Precision Timing with the CMS MIP Timing Detector

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On behalf of the CMS Collaboration.

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Introduction

- HL-LHC upgrade will increase beam intensity to achieve $O(10)$ increase in instantaneous luminosity:
  - Baseline: peak $L = 5.0 \times 10^{34} \text{ cm}^{-1}\text{s}^{-1}$
  - Baseline: peak $L = 7.5 \times 10^{34} \text{ cm}^{-1}\text{s}^{-1}$
- Pileup increases as instantaneous luminosity

Density of pp collisions per unit distance along beam axis
Impact of pileup in CMS

• Due to the increased line density, a larger number of spurious (pileup) tracks are associated to the primary vertex

• In the ultimate scenario, at the leveled luminosity, 30% of tracks associated to the PV are spurious
Using Precision Timing to Mitigate Pileup

- Time-of-arrival measurement can discriminate between collisions occurring very close in space, but separated in time.
- Suppress spurious track-to-PV association by more than factor of 3
Pileup Mitigation with Timing

- Lepton and Photon isolation improves by using timing information
- At 97% efficiency working point, recover ~6-7% off at the same background rejection
- For precision measurements it’s critical to maintain low fake lepton background due to large systematic uncertainties
Significant Impacts on Physics Reach I

• Significant impact on HL-LHC Higgs program
  - 26% increase in effective luminosity for $H \rightarrow ZZ \rightarrow 4\ell$
  - 22% increase in effective luminosity for $HH \rightarrow bb\gamma\gamma$
  - 25% increase in effective luminosity for $VBF H \rightarrow \tau\tau$
Significant Impacts on Physics Reach II

• New window to probe Long-lived particles.
  - Vertex timing enhances Long-lived particle physics program
  - In topologies involving secondary vertices, **MTD provides a unique handle to reconstruct the mass of the long lived NEUTRAL particles (eg. \( \chi^0 \))**

\[
\begin{align*}
\text{(a) } & \chi_1^0 \rightarrow G + \gamma \text{ Limits}
\end{align*}
\]

\[
\begin{align*}
\text{(b) } & \chi_1^0 \rightarrow G + Z \text{ Peaking variable}
\end{align*}
\]
Significant Impacts on Physics Reach III

- New window to probe Long-lived particles.
  - Vertex timing enhances Long-lived particle physics program
  - Using ISR particle to reconstruct vertex time

Recent paper in Arxiv

Significant reach
Improvement in
- Lifetime
- Mass

Arxiv: 1805.05957 J.Liu, Z. Liu, LT Wang
MTD Design Overview

MTD design overview

- Thin layer between tracker and calorimeters
- MIP sensitivity with time resolution of ~30 ps
- Hermetic coverage for |η|<3

BARREL
- TK/ECAL interface ~ 25 mm thick
- Surface ~ 40 m²
- Radiation level ~ 2x10^{14} n_{eq}/cm²
- Sensors: LYSO crystals + SiPMs

ENDCAPS
- On the CE nose ~ 42 mm thick
- Surface ~ 12 m²
- Radiation level ~ 2x10^{16} n_{eq}/cm²
- Sensors: Si with internal gain' (LGAD)
# Technology Choice and Considerations

<table>
<thead>
<tr>
<th>Coverage</th>
<th>Barrel LYSO+SiPM</th>
<th>Endcap LGAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt; 1.5$</td>
</tr>
<tr>
<td>Surface Area</td>
<td>$\sim 36.5 \text{ m}^2$</td>
<td>$\sim 12 \text{ m}^2$</td>
</tr>
<tr>
<td>Power Budget</td>
<td>$\sim 0.5 \text{ kW/m}^2$</td>
<td>$\sim 1.8 \text{ kW/m}^2$</td>
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<tr>
<td>Radiation Dose</td>
<td>$\leq 2\times10^{14} \text{ neq/cm}^2$</td>
<td>$\leq 2\times10^{15} \text{ neq/cm}^2$</td>
</tr>
<tr>
<td>Installation Date</td>
<td>2022</td>
<td>2024</td>
</tr>
</tbody>
</table>

- **Barrel Timing Layer (LYSO+SiPM)**
  - Larger surface area
  - Lower radiation dose
  - Mature readout ASIC technology

- **Endcap Timing Layer (LGAD)**
  - Larger radiation dose
  - More flexible installation schedule → time for R&D
  - R&D synergies with ATLAS
BTL Sensor Performance

Single sensor performance requirement demonstrated

30 ps resolution demonstrated

![SiPM and wrapped crystal tile](image)

- $\sigma_t = 34$ ps (uncorrected)
- $\sigma_t = 21$ ps (t-fold correction)
- $\sigma_t = 30$ ps (no wrapping)
- $\sigma_t = 30$ ps (rear wrapping)
- $\sigma_t = 27$ ps (rear + front wrapping)
Barrel Timing Layer Design

- 11.5x11.5 mm² LYSO tiles
- 4x4 mm² SiPM
- 250k channels

BTL tray in the rails of the tracker support tube (TST)

- CO₂ cooling
- Fully tested trays (20 kg) inserted into TST
Barrel Timing Layer Electronics

- **TOFHIR ASIC:**
  - Overall chip integration close to finalization
- **Front-end boards:**
  - Engineering design of readout units boards concluded
  - Concentrator card and adapter board at hand
- **Front-end board demonstration:**
  - Nov: board assembled with chip
  - 2019 Q1: board fully validated

![Image of electronics layout and concentrator card](image-url)
Endcap Design

- Low-gain avalanche diode (LGAD) are silicon sensor with a special avalanche gain-layer
  - Typical gain: 10-30

- Overlapping disk structure

- 1x3 mm$^2$ sensor channels
- Total 1.8 M channels
ETL Sensor Performance

• Target performance has been achieved for sensors irradiated up to fluence of $1.5 \times 10^{15}$ eq. neutrons

30 ps resolution up to $1.5 \times 10^{15}$ demonstrated
Sensor performance

- Target performance has been achieved for sensors irradiated up to $1.5 \times 10^{15}$ eq. Neutrons
- Sensor uniformity precisely measured. Meets specification
- Efficiency $\sim 100\%$

Figure 11: Signal amplitude MPV measurement across the X-axis of the HPK 50A-, 50B-, 50C-, and 50D-PIX sensors mounted on the KU board. The scan of pixels 1 and 2 along the X-axis, and pixel numbering scheme is defined in Fig. 3.

Figure 13: Time resolution measurements as a function of the X position of the beam particle for the HPK 50A-, 50B-, 50C-, and 50D-PIX sensors mounted on the KU board. The scan of pixels 1 and 2 along the X-axis is shown. The pixel numbering scheme is defined in Fig. 3.
ETL Sensor R&D

- New Production addressing:
  - Increased radiation tolerance
  - Large sensor production
  - Improved fill factor

Conceptual design of HPK mask

FBK and CNM
They are also underway
ETL Sensor R&D

• New Production addressing:
  - Increased radiation tolerance
  - Large sensor production
  - Improved fill factor

NEW sensor to be test at FNAL
In a few weeks
ETL R&D: ASIC and readout

- One chip is matrix of ~100 LGAD pixels:
  - Measurement of Time-of-Arrival in every pixel within 25 ns LHC BX with 30 ps time resolution for the whole system.
- Chip development lead by Fermilab:
  - TSMC 65nm: experience, library, rad. dam. models from RD53
  - Ongoing design study of the preamp and CFD implementation
  - Exploring the possibility of common developments with ATLAS
Summary

• CMS MIP Timing Detector will significantly improve detector capabilities and expand physics reach for the HL-LHC program
  - 20-25% effective luminosity increase in crucial Precision Higgs Measurements
  - Expands reach for BSM searches using MET
  - Enables new capability to probe long-lived particles
• Project is significantly advanced.
  - Sensor performance close to specification
  - ASIC and Integration efforts ongoing
• Progress on sensor R&D, beam tests, and engineering design.
  - Optimize sensors to ensure 30 ps time resolution throughout the HL-LHC run
R&D advancing on SiPMs to improve light collection efficiency and uniformity

- Large Area Sparse SiPM
- Ordered:
  - 25 of 20μm pitch
  - 25 of 15μm pitch
  - 10 assembled with 11.5x11.5 crystal
- Delivery in Sept 2018