Fast Timing in Higgs Factory Detectors

Ariel Schwartzman (SLAC)

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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 of tracks to vertices becomes ambiguous!**

Exploit the time spread of collisions to reduce pileup contamination

Nominal HL-LHC Luminous region $\sigma_t = 180\text{ps}$

(30ps detector) $\rightarrow 30/180 = 6x$ pile-up rejection
• 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

CMS Phase-2 Simulation

If, PU = 200, jet $p_T > 30$ GeV
udsg jet misid. = 0.01

- [Blue squares] without MTD
- [Red circles] with MTD

- Barrel $|\eta| < 1.5$
- Endcap $1.5 < |\eta| < 3.0$

20% increased acceptance

HH $\rightarrow$ bbbb (200 Pileup Distribution)

- No Timing
- Barrel Timing Only
- Barrel+Endcap Timing

Increase in HH $\rightarrow$ bbbb Yield
Barrel Timing Only: 14%
Barrel+Endcap Timing: 18%
Fast timing in Higgs Factories

- Suppression of beam induced backgrounds at muon colliders
- Time of Flight for Particle ID at low momentum and Long Lived particles
- Exploit the time structure of hadronic showers to enhance PFA and improve jet energy resolution

**Full 4D tracking**

**Timing layers**

**5D Calorimetry**
Timing layers or volumetric timing
Muon collider: 4D Tracking

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

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

<table>
<thead>
<tr>
<th></th>
<th>Vertex Detector</th>
<th>Inner Tracker</th>
<th>Outer Tracker</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell type</td>
<td>pixels</td>
<td>macropixels</td>
<td>microstrips</td>
</tr>
<tr>
<td>Cell Size</td>
<td>(25\mu m \times 25\mu m)</td>
<td>(50\mu m \times 1\text{mm})</td>
<td>(50\mu m \times 10\text{mm})</td>
</tr>
<tr>
<td>Sensor Thickness</td>
<td>(50\mu m)</td>
<td>(100\mu m)</td>
<td>(100\mu m)</td>
</tr>
<tr>
<td>Time Resolution</td>
<td>30ps</td>
<td>60ps</td>
<td>60ps</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>(5\mu m \times 5\mu m)</td>
<td>(7\mu m \times 90\mu m)</td>
<td>(7\mu m \times 90\mu m)</td>
</tr>
</tbody>
</table>
ToF: Particle ID

- 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 (\(~100\)ps) for background suppression

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

**Strange quark as a probe for new physics in the Higgs sector**, J. Va’vra, et.al.
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
• Performance of particle flow reconstruction depends on the ability to associate showers to particles
  o 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
  o separate delayed shower components from neutron induced processes
  o 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

- **CALICE AHCAL LTP**
  - cell-by-cell time measurement for full 5D reconstruction of particle showers

- Local software compensation incorporating time:
  \[
  E_{\text{local reco}} = \sum e_j w(e_j, E_{\text{std}})
  \]

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

Graph Neural Network

charged pion

electron
Longitudinal segmentation by timing in dual-readout fiber calorimeters

- Optical fibers inserted longitudinally and attached to SiPMs at 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 $O(10\text{ps})$ and $O(10\text{um})$ 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.]

- **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

Detection of high energy muons with sub-20 ps timing resolution using L(Y)SO crystals and SiPM readout [Benaglia, et. al.]
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, …
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/cm²) depending on electronics

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

**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.


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<tbody>
<tr>
<td>ETROC</td>
<td>LGAD</td>
<td>65</td>
<td>1300x1300</td>
<td>~ 40</td>
<td>0.3</td>
</tr>
<tr>
<td>ALTIROC</td>
<td>LGAD</td>
<td>130</td>
<td>1300x1300</td>
<td>~ 40</td>
<td>0.4</td>
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<tr>
<td>TDCpix</td>
<td>PIN</td>
<td>130</td>
<td>300x300</td>
<td>~ 120</td>
<td>0.32 matrix + 4.8 periphery</td>
</tr>
<tr>
<td>TIMEPIX4</td>
<td>PIN, 3D</td>
<td>65</td>
<td>55x55</td>
<td>~ 200</td>
<td>0.4 analog + 0.3 digital</td>
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<tr>
<td>TimeSpot1</td>
<td>3D</td>
<td>28</td>
<td>55x55</td>
<td>~ 30 ps</td>
<td>3.5</td>
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<tr>
<td>FASTPIX</td>
<td>MAPS</td>
<td>180</td>
<td>20x20</td>
<td>~ 130</td>
<td>5-10</td>
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<tr>
<td>miniCACTUS</td>
<td>MAPS</td>
<td>150</td>
<td>50x100</td>
<td>~ 90</td>
<td>0.15 – 0.3</td>
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<tr>
<td>MonPicoAD</td>
<td>MAPS</td>
<td>130 SiGe</td>
<td>100x100</td>
<td>~ 36</td>
<td>1.8</td>
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<tr>
<td>Monolith</td>
<td>Multi Junct. MAPS</td>
<td>130 SiGe</td>
<td>100x100</td>
<td>~ 25</td>
<td>0.9</td>
</tr>
</tbody>
</table>

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

\[ \sigma_t^2 = \sigma_{\text{Landau}}^2 + \sigma_{\text{timewalk}}^2 + \sigma_{\text{jitter}}^2 + \sigma_{\text{TDC}}^2 + \sigma_{\text{clock}}^2 \]

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)

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

\[ \sigma_{\text{jitter}} = \frac{N}{dV/dt} \propto \frac{t_{\text{rise}}}{S/N} \]

- TDC quantization error (bin size)
  - ATLAS/CMS 20-30ps ToA
  - ATLAS/CMS 40-100ps TOT
  - \[ \sigma_{\text{TDC}} = \frac{\text{bin size}}{\sqrt{12}} \sim 7\text{ps} \]