Precision timing for the High Luminosity Upgrade of CMS

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Fully exploiting the High Luminosity LHC (HL-LHC) necessitates significant upgrades:

- Higgs studies with better precision, including exotic decay searches
- Searches for rare heavy particles associated with supersymmetry (SUSY) and other Standard Model (SM) extensions
- Searches for long-lived or non-interacting particles

CMS upgrade philosophy: equal or better performance under HL-LHC conditions
Current CMS Phase 2 upgrade plan

Silicon tracker
- Full replacement (Si bulk defects)
- 4× increased granularity
- L1 triggering
- Reduced mass

Endcap calorimeter
- Full replacement (light loss)
- High granularity sampling calorimeter using silicon and scintillator sensors as active material

Barrel electromagnetic calorimeter (ECAL)
- Front end electronics upgrade to meet trigger requirements
- Single crystal trigger primitives
- Cooling to 8°C to reduce dark-current-induced noise

<PU> = 140

750 kHz Level-1 trigger accept rate

Endcap muon detector
- Replacement of radiation-damaged electronics
- Front end electronics upgrade to meet trigger requirements
- Increased redundancy
- Possible extension to higher η
Vertex merging at high PU

- Current CMS detector upgrades address increased pileup with increased channel granularity.
- In 140-200 PU events, granularity may not be enough.

<table>
<thead>
<tr>
<th>&lt;PU&gt;</th>
<th>3D merged vertex fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>3.3%</td>
</tr>
<tr>
<td>200</td>
<td>13.4%</td>
</tr>
</tbody>
</table>

CMS Simulation $<\langle PU \rangle> = 50$

- Simulated Vertices
- 3D Reconstructed Vertices
- 4D Reconstructed Vertices
- 4D Tracks

CMS Simulation $<\langle PU \rangle> = 200$

- Simulated Vertices
- 3D Reconstructed Vertices
- 4D Reconstructed Vertices
- 4D Tracks

Few merged vertices at 50 PU

Many merged vertices at 200 PU

CMS-DP-2016-008

CMS-DP-2016-008
Effects of vertex merging

- Track associated to wrong primary or secondary vertex
  - Jet identification suffers
  - Wrong isolation energy sum calculated → photon and lepton identification suffers
- Vertex with highest activity incorrectly identified → diphoton mass resolution suffers
- All effects lead to a degradation of jet and missing transverse energy ($ME_T$) resolution
- All effects increase the trigger bandwidth consumed by uninteresting PU interactions

Blue solid: minimum bias
Black dashed: $Z \rightarrow \mu \mu$ hard scatter
Red dotted: minimum bias with 100% $2 \rightarrow 1$ vertex merging
Partial mitigation with upgrade detector

- $H \rightarrow \gamma\gamma$ events
- Assumed 30 ps time resolution on high energy photons from Higgs decay
- Vertex $z$ position estimated from timing of two candidate Higgs decay photons
- Phase 1 performance: 10 mm precision on vertex location \textit{accuracy}, i.e. 10 mm Gaussian spread in $|\text{true vertex } z - \text{reconstructed vertex } z|$
Partial mitigation with upgrade detector

The information of the 4D vertices. A triple coincidence, seen at (2.4 cm, -0.05 ns), of the photons from the hard scatter, in green, can be cross referenced with the time measurement of each photon. A common vertex position is defined via minimization of:

$$\sum_{i=1,2} \left[ t_i - \left( z_i - \left( \frac{1}{\gamma} \cdot \frac{1}{c} \cdot v \right) \right) \right]$$

where $t_i$ is the measured time of each photon, $z_i$ is the reconstructed vertex position along the beam direction, $\gamma$ is the Lorentz factor, $c$ is the speed of light, and $v$ is the velocity of the photon.

Calorimeter timing is exploited to reconstruct a "virtual" vertex position using triangulation, as demonstrated schematically in the left plot, showing a zoom-in of the beamspot region in $(z,t)$.

For events with decay into photons with pseudorapidity gap of $|\Delta \eta| > 0.8$, the vertex can be located with an RMS precision of about 1 cm, as displayed in the right plot, showing the distribution of the distance between the virtual vertex and the true vertex position along the beam direction, z, for Gaussian resolutions of 30 ps in the measurement of the photon time. Decay into photons with $|\Delta \eta| < 0.8$ are shown in the left and right panel respectively. The red and green (right only) histograms show the results for the HL-LHC baseline optics, and for "Crab Kissing" optics with a luminous region time spread of 100 ps. The green histogram shows that the vertex location accuracy only marginally improves with the Crab-kissing optics, with a luminous region time spread of 100 ps.

For events with decay into photons with $|\Delta \eta| > 0.8$, roughly 50% of the events are shown. The red and green (right only) histograms show the results for the HL-LHC baseline optics, and for "Crab Kissing" optics with a luminous region time spread of 100 ps. The green histogram shows that the vertex location accuracy only marginally improves with the Crab-kissing optics, with a luminous region time spread of 100 ps. For the $|\Delta \eta| < 0.8$ events, the improvement is marginal over crab-crossing. For the $|\Delta \eta| > 0.8$ events, the vertex location accuracy improves significantly with the Crab-kissing optics, as shown in the right plot, with a luminous region time spread of 100 ps.
Need for additional timing information

- **Equal or better performance under HL-LHC conditions** may not be achievable without more effective PU rejection
- Precision timing of minimum ionizing particles (MIPs) adds a crucial independent handle on PU identification
  - **30 ps MIP timing resolution** effectively reduces PU in the 180 ps beamspot
  - Merged vertex rate reduced to ~current level
  - Isolation and jet ID performance comparable to current detector
Technologies under consideration

In front of ECAL barrel (EB)
- LYSO:Ce scintillating crystal layer
- Silicon photomultiplier (SiPM) readout

In front of ECAL endcap (EE)
- Silicon low gain avalanche detector (LGAD)
- Readout via bump bonded custom chip

Recall M. M. Obertino’s talk on Tuesday
BTL mechanics

- 2.40-3.75 mm thick LYSO:Ce crystal with $12 \times 12 \text{ mm}^2$ cross section glued to $4 \times 4 \text{ mm}^2$ SiPM

- Occupancy < 3% with 0.5 MIP threshold per channel

- 1 MIP ~ 5k pe

- Tile thickness decreases with increasing $|\eta|$ to maintain uniform material budget

- Cracks between tiles minimized with 0.5 mm edge overlap

- CO$_2$ cooling to -30°C to mitigate SiPM dark current
BTL tile time resolution

- Coincidence time resolution (CTR) measured in 150 GeV muon beam at CERN
- $\Delta t$ measured between 2 LYSO/SiPM tiles $\Rightarrow$ single-tile time resolution = CTR/\sqrt{2}
- Timewalk corrected single-tile resolution better than 25 ps in 2 different geometries
**BTL tile radiation hardness**

- **1.3-1.6 \times 10^{14} \text{n}_{\text{eq}}/\text{cm}^2** and **20 \text{kGy}** expected after 10 years of HL-LHC operation
- Radiation-induced absorption coefficient (RIAC) at **2 \times 10^{14} \text{p}/\text{cm}^2**
  - \sim 3 \text{ m}^{-1} \Rightarrow not a problem for 3 \text{ mm} tiles
- **Relative light loss \sim 10\%** at **100 \text{ kGy}** exposure
- Time resolution degradation from increased SiPM dark count rate (DCR): \sim 20 \text{ ps} \rightarrow \sim 40 \text{ ps}
- Room for optimization: reflective wrappings, smaller SiPMs, thicker tiles

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### Table 2.4: End-of-life specifications for the SiPMs of the barrel timing layer compared to the performance of existing devices of 4

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Spec</th>
<th>FBK</th>
<th>FBK</th>
<th>HPK</th>
<th>HPK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>&gt; 9 mm²</td>
<td>16 mm²</td>
<td>9 mm²</td>
<td>16 mm²</td>
<td>9 mm²</td>
</tr>
<tr>
<td>Cell pitch</td>
<td>-</td>
<td>12.5(\mu\text{m})</td>
<td>12.5(\mu\text{m})</td>
<td>15(\mu\text{m})</td>
<td>15(\mu\text{m})</td>
</tr>
<tr>
<td>Number of cells</td>
<td>&gt; 30k</td>
<td>&gt; 100k</td>
<td>&gt; 56k</td>
<td>&gt; 71k</td>
<td>&gt; 39k</td>
</tr>
<tr>
<td>PDE</td>
<td>&gt; 10%</td>
<td>10%</td>
<td>10%</td>
<td>15%</td>
<td>15%</td>
</tr>
<tr>
<td>Operating voltage</td>
<td>-</td>
<td>34V</td>
<td>34V</td>
<td>40V</td>
<td>40V</td>
</tr>
<tr>
<td>Current/device</td>
<td>-</td>
<td>0.7 mA</td>
<td>0.4 mA</td>
<td>1.3 mA</td>
<td>0.7 mA</td>
</tr>
<tr>
<td>Power consumption</td>
<td>&lt; 57 mW</td>
<td>25 mW</td>
<td>14 mW</td>
<td>52 mW</td>
<td>29 mW</td>
</tr>
<tr>
<td>Gain</td>
<td>&gt; 10^3</td>
<td>0.8 \times 10^3</td>
<td>0.8 \times 10^3</td>
<td>1.8 \times 10^3</td>
<td>1.8 \times 10^3</td>
</tr>
<tr>
<td>DCR/device</td>
<td>&lt; 70 GHz</td>
<td>41 GHz</td>
<td>23 GHz</td>
<td>43 GHz</td>
<td>24 GHz</td>
</tr>
</tbody>
</table>

PDE = photon detection efficiency
ETL mechanics

- LGAD concept
  - Extra p⁺ doping layer locally generates high electric fields for charge multiplication (gain ~ 20)
  - Thin sensor (50 μm) insures fast rise time
  - Both effects increase slew rate and time resolution
- 1 × 3 mm² LGAD pixels on 48 × 96 mm sensors
  - Occupancy <5%
  - Capacitance 7 pF
- 3→1 pixel ganging at low |η| after comparator stage
- CO₂ cooling to -30°C to mitigate dark current
ETL time resolution

- CTR measured in 180 GeV pion beam at CERN

- Δt measured between pairs of LGADs and between LGAD and SiPM

- For $V_{bias} > 200$ V, single LGAD time resolution better than 35 ps

<table>
<thead>
<tr>
<th>$V_{bias}$ [V]</th>
<th>200V</th>
<th>230V</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_t(N=1)$</td>
<td>34.1 ps</td>
<td>27.4 ps</td>
</tr>
<tr>
<td>$\sigma_t(N=2)$</td>
<td>24.2 ps</td>
<td>19.8 ps</td>
</tr>
<tr>
<td>$\sigma_t(N=3)$</td>
<td>19.9 ps</td>
<td>16.4 ps</td>
</tr>
</tbody>
</table>
ETL sensor radiation hardness

- Maximum expected HL-LHC fluence: $1 \times 10^{15} \text{n}_{\text{eq}}/\text{cm}^2$

- Gain decreases with irradiation, worsening time resolution as expected (slower slew rate)

- Timing performance can be recovered with higher bias voltage
4D vertexing

- Assuming 25 ps vertex timing resolution, mis-assignment of pileup tracks to hard interaction in HL-LHC conditions reduced to ~LHC levels

- Significant improvement even with timing layer $|\eta| < 3$

- Ambiguities in $H \rightarrow \gamma\gamma$ vertex location by triangulation much reduced by correlation with vertex timing
Isolation with precision timing

- $|t_{\text{track}} - t_{\text{vertex}}| < 4\sigma_{\text{time}}$
- Isolation efficiency nearly recovered to LHC levels
MET with precision timing

- Black and red: 2 different PU subtraction techniques
- Dashed (dotted): loose(tight) cuts on timing
- PU subtraction markedly improved with timing information
Conclusion

- To exploit the HL-LHC physics potential, significant upgrades to CMS are required
- 30 ps MIP timing provides crucial discriminating information for resolving 140-200 PU vertices
- Technology is within reach
LYSO-SiPM light collection efficiency

Geant4 Preliminary Simulation  LSO:Ce tile 12x12x3 mm$^3$ - SiPM 4x4 mm$^2$
LYSO radiation tolerance

Figure 8. The spectra of 0.511 MeV $\gamma$-rays from a $^{22}$Na source, measured by a Hamamatsu R1306 PMT (Left) and two Hamamatsu S8664-55 APDs (Right), with a coincidence trigger for four long LSO and LYSO samples from CTI, CPI, Saint-Gobain and SIPAT.

<table>
<thead>
<tr>
<th>Sample</th>
<th>LO (p.e./MeV)</th>
<th>ER (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTI-LSO-L</td>
<td>1100</td>
<td>11.3</td>
</tr>
<tr>
<td>CPI-LSO-L</td>
<td>1020</td>
<td>21.2</td>
</tr>
<tr>
<td>SG-LSO-L</td>
<td>1090</td>
<td>11.3</td>
</tr>
<tr>
<td>SIPAT-LSO-L</td>
<td>1080</td>
<td>11.4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>LO (p.e./MeV)</th>
<th>ER (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTI-LSO-L</td>
<td>1580</td>
<td>27.0</td>
</tr>
<tr>
<td>CPI-LSO-L</td>
<td>1310</td>
<td>42.9</td>
</tr>
<tr>
<td>SG-LSO-L</td>
<td>1610</td>
<td>25.5</td>
</tr>
<tr>
<td>SIPAT-LSO-L</td>
<td>1590</td>
<td>26.3</td>
</tr>
</tbody>
</table>

Figure 9. Left: The longitudinal transmittance spectra are shown as a function of wavelength in an expanded scale together with the photo-luminescence spectra for four LSO and LYSO samples before and after the irradiation with integrated doses of $10^2$, $10^4$ and $10^6$ rad. Right: The normalized light output is shown as a function of the integration dose for four long LSO and LYSO samples with PMT (top) and APD (bottom) as the readout devices.