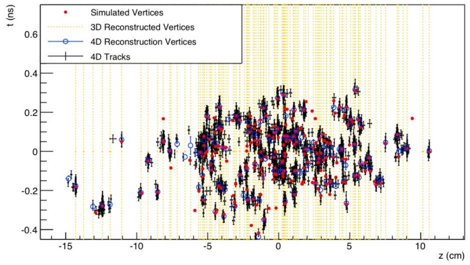
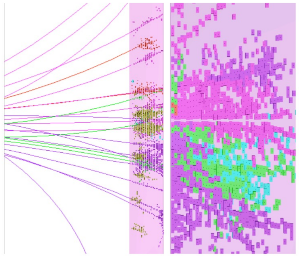
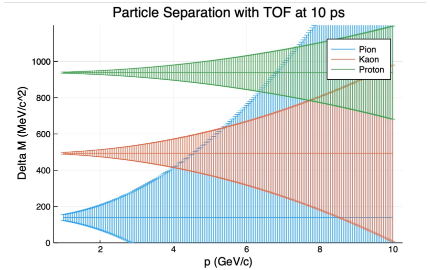
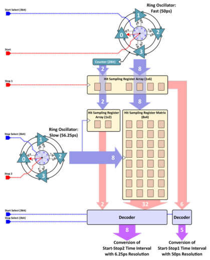
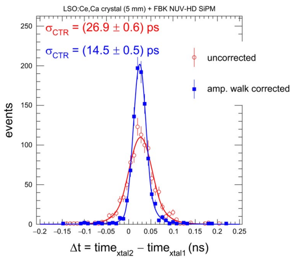







# Fast Timing at Future Colliders

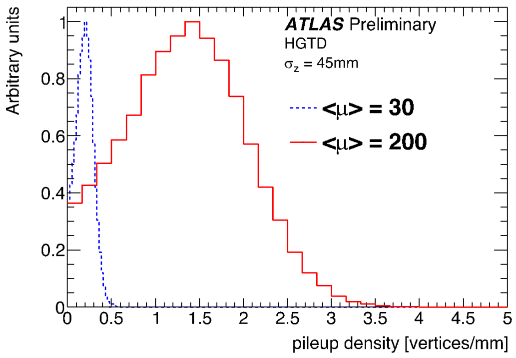
**Ariel Schwartzman**
**(SLAC)**

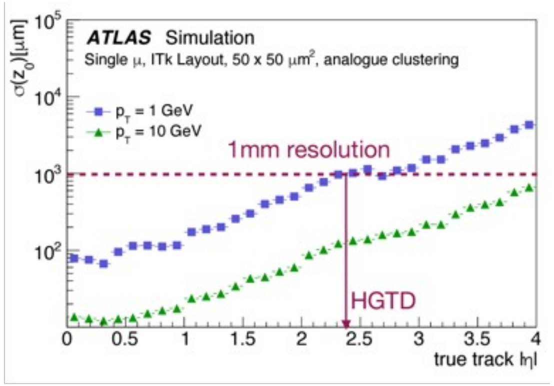
Cool Coper Collider Workshop
14-Oct-2022

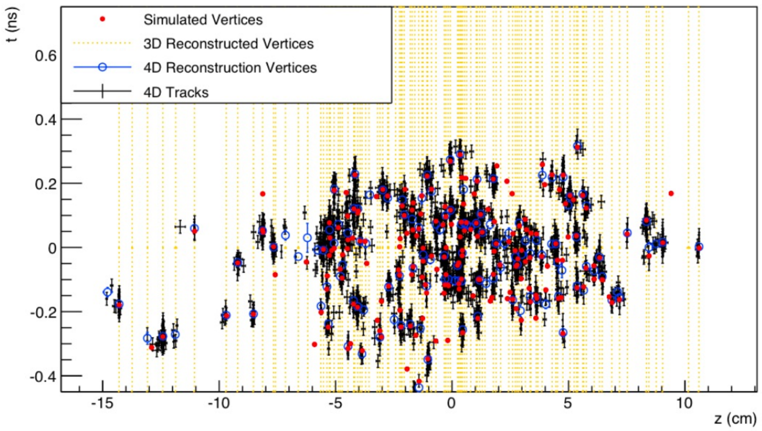
# Introduction

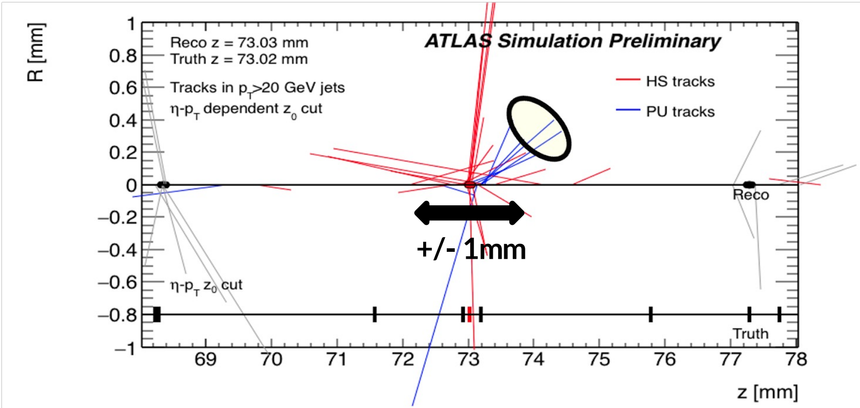
- **Precision timing at the level of 10-30ps is a new capability for the next generation of particle physics detectors at all future colliders**
  - Address the increasing complexity of events at hadron colliders
    - 4D trackers to resolve vertices at very high pileup densities
  - Identify long-lived particles (LLPs) and expand the reach for new phenomena
  - Enable particle ID capabilities at low momentum
  - Enhance calorimetry measurements
  - Suppress out-of-time beam Induced backgrounds
- Coarse timing at the ns-level can complement fast timing layers for enhanced overall 4D tracking and 5D calorimetry
- **R&D to investigate the full potential of fast timing detectors in future colliders is an exiting opportunity for the particle physics community**

# Hadron colliders



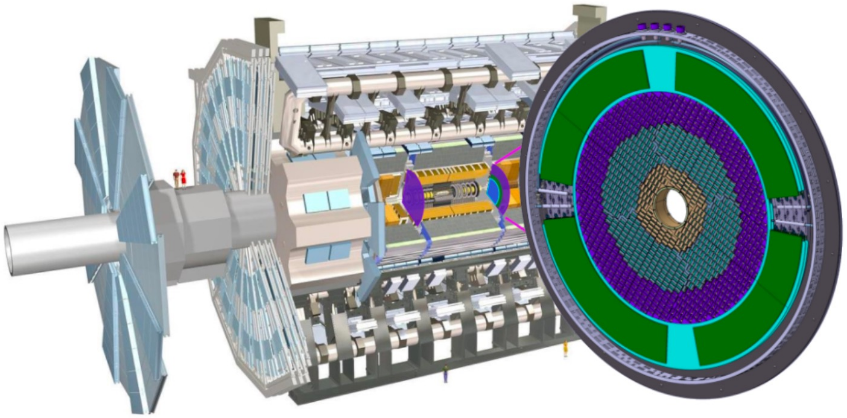

HL-LHC pileup density is comparable or larger than the track longitudinal impact parameter: **the association of tracks to vertices becomes ambiguous**!

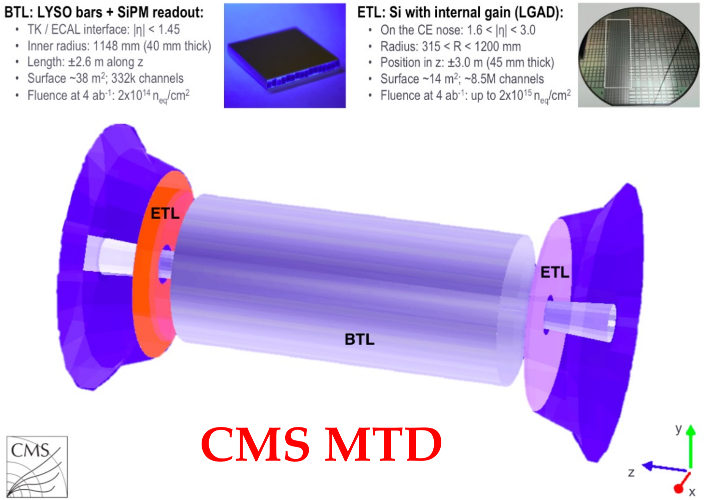
**Exploit the time spread of collisions to reduce pileup contamination**

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

# ATLAS and CMS

## ALTAS HGTD

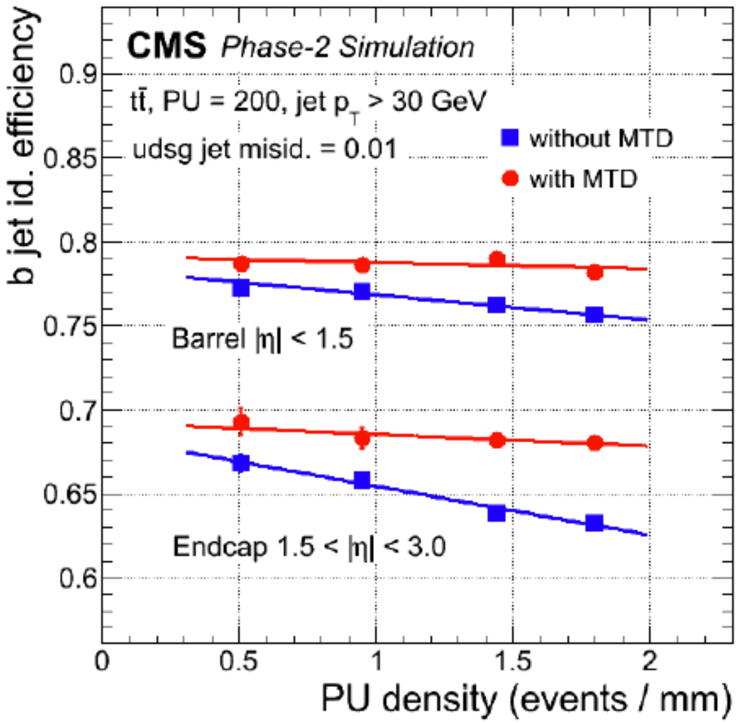


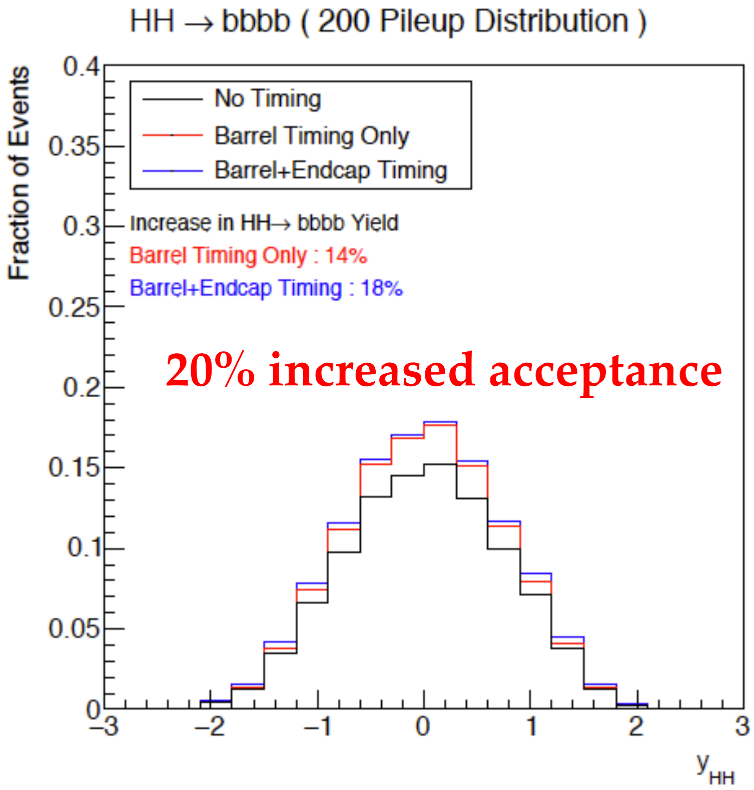



## CMS MTD

- LGAD sensors in the endcap/forward regions (1.3 x 1.3 mm$^2$)
- ~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
- ATLAS and CMS HL-LHC timing layers are precursors to future 4D trackers and excellent first platforms for developing precision timing in collider environments

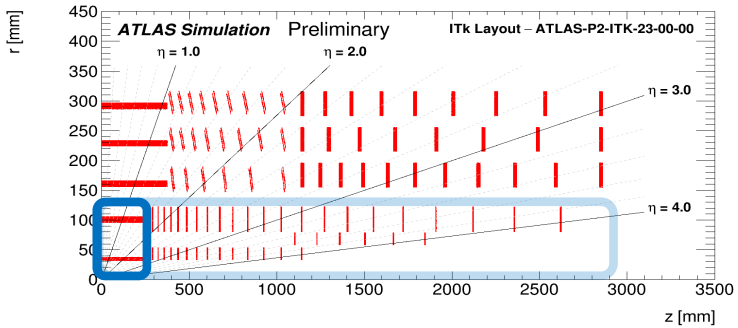
# Physics impact: Di-Higgs



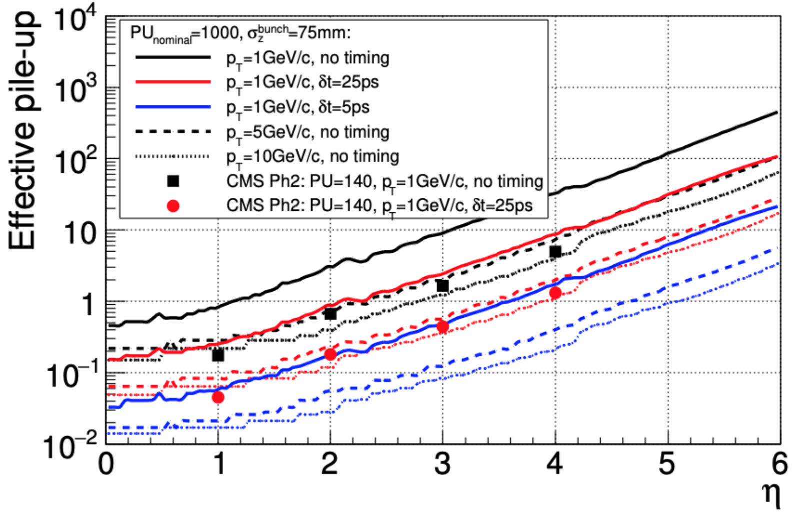



# Future Hadron colliders

- **ATLAS inner pixel** is designed to last 2000 $fb^{-1}$, to be replaced mid-way through HL-LHC
  - Exciting opportunity to introduce a 4D single pixel layer for additional barrel coverage and improved physics performance




- **FCC-hh**
  - Unprecedent O(1000) pileup conditions
  - Very clear case for the use of 4D technology in all tracking layers
    - Associate hits consistent in time
  - Need 5-10ps resolution per track
  - Dedicated R&D required to archive a radiation hardness for an intensity 30 times larger than HL-LHC



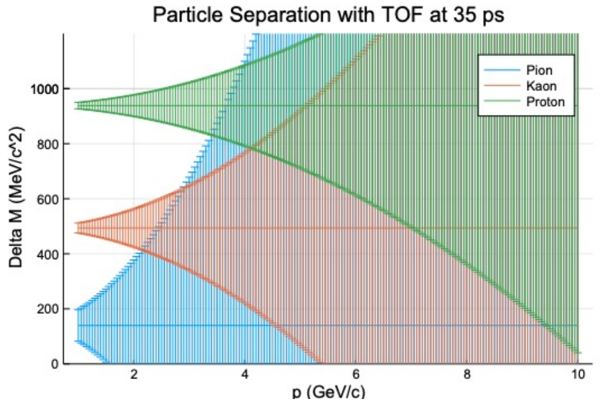
# $e^+e^-$ colliders

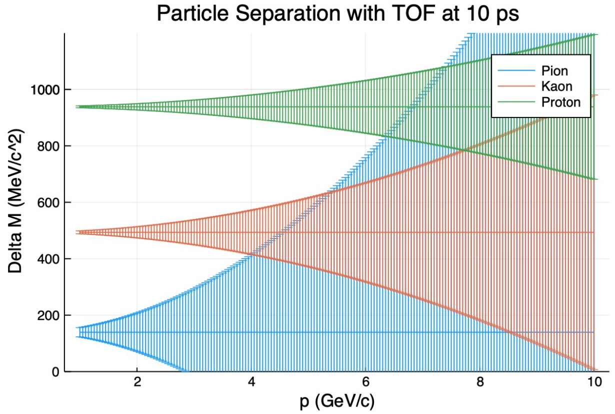
- **Clean environment**
- **Physics measurements require very high precision → very low passive material in tracking/vertexing detectors**
- Most studies so far focus on the use of ~ns level resolution to remove particles form beam induced backgrounds
- **The community is pursuing studies to assess the potential of O(10) picosecond timing resolution to enhance the physics capabilities of the next Higgs Factory**
    - Large-area, large-radius 4D tracking layer(s) for PID
    - Enhancing calorimeter jet reconstruction:
        - timing can help resolve nearby hadronic showers, and effectively provide longitudinal segmentation in fiber dual-readout calorimeters
        - Various approaches: timing layers, "volume" timing, hybrid, … with different requirements
        - Various technologies for materials, sensors, and electronics being explored to address the many challenges involved
    - **Plenty of room for new ideas and innovation!**

# Particle ID

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

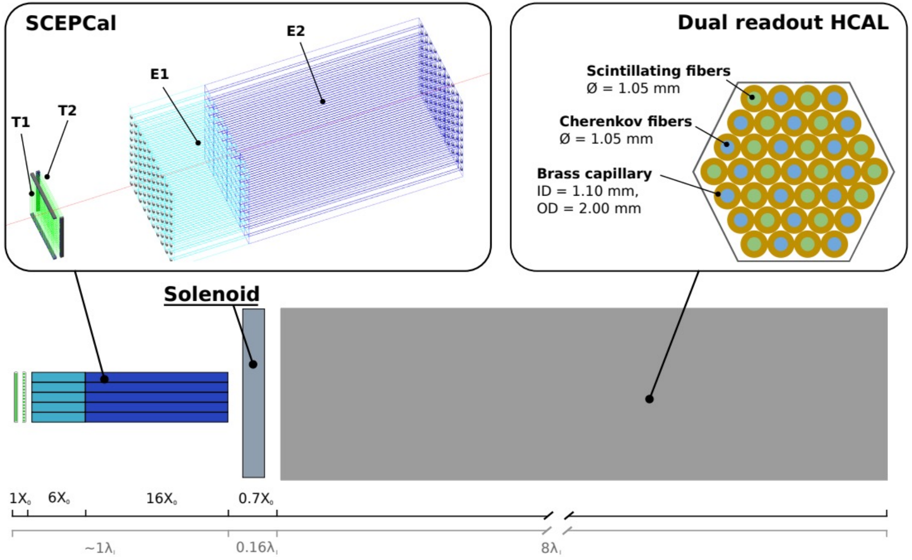
- Large-radius timing layers in the in front of the calorimeter can provide **Time-of-Flight** (ToF) for PID
- Need 10ps resolution for K/pi separation at low momentum (up to ~3 GeV)
- Complements other PID subdetectors in the low momentum region
    - for example, a RICH detector for high (10-30 GeV) momentum – See talk by J. Vavra
- Large-radius timing layers can also improve **LLP searches** (heavy particles decaying to jets and photons)
    - More study needed

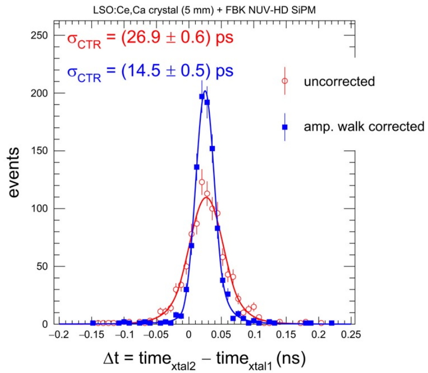


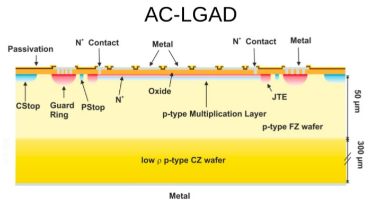
# Timing layers

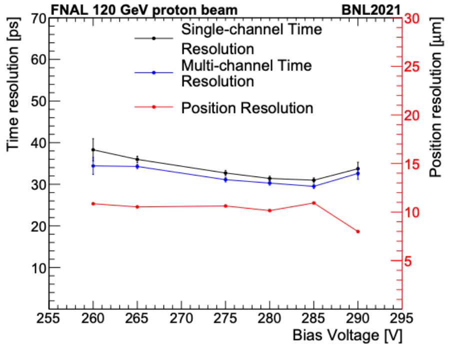
[New perspectives on segmented crystal calorimeters for future colliders [Lucchini, et. al.]]




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



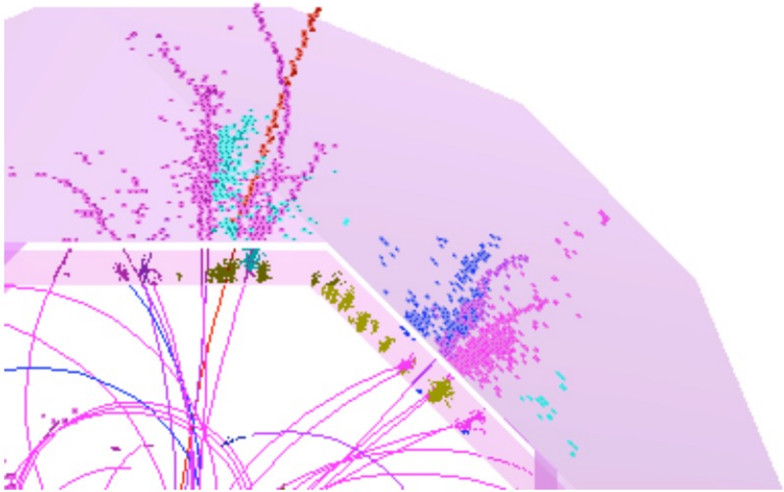

- Hybrid segmented dual-readout calorimeter
  - Two thin timing layers in front of EM Calorimeter

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

# Calorimetry

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

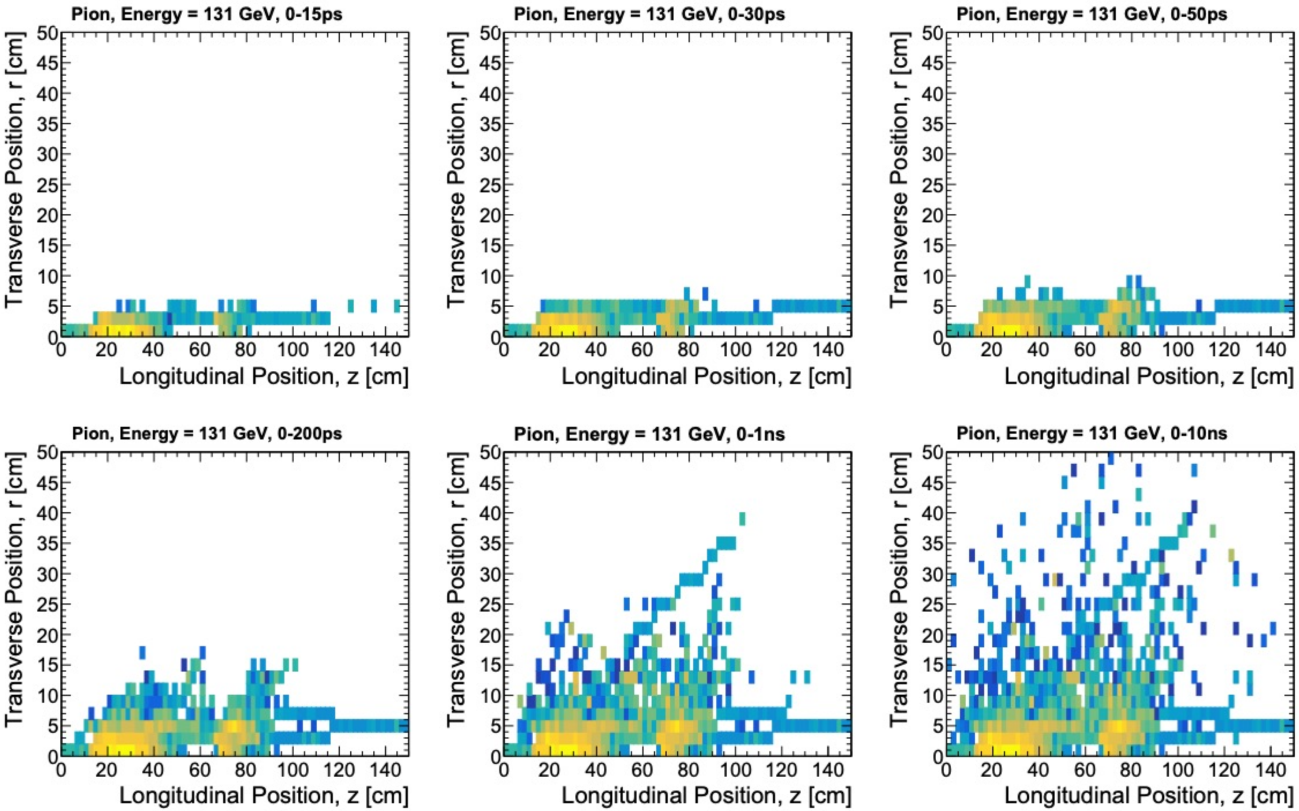
- Performance of particle flow reconstruction depends on the ability to associate showers to particles
  - Challenging when showers overlap in space
- Precision timing information can help resolve close-by showers, exploiting the full space-time structure of showers, improving the jet energy resolution



- Different approaches:
  - "Volume" (cell-level) timing
  - Dedicated timing cells
  - Timing layers within the calorimeter

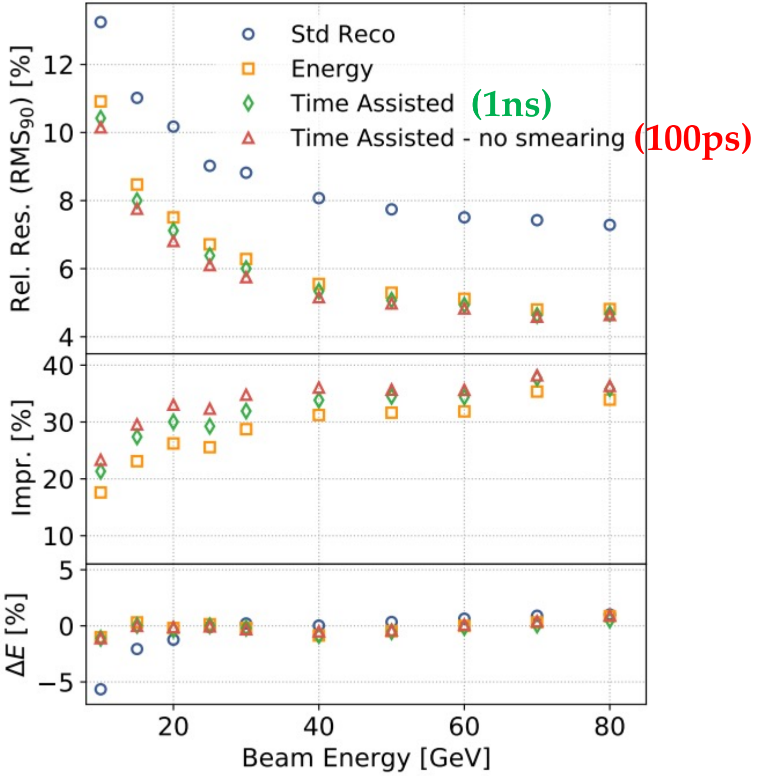
# Calorimetry

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



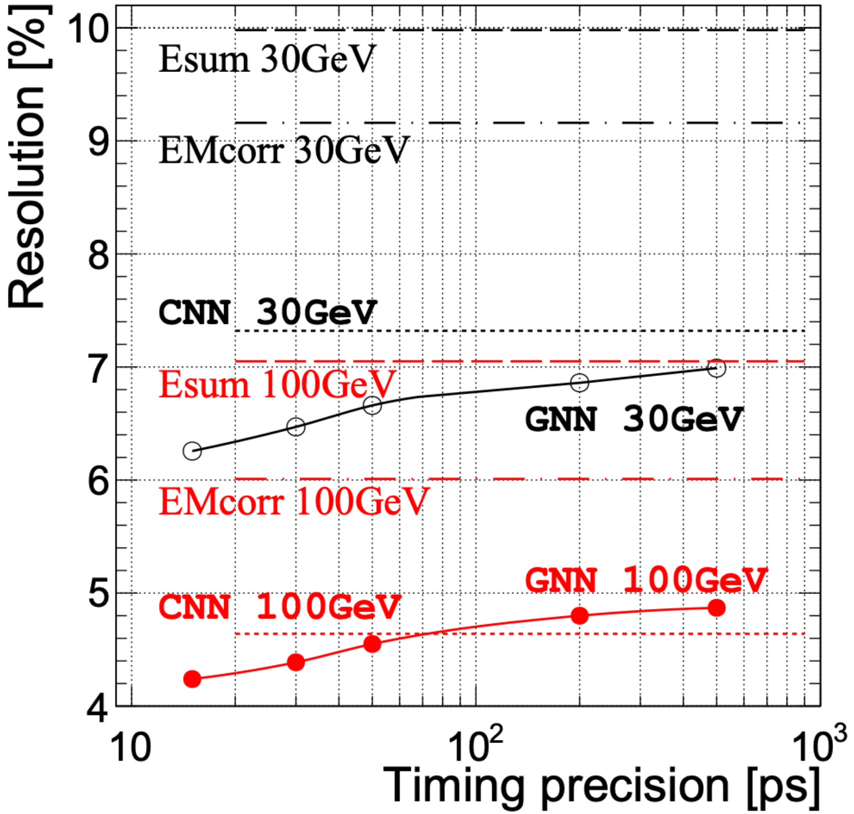
# Calorimetry

**CALICE SiPM-on-tile analog hadron calorimeter**




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

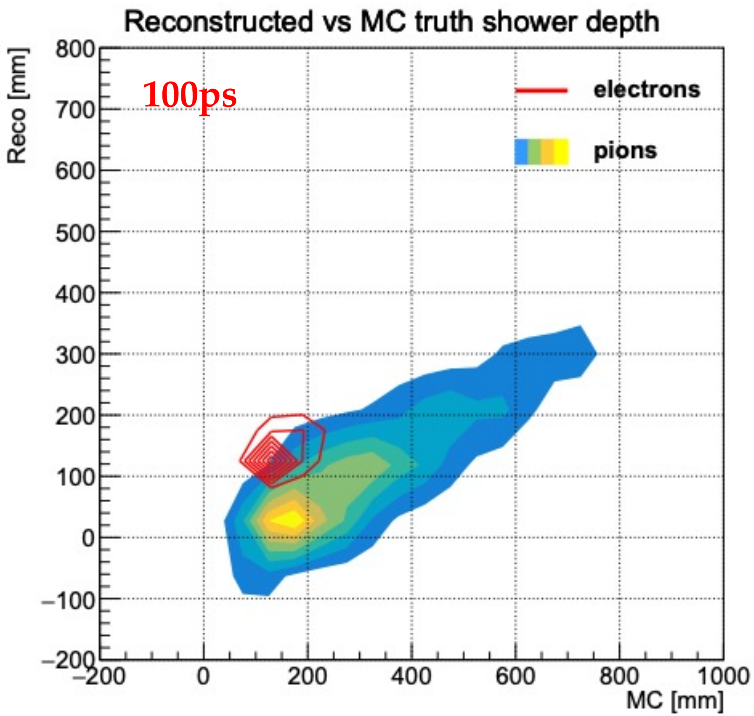
[On the Use of Neural Networks for Energy Reconstruction in High-granularity Calorimeters [Akchurin, et. al.]]



# Calorimetry

**Longitudinal segmentation by timing in dual-read out fiber calorimeters**

- Timing information at the level of 30-100ps can effectively segment longitudinally fiber calorimeters, providing new capabilities for shower shape reconstruction
- Similar concept could be used to enhance RICH ring reconstruction using SiPMs with ~100ps time resolution (See Vavra talk)



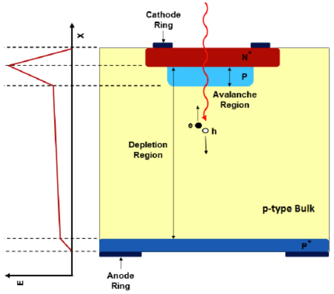

[Precision timing for collider-experiment-based calorimetry [Chekanov, et. al.]]

# Detector Technologies and R&D

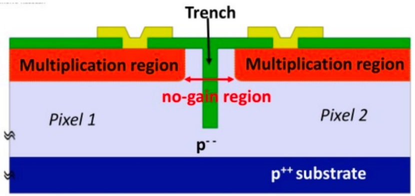
- **Timing layers:**
  - LGADs sensors with O(10ps) and O(10um) resolution
    - AC-LGAD, TI-LGAD, DJ-LGAD, Buried LGAD, DS-LGAD (see backup)
    - Silicon Carbide LGADs
    - Monolithic CMOS LGADs
  - 3D silicon sensors
  - LYSO crystals + SiPMs
- **Volume timing:**
  - LGADs or Silicon tiles (CMS HGCAL)
  - Plastic scintillator tiles or strips + SiPMs
  - …

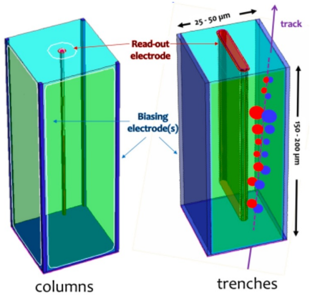
[4-Dimensional Trackers [Berry, et. al]]

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




TI-LGAD



# Electronics

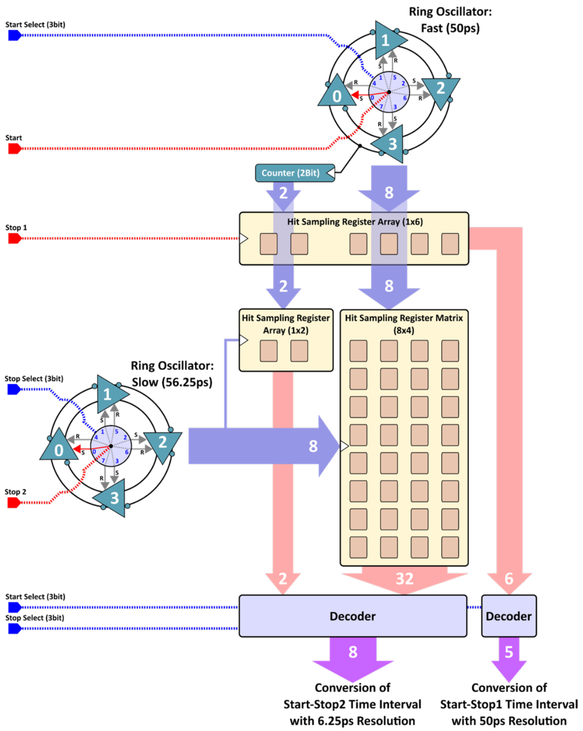
- HL-LHC timing ASICs are a revolutionary step forward to bring O(ps) timing to collider experiments, but use significant more space and power than what is required for 4D trackers → **Need R&D to minimize both power consumption and channel size**

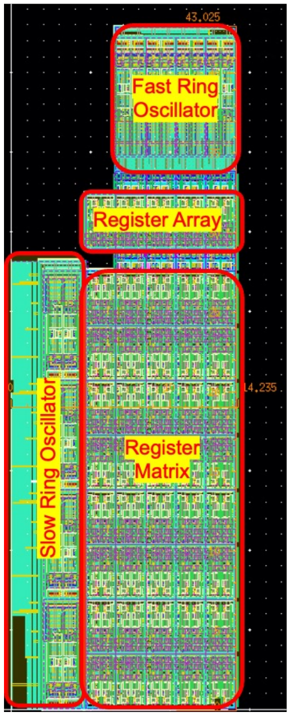
| ASIC | Technology | Pitch | Total size | Power consumption | TID tolerance |
|---|---|---|---|---|---|
| ALTIROC | 130 nm | 1.3 mm | $19.5 \times 19.5\ \mathrm{mm}^2$ | 5 mW/chan | 2 MGy |
| ETROC | 65 nm | 1.3 mm | $20.8 \times 20.8\ \mathrm{mm}^2$ | 3 mW/chan | 1 MGy |
| RD53A/HL-LHC pixels | 65 nm | 50 µm | $20 \times 11.6\ \mathrm{mm}^2$ | $< 10$ µW/chan | 5–15 MGy |

- **Some current ongoing R&D projects:**
  - CERN EP R&D WP5 has promoted the selection of 28nm CMOS node as the next step in microelectronics for HEP designs. Twice as fast and allows 4-5x circuits densities than 65nm. SLAC has designed a **TDC in 28nm with target resolution 6.25ps**. Fabrication expected January/2023
  - Fermilab has developed an ASIC in 65 nm for LGAD fast timing readout based on **Constant Fraction Discriminator** (FCFDv0) with 10ps jitter (Current collaboration to pair with SLAC 6.25ps TDC)
  - **SiGe chips optimized for low power and 10ps resolution** are being produced by Anadyne Inc. and UC Santa Cruz (TowerJazz 130nm)
  - **Full waveform digitization chip**: UC. Santa Cruz is working with Nalu Scientific to design and fabricate a waveform digitization ASIC for AC-LGAD sensor arrays (TSMC 65nm)

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

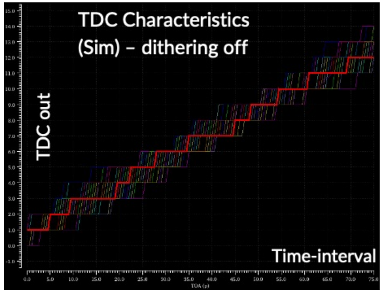
# Timing Electronics R&D at SLAC

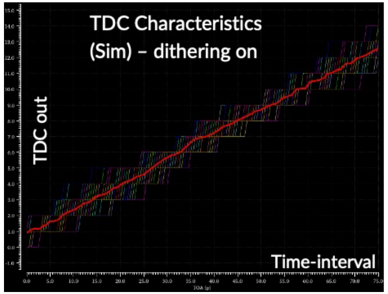



One of the critical circuit blocks necessary to enable 4D operation in trackers are low-power and compact TDCs capable of high time-measurement precision

**SLAC has designed a TDCs in 28nm technology implementing dithering with 6.25ps time resolution.**



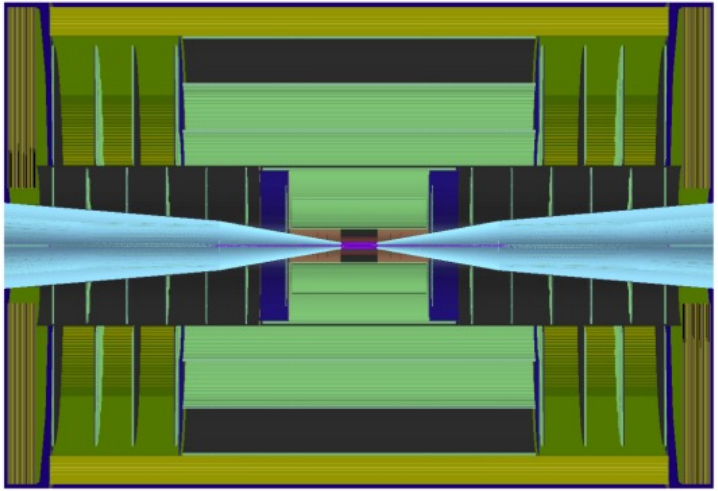

Sub-10ps resolution TDC with dithering in 28nm CMOS technology for future 4D trackers

# Summary

- **Detectors with ultra-fast timing present a new exciting opportunity for the next generation of particle colliders**
- Adding a $4^{th}$ timing dimension brings new information that can enhance the capabilities of all future particle colliders
  - The case for precision timing at $e^+e^-$ Higgs factories is being investigated with various opportunities in PID, and calorimetry
- Many interesting R&D directions in sensors, electronics, and overall detector system design need to be pursued to address the multiple challenges associated to how to best utilize timing information at a future $e^+e^-$ Higgs Factory

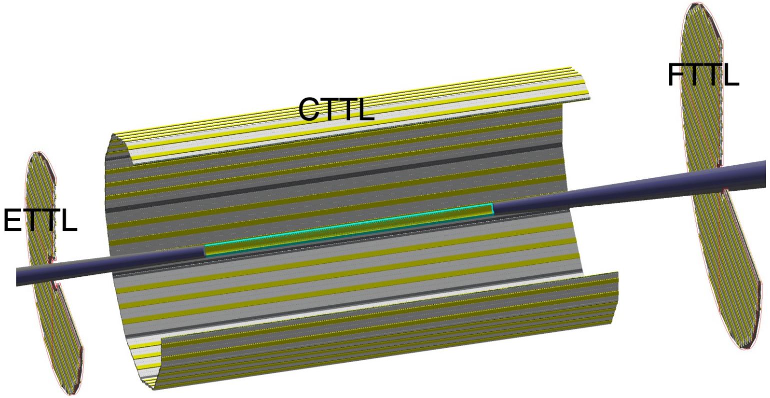
# Backup

# Muon collider and EIC



| | 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 | $5\mu m \times 5\mu m$ | $7\mu m \times 90\mu m$ | $7\mu m \times 90\mu m$ |

R&D for 4D and 5D (directional information) tracking



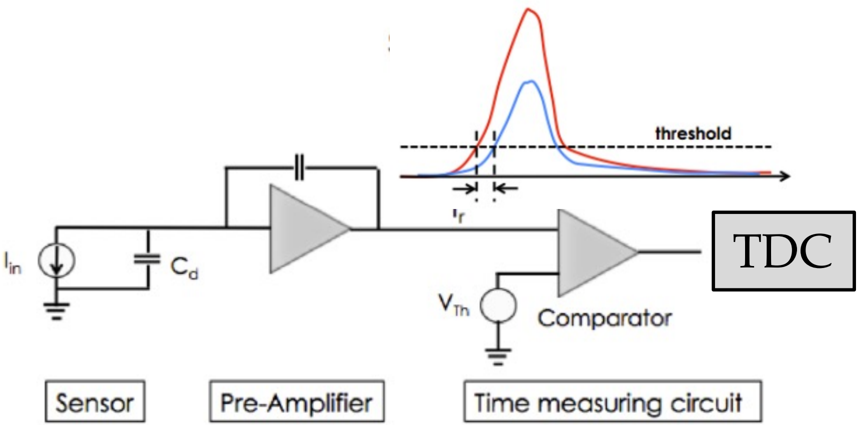

Precision timing:

- PID using TOF and vertex identification for far-forward hadrons
- **CTTL/FTTL: 4D tracking detectors with 25-30ps time resolution and 3um-50um (AC-LGADs)**

May become the first demonstration of 4D tracking layers in a collider experiment

# 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

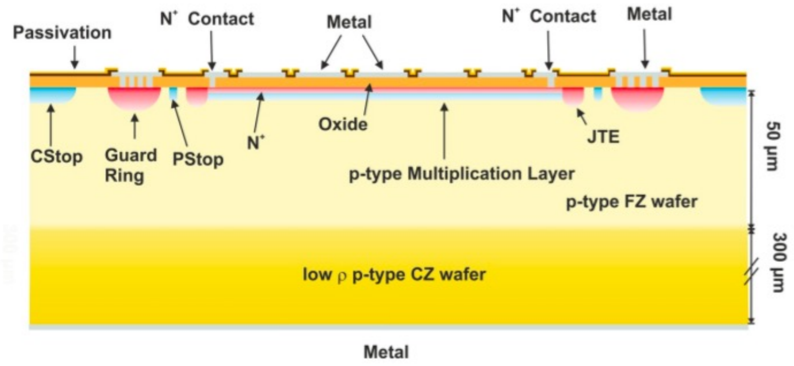
$$\sigma_{jitter} = \frac{N}{\frac{dV}{dt}} \propto \frac{t_{rise}}{S/N}$$

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

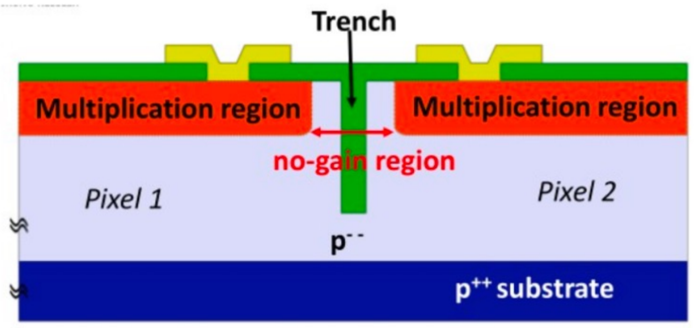
**Key to precision timing**: Large signal with short rise time and low noise (reduce jitter), limited thickness (reduce Landau), and small TDC bin size (reduce TDC component)

# Advanced LGADs

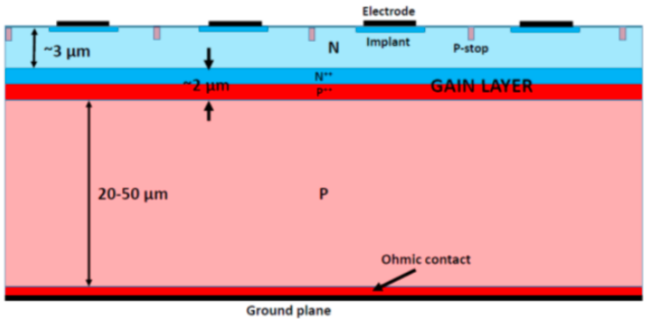
## AC-LGAD



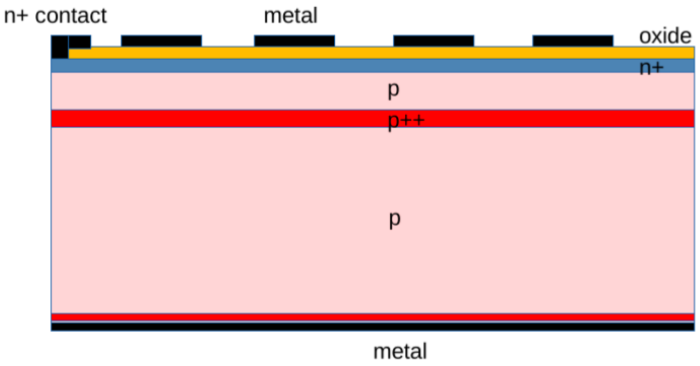

## TI-LGAD




## DJ-LGAD




## Buried-LGAD



# Si Sensor technologies

- **Based on physics requirements, future tracking sensors will require:**
  - simultaneous fine resolutions in both time and space of order 5-30ps and 5-25um
  - some colliders: radiation hardness, high occupancy, low material budget
  - coarser ns-level time resolution layers can be complementary for some applications
  - some applications will benefit from single-layer directional measurements (5D)

- **Two main approaches**

Low Gain Avalanche Detectors (LGADs)

precision timing → fine segmentation

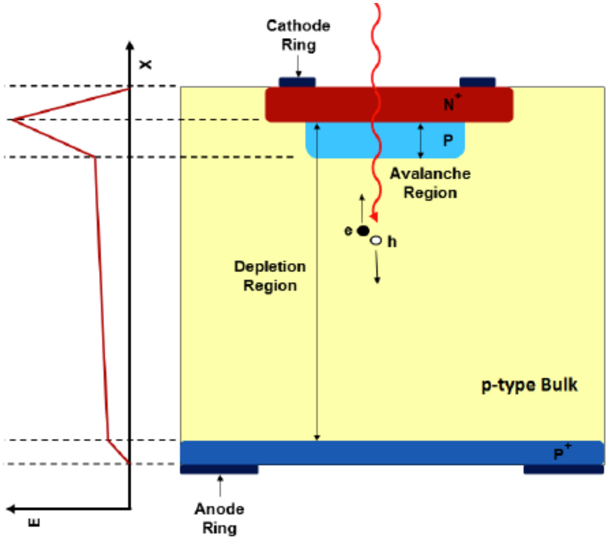
Monolithic sensors / 3D

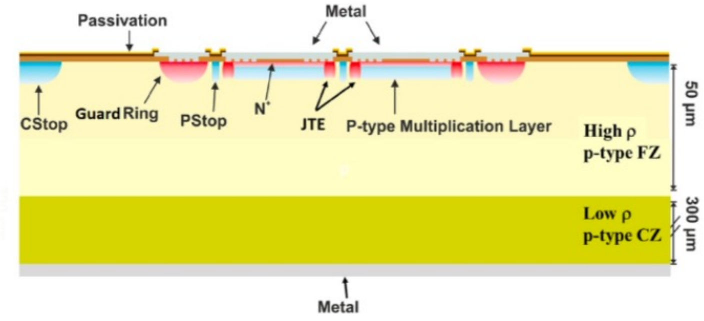
fine segmentation → precision timing

# LGADs

- **Thin silicon sensors with modest intrinsic gain (5-50) provided by a dopped 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

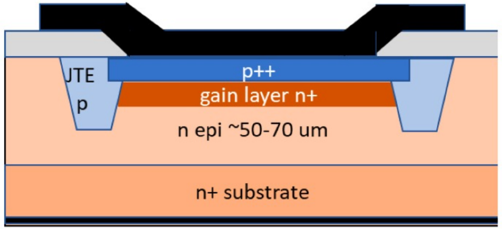
- **Standard LGADs require mm-size pads and require Junction Termination Extensions (JTE) to interrupt the gain layer between channels introducing inactive regions**
- **Advanced LGAD designs**
  - AC-coupled, Trench-isolated, Deep-Junction, Buried Layer, double sided LGAD for 5D tracking



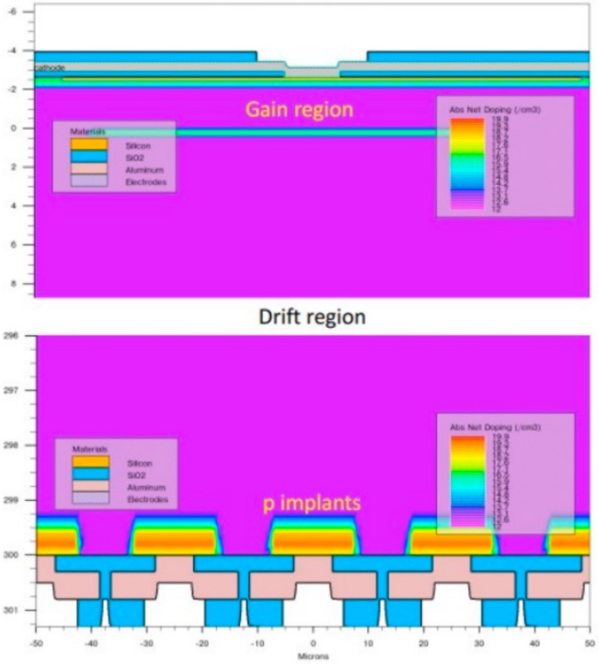
# Advanced LGADs and 3D

## Silicon Carbide LGADs

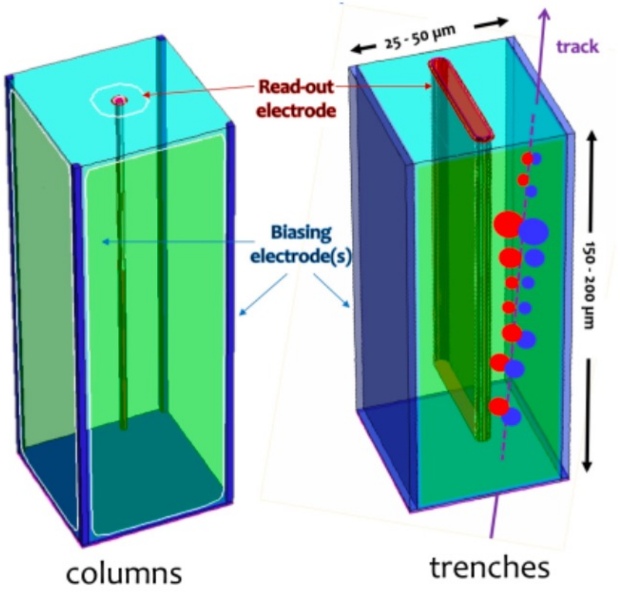



| Property | Silicon | 4H-SiC |
|---|---|---|
| Bandgap (eV) | 1.12 | 3.27 |
| Energy per ion pair (eV) | 3.6 | 7.78 |
| Dielectric constant | 11.7 | 9.7 |
| Breakdown field (MV cm$^{-1}$) | 0.3 | 3 |
| Density (g cm$^{-3}$) | 2.3 | 3.2 |
| dE/dx minimum (MeV cm$^{-1}$) | 2.7 | 4.4 |
| Atomic number Z | 14 | ~10 |
| Electron mobility (cm$^2$ V$^{-1}$ s$^{-1}$) at 300K | 1300 | 800-1000 |
| Hole mobility | 460 | 115 |
| Saturated electron velocity (10$^7$ cm s$^{-1}$) | 1 | 2 |
| Threshold displacement energy (eV) | 13-20 | 22-35 |
| e-h pairs per micron | 80 | 57 |
| Thickness for equivalent signal (μm) | 1 | 1.57 |
| Thermal conductivity (W m$^{-1}$ K$^{-1}$) | 130 | 370 |
| Radiation length | 9.4 | 8.7 |
| Impact ionization coefficient | $\alpha_e > \alpha_h$ | $\alpha_e < \alpha_h$ |

## DS-LGAD




## 3D



# Other technologies

- **Monolithic**
  - Many studies ongoing
  - State-of-the-art results from MALTA show < 2ns time resolution: suitable for e+e- colliders
  - FASTPIX dedicated sensors optimizations achieve a time resolution of 120ps
- **Induced current**
  - Same sensor as a traditional silicon detector but utilizes small pixel pitch and 3D integration (3DIC) techniques to create a low-capacitance pixel unit cell and readout chain
    - Allows the detection of the induced current at the readout electrode
    - Very fast rising edge (15ps) and angle of incidence information

# Electronics

- While redout prototypes for the timing detectors at the HL-LHC upgrades have demonstrated their required performance, applying similar techniques to **4D trackers present several 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**
    - High luminosity hadron colliders will require trackers to survive in **extreme radiation environments**

# 4D Tracking layout

- A major next step towards 4D tracking at future colliders is the study of **how to best combine timing with spatial information**
- Fine spatial resolution demands towards small pixels with low material budget and power may make it impractical to instrument finest timing capabilities on all layers → **4D trackers with a different balance of spatial/timing resolution may lead to an overall optimal design**
  - Alternating spatial with timing layers, or 4D with 3D layers, or coarse/fine timing
  - More layers with coarser timing vs fast-timing layers
- Physics drivers: tracking/b-btagging, BIB (inner layers) vs LLP and TOF (outer layers)