Precision Timing with the CMS Detector

CIPANP 2018

Irene Dutta
On behalf of the CMS Collaboration
Outline

● Future of the LHC: The case for a Timing detector

Design of the MIP Timing Detector (MTD):

● Barrel Timing Layer at the CMS
● Endcap Timing Layer at the CMS
LHC’s future

- Upgrade to High Luminosity-LHC (HL-LHC) by year 2026
- Operation at stable luminosity of \(5.0 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}\) (140 PU)
- Ultimate luminosity of \(7.5 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}\) (200 PU)
- More collisions at the same energy!

Number of pp collisions per unit length of beam axis

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Physics at the HL-LHC

Advantages

- Better chances of finding BSM phenomena
- SM measurements with increased precision

Challenges

- Greater spatial overlap between particles → failure of the existing Particle Flow algorithm
- Track-vertex association
- Acceptance reduction for isolated objects
- Reduced resolution on missing transverse momentum and jet energies etc

What’s the solution to this challenge?
The CMS Detector
The new CMS Detector
The case for a Timing Detector

- Time of arrival measurement can separate collisions very close in space but separated in time.
- Slice bunch crossing in exposures of 30 ps.
- PU levels drop to current LHC levels.
The case for a Timing Detector

Physics Impact (see more in Olmo’s talk!)

- $HH \rightarrow 4b$: increase in signal yields by 15-20%
- $H \rightarrow 4\mu$: increase in signal yields by 20-26%
- $HH \rightarrow bb\gamma\gamma$: barrel yield increases by 17% and 22% with hermetic coverage
- Improved MET resolution in the tails almost overcomes the increased pileup effect → good for BSM searches
MIP Timing Detector

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 ~ $2 \times 10^{14}$ n$_{eq}$/cm$^2$
- Sensors: LYSO crystals + SiPMs

ENDCAPS
- On the CE nose ~ 42 mm thick
- Surface ~ 12 m²
- Radiation level ~ $2 \times 10^{14}$ n$_{eq}$/cm$^2$
- Sensors: Si with internal gain (LGAD)
# MIP Timing Layer Technology

<table>
<thead>
<tr>
<th></th>
<th>Barrel (LYSO:Ce+SiPM)</th>
<th>Endcap (LGAD)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Region</strong></td>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td><strong>Surface Area</strong></td>
<td>36.5 m$^2$</td>
<td>12 m$^2$</td>
</tr>
<tr>
<td><strong>Power consumption</strong></td>
<td>0.5 kW/m$^2$</td>
<td>1.8 kW/m$^2$</td>
</tr>
<tr>
<td><strong>Radiation Dose</strong></td>
<td>$2 \times 10^{14}$ n$_{eq}$/cm$^2$</td>
<td>$2 \times 10^{15}$ n$_{eq}$/cm$^2$</td>
</tr>
<tr>
<td><strong>Installation Date</strong></td>
<td>2022</td>
<td>2024</td>
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</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 Technology
Silicon photomultiplier (SiPM)

- Fast photodetectors with single photon time resolution (SPTR) better than 50 ps RMS.
- Low operating voltages
- Immune to magnetic field and radiation tolerant
- Mass produced and cheap.
Sensor performance

30 ps resolution demonstrated

CERN-LHCC-2017-027/LHCC-P-009

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BTL Readout 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
BTL Design

- 11x11 mm$^2$ LYSO tiles
- 4x4 mm$^2$ SiPM
- 250 k channels

- Cooling with CO$_2$ shared with the tracker
- Trays (~20 kg) into the tracker support tube
ETL Technology
ETL Design

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

- Modules with odd numbered rings mounted on the first wheel of the ETL.

- Even-numbered rings on separate disk located 2 mm in z closer to IP

- Rings designed for full radial coverage with both disks combined

- Double disk structure
- 1x3 mm² sensor size
- Total 1.8 M channels
Sensor Performance

arXiv: 1707.04961

30 ps resolution upto $1.5 \times 10^{15}$ $n_{eq}$
Sensor Performance

- Uniformity across sensor
- 100% Efficiency

A. Apresyan et al., NIM A, Volume 895, 2018, Pages 158-172, ISSN 0168-9002
ETL Sensor R&D

New Production addressing:

- Increased radiation tolerance
- Large sensor production
- Improved fill factor

Conceptual design of HPK Mask
ETL Sensor R&D

New Production addressing:

- Increased radiation tolerance
- Large sensor production
- Improved fill factor

New sensors to be tested 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 technology:** We have experience, all the libraries and radiation damage models from RD53 collaboration
- Ongoing design study of the preamp and time tagging implementation
- Exploring the possibility of common developments with ATLAS
Conclusions

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
Thank you for your attention!
Backup
Silicon photomultiplier (SiPM)

- Pixelated devices with arrays of microcells in parallel.
- Microcell: an avalanche photodiode (APD) and a quenching resistor in series.
- An impinging photon causes an avalanche in the depletion region of APD generating $10^5 - 10^6$ electrons.

Figure from Hamamatsu Photonics.

Figure from SensL’s note on SiPMs.
Lutetium intrinsic radioactivity

http://arxiv.org/abs/1501.05372
Fixed threshold triggering causes a dependence of the trigger time on the signal's peak height known as **time walk**.

**Constant fraction discriminator** - Identical rise times and peak shapes yield trigger times independent from peak heights.

The readout electronics for the LYSO+SiPM : TOFPET2 chip[1].

- 64 channel ASIC based on CMOS 110 nm technology.
- Two outputs per channel - time and energy.

The actual readout chip for BTL: modified version of the TOFPET2 chip (TOFHIR).

**Advantages of TOFHIR:**
- Small detector area
- High input rate

TOFPET thresholds

- TH1 threshold for time stamp (for optimum PET time resolution).
- TH2 threshold for charge integration start (for dark counts and low pulse rejection).
- TH3 threshold for event filtering based on the amplitude (to trigger the event).
Timing Box and BTL module (FNAL Testbeam December 2017)

Beam
BTL module on ASIC board

TOFPET Front End Board
MCP-PMT

LYSO+SiPM : Teflon wrapped

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