Physics with precision timing at HL-LHC in ATLAS and CMS

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on behalf of the ATLAS and CMS collaborations

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Motivation: pileup at the HL-LHC ($\mathcal{L} = 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$)
The solution: Exploit the *time dimension* of the beam spot
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- Tracks coming from highlighted $z$ region can look like they’re from the same vertex
- Expect up to $\sim 10$ vertices in $z$ region the size of $\sigma(z_0)$

![Graph showing bunch charge and vertex density over time and position along z]
The solution: Exploit the *time dimension* of the beam spot

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- Expect up to $\sim 10$ vertices in $z$ region the size of $\sigma(z_0)$

High-precision timing measurements can resolve spatially overlapping vertices!

(NB! At $v = c$, 1 mm corresponds to 3 ps
\[\Rightarrow\] Primary gain is *not* improved position from time-of-flight, but from knowing *times of vertices*)
The detectors
ATLAS: High-Granularity Timing Detector (HGTD)

Focus on challenging forward region

- Two endcap disks at $z = \pm 3.5$ m, instrumenting $120 \text{ mm} < R < 640 \text{ mm}$
  $\Rightarrow 2.4 < |\eta| < 4.0$

- Radiation up to $5.6 \times 10^{15} \text{n}_{eq} / \text{cm}^2$ fluence, $3.3 \text{ MGy TID (incl. safety)},$
  and very limited space
  $\Rightarrow$ Low Gain Avalanche Diodes

- $1.3 \times 1.3 \text{ mm}^2$ pitch, $6.4 \text{ m}^2$
  active area $\Rightarrow$ 3.6M channels

Several layers give typically 2–3 hits per track $\Rightarrow \sigma_t \lesssim 30–50 \text{ ps/track}$
CMS: MIP Timing Detector (MTD) - full coverage for $|\eta| < 3.0$

BTL: L(Y)SO bars + SiPM readout:
- TK/ECAL interface ~ 45 mm thick
- $|\eta| < 1.45$ and $p_T > 0.7$ GeV
- Active area ~38 m$^2$; 332k channels
- Fluence at 3 ab$^{-1}$: $2 \times 10^{14}$ n$_{eq}$/cm$^2$

ETL: Si with internal gain (LGAD):
- On the HGC nose ~ 65 mm thick
- $1.6 < |\eta| < 3.0$
- Active area ~14 m$^2$; ~8.5M channels
- Fluence at 3 ab$^{-1}$: up to $2 \times 10^{15}$ n$_{eq}$/cm$^2$
Impact on performance of physics object reconstruction
Pileup-jet rejection: ATLAS

1. “Self-tagging”: require consistent times for tracks in jet

2. Require jet time consistent with hard-scatter vertex time \( (t_0) \)
Improvements in $p_T^{\text{miss}}$ by requiring PV-track time consistency: CMS

10–15% resolution improvement

Restores performance at $\langle \mu \rangle = 200$ to that at 140 without MTD, important for e.g. BSM searches and $H \to \tau\tau$
Improvements for lepton isolation: ATLAS

- Efficiency for **electron isolation** selection in $Z \rightarrow e^+e^-$ events as function of pileup vertex density

- **Without timing** and with initial and **final** timing resolution

- HGTD removes majority pileup deterioration, recovers 10% for average HL-LHC vertex density
Tagging of heavy-flavor jets: CMS

Figure 5.16: Secondary vertex tagging ROC curves for light and charm jets for $|\eta| < 1.5$ (left) and for $1.5 < |\eta| < 3.0$ (right). Results with and without (blue) and with timing for $30$ (red) and $60$ ps (green) resolution hypotheses are compared to the zero pileup case (grey).

Figure 5.17: Left: Efficiency of the b-tagging vs. the average pileup density, with a constant light-jet efficiency of 0.01. Right: Projections for yield enhancement in $HH! bbb b$ as function of the Higgs boson rapidity. The distributions are normalized to the no-timing case.

Pileup tracks can be mistaken for tracks from HS vertex with large impact parameter, and give rise to fake $b$-jets
\[ \Rightarrow \text{require } \Delta t(vtx, trk) < 3\sigma(t) \]

\[ \Leftarrow b\text{-jet efficiency stable wrt vertex density} \]

(Rejection of both $c$-jets and light-flavor jets approaching performance without pileup – see backup slide)
CMS: Improved particle identification in heavy-ion collisions

- Particle identification can be improved using time-of-flight measurements at low $p$
- Proton identification for $p < 5$ GeV
- Separation of $\pi^{\pm}$ and $K^{\pm}$ for $p < 3$ GeV
- Performance for Endcap Timing Layer similar in $1.5 < |\eta| < 3.0$
CMS: Improved particle identification in heavy-ion collisions

- Particle identification methods are crucial for analyzing heavy-ion collisions.
- Time-of-flight measurements at low momentum are used to separate protons and pions.
- CMS Phase-2 and LHCb Phase-2 use different configurations, with CMS Phase-2 focusing on PbPb collisions.
- MTD efficiency (up to 50%) is leveraged to deliver luminosity in HL-LHC.
- The search for long-lived particles (LLP) in BSM models benefits from the MTD-improved object reconstruction.
- Performance improvements include sensitivity gains and better signal-to-background ratios. 
- An example of projected D^0 mixing with and without the MTD shows significant improvements.
Examples on impact on physics studies
ATLAS: Measurement of weak mixing angle

- Precision SM: Measurement of weak mixing angle, $\sin^2 \theta_W$

- In $Z \to ee$ channel, **improved isolation performance** enhances sensitivity

- Plot shows reduced uncertainty for important forward-forward category

- Inclusively, HGTD gives **11% reduction** of total experimental uncertainty

Solid red corresponds to variations of $\sin^2 \theta_{\text{eff}}$ of $40 \times 10^{-5}$, dashed blue illustrate the total error from CT14 NNLO PDF, and green shows the particle-level AFB prediction.
**CMS: Vertex selection for** $H \rightarrow \gamma\gamma$

- Timing for vertices allows efficient photon-to-vertex association, “triangulation” in $t$-$z$ space
- Restores vertex selection eff. to Run-2 level (75%), adding $\sim 30\%$ effective lumi for $H(\gamma\gamma)$
  $\Rightarrow$ Significant increase in stats-limited measurements of differential cross sections
CMS: Measurement of Di-Higgs production

Measurements of Di-Higgs production and determination of the Higgs self-coupling highest priority for HL-LHC physics program

- Including impact of all object-level improvements that MTD brings, the impact on all relevant channels were assessed

For example, improved $b$-tagging enables selecting 18% more $HH(4b)$ events

(Assuming average $\sigma(t) = 50$ ps)
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For example, improved $b$-tagging enables selecting 18% more $HH(4b)$ events

<table>
<thead>
<tr>
<th>Di-Higgs decay</th>
<th>Expected significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$bbbb$</td>
<td>0.88</td>
</tr>
<tr>
<td>$bb\tau\tau$</td>
<td>1.3</td>
</tr>
<tr>
<td>$bb\gamma\gamma$</td>
<td>1.7</td>
</tr>
<tr>
<td>$bbWW$</td>
<td>0.53</td>
</tr>
<tr>
<td>$bbZZ$</td>
<td>0.38</td>
</tr>
<tr>
<td>Combined</td>
<td>2.4</td>
</tr>
</tbody>
</table>

(Assuming average $\sigma(t) = 50$ ps)
ATLAS: invisibly decaying Higgs produced via vector boson fusion

- \(Z(\nu\nu)+\text{jets}\) big bg, pileup jets mimic VBF

- Normalized S/B to ITk-only performance, study how S/B improves with additional pileup-jet rejection from HGTD

- Background has two components
  - central-forward (CF)
  - forward-forward (FF)

- HGTD could help for both, giving up to 27% improvement in S/B with 40% additional pileup-jet rejection

\[
\begin{align*}
\text{ATLAS Simulation} \\
\sqrt{s} = 14 \text{ TeV, HL-LHC} \\
\text{VBF preselection, 85% ITk PU-tag HS efficiency}
\end{align*}
\]
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CMS: Examples for long-lived beyond-SM particles

LLPs give spectacular low-bg signatures that can offer discoveries of BSM at HL-LHC

Time-of-flight gives $\beta$, which can separate heavy particles from SM also at larger momenta

Long-lived $\tilde{\chi}^0$ decaying to delayed photons $\Rightarrow$ improved low-$\tau$ sensitivity with $\Delta t(\text{vtx}, \gamma)$

Measurement of $\beta$ improved discriminator for SM bg and LLPs with muon-like signature
Many traditional luminometers rely on zero counting and will struggle at HL-LHC (too high occupancy)

HGTD will provide powerful luminosity capabilities:

- High granularity ⇒ low occupancy
- Can provide bunch-by-bunch luminosity estimates at 40 MHz
- Fast, short detector signal ⇒ handle on “afterglow”
- Excellent $n_{\text{hits}}$ vs. $\mu$ linearity!

Luminosity measurement at HL-LHC very challenging, aiming for 1% uncertainty to not be limiting in many flagship measurements at HL-LHC!
Summary: ATLAS and CMS timing detectors

- Increased vertex density at HL-LHC is a serious challenge

- Spatially overlapping vertices can be resolved in the time dimension with accurate MIP (→ vertex) timing measurements

- **ATLAS: HGTD**
  - Forward focus: $2.4 < |\eta| < 4.0$
  - $\sigma_t = 30$ ps/MIP and high rad. ⇒ LGADs

- **CMS: MTD**
  - Full barrel and endcap coverage ($|\eta| < 3.0$)!
  - LYSO+SiPM (barrel) and LGADs (endcap)

- Very different detectors, acceptances – and also challenges!

- Significant object-level improvements:
  - Pileup-jet tagging
  - $p_T^{\text{miss}}$ resolution and tails
  - Lepton isolation
  - Flavor tagging
  - Particle identification through ToF

⇒ Sensitivity gains across physics program, from electroweak SM and Higgs sector measurements to heavy-ion physics BSM searches

*All results shown here are from the TDRs for the ATLAS HGTD and CMS MTD!*
Back-up
ATLAS: Material in front of HGTD

- PP1 and enclosure
- Dry Nitrogen
- Strip services and cooling
- Strip supports
- Strip modules
- Pixel services and cooling
- Pixel supports
- Pixel modules
- Beam pipe and IPT

ATLAS Simulation
ITk Layout
ATLAS-P2-ITK-22-00-00

Interaction length [\lambda]
ATLAS: Material in HGTD
Figure 2.2: BTL layout parameters along detector axis $z$: slant thickness and radiation length (left), SiPM area and radiation levels (right).
• **Jitter**: the jitter term is given by the ratio of the noise $N$ over the signal slew rate $\frac{dV}{dt}$,

$$s_{\text{Jitter}} = \frac{N}{\left(\frac{dV}{dt}\right)}.$$  

The noise is the sum of components from electronic noise and sensor shot noise:

$$N = q_{\text{El.}} + N_{\text{Shot}}.$$  

The sensor shot noise is a sub-leading contribution, see Section 3.2.4. Ignoring $N_{\text{Shot}}$, the jitter can be expressed as

$$s_{\text{Jitter}} \mu e_n C dQ_{\text{in}} t_{\text{rise}}$$  

where $e_n$ is the electronic noise, $C$ the detector capacitance, $Q_{\text{in}}$ the total signal charge and $t_{\text{rise}}$ the signal rise time at the input of the comparator.

The jitter is therefore minimized by large signals, small capacitance, and fast rise time.

• **Total ionization** + **Local ionization**: the ionization process changes on an event-to-event basis both in total magnitude ($s_{\text{Total ionization}}$) and in the non-uniform creation of electron-hole pairs along the particle path ($s_{\text{Local ionization}}$). These two effects are correlated as large non-uniform ionizations often lead to large total ionizations, e.g., due to delta rays. The effect on the time resolution of varying total ionization, the so-called time-walk effect, is largely compensated using a correction from measurements of the total ionization with a time-over-threshold circuit (Section 3.3.6).

The second term, $s_{\text{Local ionization}}$, arises from the variation of the signal shape due to non-uniform ionization. These signal shape variations, called Landau noise, are the intrinsic limiting factor for the achievable time resolution. They depend on the sensor thickness \[65\], but not on the gain value. As explained in more detail in Section 3.2.4.6, the Landau noise contributes 30–35 ps to the time resolution, and it dominates over the jitter term once the gain is larger than about 10–20.

• **Distortion**: this term is due to the non-uniform weighting field and the non-saturated drift velocity. The first term is reduced to a small contribution by using a parallel plate geometry that has a uniform weighting field; in the ETL design each pad has an extension of at least 1 mm in each direction, while the thickness is about 50 $\mu$m, yielding an almost perfect parallel plate configuration. Distortion due to the non-saturated drift velocity is minimized by operating the sensor at a sufficiently high bias voltage where the charge carriers’ velocity is saturated.

• **TDC**: the effect of the TDC binning is discussed in Section 3.3.6.

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**Figure 3.4**: Left: ETL exposure to irradiation, in 1 MeV neutron equivalent per cm$^2$, as a function of radius for three points in time during the expected HL-LHC 3000 fb$^{-1}$ lifetime. Right: The maximum fluence experienced by a given fraction of the ETL area.
CMS: Flavor-tagging ROC curves

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5.3. Performance in the reconstruction of final state observables

 Hadronic tau decays are characterized by a complex final state topology, with the so-called 3-prong, 1-prong, and 1-prong+ tau categories, related to the decay multiplicity of the tau candidate. The tau identification is more complex and the background more severe than for muon and electrons, resulting in efficiencies that are typically in the range between 30 and 50%, much lower than for muons and electrons. Hence, the potential gain from timing is larger, as indicated by preliminary studies reported in Ref. [8]. Updated results for 40 ps and 50 ps resolution and an average efficiency for a track time measurement of 85% are shown in Fig. 5.21. An efficiency gain of 10–15% for prompt hadronic taus is observed for fixed jet misidentification probabilities of a few percent, corresponding to typical working points in Higgs boson searches.

As discussed for the tagging of b jets, the efficiency gains due to the charge isolation selection, albeit limited at the single-object level, combine in multi-object final states resulting in a signal...
Figure 2.13: Time resolution per hit (left) and per track (right) within HGTD acceptance as a function of the radius. The time resolution is shown for various integrated luminosities. The time resolution is improved at higher luminosities corresponding to the replacements of inner-most rings during the lifetime of the detector.
Figure 2.14: Expected nominal Si1MeV $n_{eq}$ fluence and ionising dose as functions of the radius in the outermost sensor layer of the HGTD for $L_{int} = 4000 \text{ fb}^{-1}$, i.e. before including safety factors. The contribution from charged hadrons is included in 'Others'. These estimations used Fluka simulations using ATLAS Fluka geometry 3.1Q7 (from December 2019).
ATLAS: event display