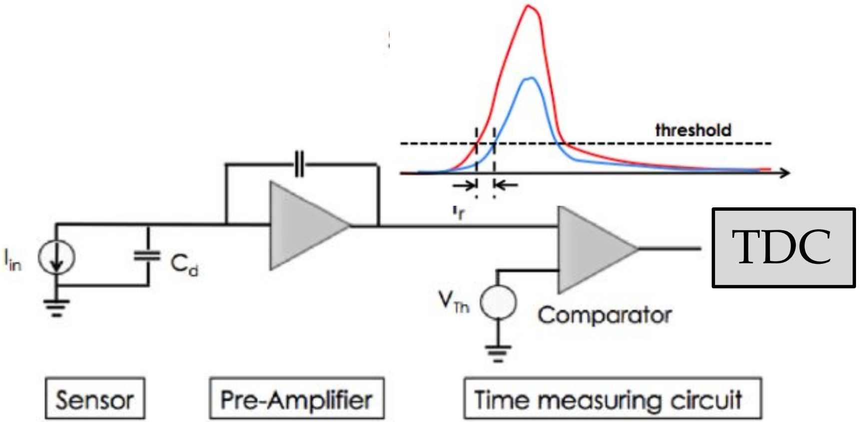
- **Fast timing capabilities present an exciting opportunity for the next generation of detectors at Higgs Factories**
  - 4D Tracking will be crucial to suppress BIB at Muon Colliders
  - Timing layers can enhance particle identification and long lived particle searches
  - 5D Calorimetry can improve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

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

- 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)