Precision Timing with the CMS MIP Timing Detector

ICHEP 2018 Seoul
July 5th, 2018

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Outline:
– motivations for precision timing at the HL-LHC
– overview and performance of the proposed detector
– beam test results and ongoing R&D
Challenges at HL-LHC

- The **High Luminosity phase** of LHC (HL-LHC) foresees:
  - **baseline**: $L_{\text{inst}} = 5.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
    140 pileup events, $\sim 1.2$ vertex mm$^{-1}$
  - **ultimate**: $L_{\text{inst}} = 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
    200 pileup events, $\sim 1.9$ vertex mm$^{-1}$

Real-life event from a high PU run in 2016
\( \sqrt{s} = 13 \text{ TeV} \quad \text{PU} = 100 \)
Challenges at HL-LHC

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- The full CMS physics program at HL-LHC would benefit from an effective **pileup (PU) mitigation** that allows **current PU\( \sim 30–50 \text{ performance} \)** to be maintained at high pileup
  - **Pileup mitigation**: reject charged particles not associated with the hard interaction (PV)
  - **Optimized selection**: \(|\Delta z(\text{track}, \text{PV})| < 1 \text{ mm.} \)
    - \( \Rightarrow \) **non-negligible contamination for vertex density \( > 1 \text{ mm}^{-1} \)**
Pileup mitigation with track timing

• Precision track timing allows:
  – 4D vertex reconstruction
    ⇒ resolve vertices that are close in space but separated in time
  – additional requirement in track-PV association: $|\Delta t(\text{track}, \text{PV})| < 3 \cdot \sigma_t$
    ⇒ suppress spurious pileup tracks

• With ~30 ps resolution, effective vertex line density as for current LHC
Impact on Higgs physics

- A hermetic precision timing detector allows a **20-30% gain in effective integrated luminosity** across multiple channels (at constant rejection power for reducible background)
  - 5-10% efficiency gains on single objects
    » vertex identification, lepton isolation sums, secondary vertices (b-tag), jets, etc.
  - large gains on multi-object final states

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Ex. 1: $HH \rightarrow bb\gamma\gamma$

Ex. 2: $H \rightarrow ZZ \rightarrow 4l$
Impact on BSM and LLP searches

- 40% reduction of reducible backgrounds for $\vec{p}_{T}^{\text{miss}}$ tails above 140 GeV
  $\Rightarrow \gtrsim 100$ GeV extension of the mass reach for several $\vec{p}_{T}^{\text{miss}}$-based searches

- Enhancements for massive Long Lived Particles (LLP) searches:
  
  - **extension of search reach** for massive LLP decaying to photons combining vertex and calorimeter timing for photon TOF measurements

Ex. 1: $\chi_{1}^{0} \rightarrow G + \gamma$

- allowing a fundamentally new approach through the reconstruction of a peaking mass variable for LLPs searches involving secondary vertices
MTD design overview

• Proposed MIP Timing Detector (MTD):
  – thin layer between tracker and calorimeters, minimal impact on cal.
  – ~30 ps resolution for charged tracks (above 0.7 GeV)
  – hermetic coverage for $|\eta| < 3.0$

Barrel: LYSO tiles + SiPM readout
• at tracker-ECAL interface, 25 mm thick
• 40 m$^2$ — 250k channels
• radiation (4/ab): $2 \times 10^{14}$ n$_{eq}$/cm$^2$
• Integration with tracker in 2022

Endcap: Si with internal gain (LGAD)
• on the CE nose, 42 mm thick
• 12 m$^2$ — 4M channels
• radiation (4/ab): $2 \times 10^{15}$ n$_{eq}$/cm$^2$
• Integration with tracker in 2024
Barrel detector design

**Fundamental detector unit**

- Operated at -30° C
- SiPM active area limited to < 16 mm² (radiation-induced noise and power dissipation considerations)

**Electronics**

- ASIC: TOFHir (adapted from commercially-available TOFPET)
  - leading edge discrimination + amplitude measurement for time-walk corrections
- Front-end boards: ASIC + power distribution + clock & data links (LpGBT)
  - 1.2 TB/s data volume

**Integration with tracker**

- Barrel modules assembled in “trays”
- Trays inserted and embedded in the Tracker Support Tube

**Challenge:**
cope with SiPM dark count rate expected after irradiation
Crystal+SiPM beam tests and R&D

- **Target timing resolution** demonstrated at beam tests:
  - however, **timing dependence on hit position** on the tile observed

- Hardware solutions being considered:
  - tailored SiPM with **uniform tile surface coverage** at **constant active area** (Large Area Sparse Cell SiPM)
    » response is uniform by construction, but large Si area
  - replace **crystal** tiles with **bars** (dimensions $3\times3\times45$ mm$^3$), read out on both sides (measure $t_1$ and $t_2$)
    » $\langle t_1+t_2 \rangle$ is ~ independent on position
    » position information deduced from $t_1-t_2$
Endcap detector design

**Fundamental detector unit**

- Low-gain avalanche diode (LGAD), typical gain: 10-30
- 1×3 mm² pads
- 3-to-1 ganging for |\( \eta \) | < 2.1

**Endcap module**

- Module size: 50×100 mm²
- LGAD sensor size: 48×96 mm²
- 1536 pads/module

**Endcap disk**

- Overlapping 2-disk structure on HGCal “nose”
- Al wedges with embedded cooling pipes (CO₂, -30° C)

**Read out**

LGAD sensor ASIC

- ASIC (design ongoing): pre-amp. + disc. + ToA + TDC

**Challenge:**

ASIC with ~20 ps resolution
LGAD beam tests and R&D

- **Target timing resolution** demonstrated at **beam tests**:  
  - $< 40$ ps throughout the whole HL-LHC (up to $1-2 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$)  
  - resolution maintained increasing bias voltage ($300 \text{ V} \rightarrow 600 \text{ V}$)

- **R&D activity**:  
  - improve radiation resistance (reduce need of bias voltage increase)  
  - increase sensor fill factor (detector has 1! sensitive layer)  
  - increase sensor dimension
Summary

• The capability of measuring the time of charged tracks with ~30 ps precision is a powerful tool for pileup mitigation at the HL-LHC

• Significant performance gains have been outlined for a wide range of physics channels that are critical for the HL-LHC program

• The CMS Collaboration has proposed a hermetic MIP timing detector with maximal $p_T$ and $\eta$ coverage for charged tracks
  – complementing timing measurements from upgraded calorimeters

• The project is well advanced, R&D on sensor and ASIC optimization is progressing to ensure the timing performance can be maintained until the end of HL-LHC operations
Bonus material
Lepton isolation and b-tagging

- **Isolation**: at 97% efficiency working point, recover ~6-7% off at the same background rejection

- **b-tagging**: removal of tracks with incompatible time with PV reduces the number of spurious secondary vertices by 30%; no-PU performance almost recovered, esp. for tight working points
## Summary of impact on various benchmark channels

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<tr>
<th>channel</th>
<th>physics measurement</th>
<th>timing detector impact</th>
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<tbody>
<tr>
<td>$H \rightarrow \gamma\gamma$</td>
<td>+25% statistical precision on $\sigma \Rightarrow$ couplings</td>
<td>Isolation, vertex identification</td>
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<tr>
<td>$H \rightarrow ZZ \rightarrow 4l$</td>
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<tr>
<td>$qqH \rightarrow \tau\tau$ (VBF)</td>
<td>+25% statistical precision on $\sigma \Rightarrow$ couplings</td>
<td>Isolation, VBF jet tagging, MET</td>
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<tr>
<td>$HH \rightarrow bb\gamma\gamma$</td>
<td>+25% gain in signal yield $\Rightarrow$ consolidate searches</td>
<td>Isolation, b-tagging</td>
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<tr>
<td>EWK SUSY</td>
<td>40% red. background reduction $\Rightarrow +150$ GeV mass reach</td>
<td>MET tail reduction</td>
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<td>Long-lived particles (LLP)</td>
<td>peaking variable reconstruction $\Rightarrow$ unique discovery potential</td>
<td>$\beta_{LLP}$ from displaced vertices</td>
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