Studies of precision time-tagging with scintillating crystals for the Phase-II upgrade of CMS

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High Luminosity – LHC (Phase-II)

**HL-LHC**: Upgrade of LHC and injectors to increase beam intensity
- \( L_{\text{inst}} > 5 \times 10^{34} \text{ cm}^{-1} \text{ s}^{-1} \), up to 140-200 pileup
- Ultimate integrated luminosity target of 3000 fb\(^{-1}\) (10x LHC) - baseline

**Experiments**: ATLAS and CMS upgrades for HL-LHC conditions
- Radiation hardness
- Mitigate physics impact of high pileup (more than 5x LHC)
Luminous region

- Luminosity leveled to “what the experiments can stand”
  - Adjust the beam transverse size at the interaction point ($\beta^*$ function)
  - $L_{\text{inst}} = 5.3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \rightarrow 140 \text{ pileup}$
  - $L_{\text{inst}} = 7.6 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \rightarrow 200 \text{ pileup}$
Proof of concept

- Real life event with HL-LHC-like pileup from special run in 2016 with individual high intensity bunches
  - One such collision every 25 ns at HL-LHC
Proof of challenge!

- Vertex merged in ~15% of the cases at 200 PU
  - Hardest reconstructed collision not necessarily the most interesting
- Incorrect association of tracks (and neutrals) with vertices
  - Degradation in local and global event observables
  - Incorrect reconstruction of the event kinematics

An interaction of interest at less than 1% of the collisions simultaneously recorded
Physics impact by example

- **VBF H→ττ** requires >40% more luminosity at 200 than 140 PU
- Jet fake rate and $E_T^{\text{miss}}$ resolution and tau isolation
- Searches with $E_T^{\text{miss}}$ less sensitive at 200 PU than 140 PU

Mitigation of pileup with precision timing

If beam-spot “sliced” in successive $O(30) \text{ ps}$ time exposures, effective pileup reduced by a factor 4-5:
- $\sim15\%$ merged vertices reduced to 2%
- Phase-I track purity of vertices recovered

$VBF H\rightarrow\tau\tau$ in 200 $pp$ collisions

Luminous region
- $t_{\text{RMS}} \sim 180 \text{ ps}$
- $z_{\text{RMS}} \sim 4.6 \text{ cm}$
**Bold aspects of CMS upgrade for Phase-II**

- Level-1 trigger accept rate 750 kHz
- Tracking information in “L1 track trigger”
- All silicon tracker with 4x granularity and extended acceptance
- High granularity endcap calorimeters
  - 3D development of showers

**Precision timing of all objects:**
- Timing in the electromagnetic calorimeters (barrel and endcap)
- **New MIP Timing Detector (MTD) just outside the tracker**
  - MIP timing with **30 ps precision** and almost full efficiency
  - Acceptance: $|\eta| < 3.0$ and $p_T > 0.7$ GeV
Example of time-aware vertexing

Event with 50 pileup collisions to ease eye analysis

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

EXAMPLES OF MERGED VERTICES IN 3D

4D reconstruction with track time information: \( \sigma \sim 25 \text{ ps} \)
Track-vertex association – with track timing

With timing, ‘effective vertex density’ down to LHC level!

1. Extend performance at 200 PU
2. Strengthen reconstruction at 140 PU
3. Provide robustness against adjustment of luminosity scenarios

Recovery from performance degradation in several observables
Performance gain: one example

Isolation efficiency for constant background rejection power

- Performance degradation due to pileup offset by time aware reconstruction
  - [Gain also in pileup jet rejection, missing energy reconstruction, etc.]
MTD: technologies under study

- Immunity to magnetic field (3.8 T)
- Radiation: $2\times10^{14}$ (barrel) and up to $2\times10^{15}$ n/cm$^2$ (endcap)
- Minimal impact on the calorimeters performance
- Schedule, power, service, and space constraints

**LYSO/LSO tiles with SiPM readout:**
- At the end of the tracker
- Surface $\sim 40$ m$^2$
- Installation - 2023

**Si with internal gain (LGAD):**
- In front of the new endcap ECAL
- Surface $\sim 9$ m$^2$
- Installation - 2025
Barrel timing layer (BTL) layout

- LYSO/LSO:Ce + SiPMs embedded in the tracker support tube
- Production-ready and scalable technology
- CO₂ cooling at ~ −30 °C (limit SiPMs self-heating and dark rate)

~40 m²
4k modules
250k channels

1 tray, 2 half trays

Modules (16x4 crystals)

Readout on L1-trigger-Accept

- 3% occupancy (0.5 mip threshold)
- Adapt TOFPET2 ASIC
  Leading edge timing + amplitude meas.

Variable thickness to maintain a uniform material budget
BTL tile time resolution

- **Nominal geometry:** 11 x 11 mm$^2$ + 4 x 4 mm$^2$ SiPMs
  - Slant thickness $\sim$ 4 mm

- **Production-like geometries qualified in test beams**
  - Aligned crystals in a parallel beam or impact point restricted
  - Amplitude-walk correction

\[
\begin{align*}
10 \times 10 \times 3 \text{ mm}^3 &- \text{HPK 6} \times 6 \text{ mm}^2 \\
\sigma_{CT} / \sqrt{2} &\approx 21 \text{ ps} \\
11 \times 11 \times 3 \text{ mm}^3 &- \text{FBK 5} \times 5 \text{ mm}^2 \\
\sigma_{CT} / \sqrt{2} &\approx 27 \text{ ps}
\end{align*}
\]
BTL ASIC tests

- TOFPET2 resolution close to NINO + waveform digitizer
  - Time resolution RMS: 37 ps  [25 ps with NINO, same setup]
- Reasons for the difference understood
  - Pulse slew rate (amplifier configuration) and TDC contribution
  - Will be corrected in BTL tailored ASIC (TOFHiR)
  - Radiation hard design in parallel
SiPMs+Crystal optimization

- Small area SiPMs preferable (mandatory)
  - Dark Count Rate (DCR) and power consumption with radiation
  - Capacitance

- Large area SiPMs provide better resolution:
  - $\text{CTR}/\sqrt{2}$ of two 10x10 mm$^2$ crystals in a parallel beam
  - Time-walk correction applied

- Not only a photon detector efficiency (PDE) effect…
Dependence on the impact point

- Amplitude variation [light collection efficiency]
- $\Delta t$ relative to a reference MCP [light path/components variation]

- Requires position dependent correction with $\sim$2 mm precision
- Or more uniform surface coverage (at constant active area)

RMS $\sim$50-60 ps
Dependence on the angle of incidence

- Time resolution independent of the angle
  - After amplitude walk and position correction (universal)

Amplitude variation
[slant depth effect]

Time resolution

11x11 x 3 mm$^3$ – FBK 5x5 mm$^2$
BTL tile radiation hardness

- Radiation fields at the end of HL-LHC
  - Fluence: $1.3-1.6 \times 10^{14} \text{n}_{eq}/\text{cm}^2$
  - Dose: 20 kGy

- LYSO tiles:
  - Negligible induced radio-luminescence and light loss [ RIAC = 3 m$^{-1}$ at $1 \times 10^{15}$ cm$^2$ and 100 kGy ]

- SiPMs: Time resolution degradation from increased DCR: 20 ps $\rightarrow$ 40 ps
  - Lines: resolution from simulation with different PDE and DCR
  - Points: extrapolation to $2 \times 10^{14} \text{n}_{eq}/\text{cm}^2$ of SiPMs irradiation studies
  - [A. Heering et al. NIMA 824 (2016) 111]

- Room for optimization: reflective wrappings, SiPMs size / layout, thicker tiles, …
Why LYSO/LSO?

- Well characterized for PET scanners and EM calorimeters
  - Available, radiation hard, relatively fast and bright
  - Matches the target performance for this application

- Yet, not necessarily the best choice for MIP timing with leading edge time discrimination
  - Photons beyond $\sim100$ ps not exploited
  - High Z unnecessary (unwanted)
    - Radiation length grows with Z (in front of a calorimeter)
    - Scintillation yield scales with the mass thickness ($\rho d$)
    - Cherenkov yield scales with the thickness ($d$)
  - Cost is relatively high compared to other crystals

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<tr>
<th></th>
<th>n</th>
<th>$X_0$ [cm]</th>
<th>d [mm]</th>
<th>d [(X$_0$)]</th>
<th>C Yield</th>
<th>Scint. Yield [first 40 ps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSO/LYSO</td>
<td>1.8</td>
<td>1.1</td>
<td>3</td>
<td>0.27</td>
<td>80 / eV</td>
<td>~90</td>
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- In want of a fast crystal with $d_{\text{max}} < 6$ mm and $<0.3$ $X_0$
Summary

- The exploitation of the HL-LHC physics potential requires significant upgrades to CMS
- 30 ps MIP timing provides crucial discriminating information for resolving 140-200 PU vertices
  - *Phase-I track purity of vertices recovered at 200 PU*
- Technology is within reach:
  - Room for significant optimization: crystal choice, SiPM selection and optimization and SiPM+Crystal matching