Proposal for a MIP Timing Detector in the CMS Phase 2 Upgrade

Lindsey Gray
on behalf of the CMS Collaboration

1 December 2017
Outline

- The benefits of precise timing
- Physics performance
- Overview and performance of the proposed detector

detector descriptions, physics performance, schedule, and cost estimates
Challenges of the HL-LHC

- CMS Phase-2 originally targeted 5x10^{34} Hz/cm^2 = 140 pileup (PU)
- LHC performance is *exceptional*
- Ultimate HL-LHC luminosity target is now 7.5x10^{34} Hz/cm^2 = 200PU
  - 25% increase in int. luminosity/year
  - Extending performance at high PU is the key!

- The CMS Technical Proposal (2015) introduced timing as an option
  - Since then we have developed innovative analysis techniques and performed extensive studies
  - The key technologies have made significant progress
- CMS has now included a hermetic precision MIP Timing Detector in the Phase-2 upgrade scope
Motivation

• Physics performance at high pileup will determine where CMS will level luminosity
  - High leveling integrates more luminosity
  - Hence the need for optimizing performance at 200PU

• HL-LHC may well operate with parameters different from current design (fewer bunches / increased pileup density)
  - Solution must be robust
  - Algorithms can only go so far, but always benefit from more information

• Maintaining 50PU performance in 200PU conditions benefits full range of CMS physics output
Hermetic Timing Provides 4D Tracking

With timing resolution of 30 ps, the time separation of interaction vertices is evident. Reduces the effective number of vertices from 200 to 40-50
  - for reasonable vertexing: 15% vertex merge rate reduced to 1%
  - similar to current running conditions
In this presentation we show the additional benefit of timing on top of the full Phase-2 CMS detector.

CMS reconstruction relies on **Particle Flow**
- Provide *most complete* global description of an event

Charged hadrons make up 60% of hadronic event content
- CMS is highly dependent on accurate *track assignment*
- Momentum of low $p_T$ charged hadrons measured through tracking rather than calorimetry

Tracking is key to the performance of CMS and a timing detector should be tailored to provide maximum benefit.
Calorimeter upgrades:

- Precision timing of showers
- Provide precision timing on high energy photons in ECAL Barrel
- All photons and high energy hadrons in HGCal Endcap

PROPOSING: MTD — Dedicated MIP timing layers

- MIP timing with 30 ps precision
- Acceptance: $|\eta| < 3.0$, $p_T > 0.7$ GeV in barrel, $\sim p > 0.7$ GeV in endcap
- Location: just outside the tracker

MTD = MIP Timing Detector
BTL = Barrel Timing Layer
ETL = Endcap Timing Layer
MTD = BTL + ETL
Mitigating Confusion from Pileup

- Pileup tracks are incorrectly associated to primary vertex of interest
  - Timing significantly reduces “effective” vertex line density
  - Recover performance in several observables
  - Provide additional robustness against changes in beam configuration
Lepton Isolation With Timing

- Timing cuts remove pileup tracks from lepton isolation cones
- Reduces dependence on pileup density (see backup)

▶ 60% improvement in background rejection for constant signal efficiency using pertinent working points
B-Tagging With Timing

- Precision timing rejects spurious secondary vertices
- Significant improvements for working points at constant signal efficiency or background rejection
  - Gain in efficiency amplified in multi-particle final states ($\epsilon^N$)
- Removes pileup-density dependence in b-tagging

**Signal Efficiency**

**Background efficiency**

<table>
<thead>
<tr>
<th>CMS Phase-2 Simulation Preliminary</th>
<th>14 TeV</th>
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<tr>
<td>$t\bar{t}$, $&lt;\text{PU}&gt; = 200$, jet $p_T &gt; 30$ GeV</td>
<td>$t\bar{t}$, $&lt;\text{PU}&gt; = 200$, jet $p_T &gt; 30$ GeV</td>
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<tr>
<td>udsg jet misid. = 0.01</td>
<td>udsg jet misid. = 0.01</td>
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<tr>
<td>b jet id. = 0.60</td>
<td>b jet id. eff. = 0.70</td>
</tr>
<tr>
<td>no MTD</td>
<td>no MTD</td>
</tr>
<tr>
<td>MTD ($\alpha_1 = 30$ ps)</td>
<td>MTD ($\alpha_1 = 30$ ps)</td>
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- Barrel $|\eta| < 1.5$
- Endcap $1.5 < |\eta| < 3.0$
- Barrel $|\eta| < 1.5$
- Endcap $1.5 < |\eta| < 3.0$

- Gain in efficiency amplified in multi-particle final states ($\epsilon^N$)
- Removes pileup-density dependence in b-tagging
(di-)Higgs Acceptance Improved

- Object-level acceptance improvements compound in multi-object final states

<table>
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<tr>
<th>Channel</th>
<th>Signal increase (%)</th>
<th>Relevance</th>
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<tr>
<td>HH → bbγγ</td>
<td>BTL: 17 BTL+ETL: 22</td>
<td>Higgs self-coupling</td>
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<tr>
<td>HH → bbbbar</td>
<td>BTL: 14 BTL+ETL: 18</td>
<td>Higgs self-coupling</td>
</tr>
<tr>
<td>H → ZZ → 4l</td>
<td>BTL: 19 BTL+ETL: 26</td>
<td>Mass, width, spin+parity, differential cross sections, EFTs</td>
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- Corresponds to 18-26% increase in effective integrated luminosity

- Large impact on barrel region since physics signature is central
Higgs to Di-photon Vertex Tagging

- Unique capability to match photon time to vertex time + position
  - CMS ECAL is non-pointing, but has photon timing capability
  - 50% of events additionally require MIP timing to find correct vertex

- Identifies photon vertex: improves di-photon mass resolution by 25% and also $H(\gamma\gamma)$ signal significance
• Timing cleans tracking information provided to PUPPI* so it can better identify neutrals from pileup
  - No impact on signal jet efficiency
  - Largest impact in the endcaps

- 20% (barrel), 40% (endcap) reduction in pileup jet multiplicity

* https://arxiv.org/abs/1407.6013
VBF Higgs to Tau Tau

- Performance gain from timing \((S/\sqrt{B})\) 80%:
  - +30% from isolation
  - +30% from VBF tagging (pileup jet rejection)
  - +10% from di-tau mass resolution \((p_T^{miss} \text{ resolution})\)

- Large impact from ETL
  - Timing offsets performance degradations from 140 to 200 PU
MET Performance

- PUPPI MET resolution improves 15% at 200PU
  - Recovers 140 pileup performance
- MET tails reduced 40% for MET > 150 GeV
  - Game-changer for searches in high pileup
Searches in MET Tails

- Extend the physics reach in searches for massive invisible particles
- Without timing, the search is less sensitive at 200 PU than at 140 PU
  - With timing, search at 200 PU recovers sensitivity as at 140 PU (3000 fb⁻¹)
- 200 PU running provides 4000 fb⁻¹, timing further improves sensitivity
Searches for Long-Lived Particles

- MTD vastly improves acceptance for massive long-lived particles (LLP)
- Ability to measure decay time improves search reach by orders of magnitude at highest masses
- Massive particles yield central signatures
  - MTD provides a new capability for these searches
Reconstruction of Neutral LLP Masses

- By measuring particle velocity from primary and secondary vertices, we can reconstruct a peaking variable for LLP searches
  - Model independent: can either reconstruct mass or mass splitting depending on how velocity related to model structure
  - The MTD *fundamentally* changes how we execute these searches

![Graphical representation of particle interactions]

![Histogram showing mass resolution and efficiency as a function of MTD resolution]

No peaking variable without MTD

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Lindsey Gray, FNAL
Performance Summary

- The MTD is a key addition that improves the full range of HL-LHC era physics

<table>
<thead>
<tr>
<th>Signal</th>
<th>Detector requirement</th>
<th>Analysis impact</th>
<th>Physics impact</th>
</tr>
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</table>
| $H \rightarrow \gamma\gamma$ | 30 ps photon and track timing  
- barrel: central signal  
- endcap: improved time-zero and acceptance | $S/\sqrt{B}$:  
+20% - isolation efficiency  
+30% - diphoton vertex | +25% (statistical) precision on cross section |
| $VBF^+_{H\rightarrow\tau\tau}$ | 30 ps track timing  
- barrel: central signature  
- endcap: forward jet tagging  
- hermetic coverage: optimal $p_T^{miss}$ reconstruction | $S/\sqrt{B}$:  
+30% - isolation efficiency  
+30% - VBF tagging  
+10% - mass ($p_T^{miss}$) resolution | +20% (statistical) precision on cross section (upper limit or significance) |
| $HH$ | 30 ps track timing  
- hermetic coverage | signal acceptance: +20% b-jets and isolation efficiency | Consolidate HH searches |
| $\chi^\pm\chi^0 \rightarrow W^\pm H + p_T^{miss}$ | 30 ps track timing  
- hermetic coverage: $p_T^{miss}$ | $S/\sqrt{B}$:  
+40% - reduction of $p_T^{miss}$ tails | +150 GeV mass reach |
| Long-lived particles | 30 ps track timing  
- barrel: central signature | mass reconstruction of the decay particle | unique sensitivity to split-SUSY and SUSY with compressed spectra |

- ~20-30% acceptance improvements across all measurements
- Recovery of performance for large-MET based searches
- Novel capabilities derived from LLP secondary vertex timing
What does such a detector actually look like?

- **Technology choices are driven by radiation and cost**
  - BTL: LYSO + Silicon Photomultipliers (SiPM)
  - ETL: Low Gain Avalanche Detectors (LGAD)
Hermetic MIP Timing: Barrel & Endcap

Requirements:

- Hermeticity: barrel ($|\eta| < 1.48$) and endcap ($1.6 < |\eta| < 2.95$)
- Radiation: $2 \times 10^{14} \text{n}_{eq}/\text{cm}^2$ (barrel) and up to $2 \times 10^{15} \text{n}_{eq}/\text{cm}^2$ (endcap)
- Minimal impact on calorimeter performance
- Mechanics and services compatible with existing upgrades

**LYSO:Ce tiles with SiPM readout:**
- Embedded in TK support ~ 25 mm thick
- Area ~40 m$^2$, ~250k channels
- Integrate with tracker

**Si with internal gain (LGAD):**
- On the endcap nose ~ 42 mm thick
- Area ~12 m$^2$ (total), ~4M channels
- Integrate with endcap
Barrel Timing Layer (BTL) Layout

- **LYSO:Ce + SiPM tiles embedded in the tracker support tube**
  - CO2 cooling for SiPMs at ~ -30 C

- **LYSO:Ce + SiPM is a production-ready and scalable technology**

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

- Variable thickness to maintain a uniform material budget
Radiation Hardness of BTL Sensor Package

- Radiation at the end of HL-LHC
  - Fluence: $1.7-2 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$, Dose: 16-25 kGy

- LYSO: fast, bright scintillator
  - Sufficiently radiation hard

- SiPM: existing devices close to 30ps at end of HL-LHC
  - Lines: resolution from simulation varying photon detection efficiency (PDE) and dark count rate
  - Points: extrapolation to $2 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ of SiPMs irradiation studies

To be optimized: reflective wrappings, SiPMs size / layout, thicker tiles, …
**BTL Sensor Package: Time Resolution**

- **Nominal geometry:** $11 \times 11 \text{mm}^2 + 4 \times 4 \text{mm}^2$ SiPM
  - Slant thickness is $\sim 4 \text{ mm}$

- **Timing correction for hit position necessary if SiPM small compared to Crystal**
  - Left plot: over whole tile with and without impact point correction
  - Right plot: test beam through SiPM fiducial

- Identified options to mitigate position dependence that are being pursued

\[ \sigma_{\text{CT}} / \sqrt{2} = 27 \text{ ps} \]
BTL ASIC

- BTL ASIC will be tailored version of commercial TOFPET2 chip
  - TOFPET2 with sensor package RMS already 37 ps
  - goal is 25 ps for sensor package (achieved at testbeam with NINO)

- Reasons for the difference are understood
  - Pulse slew rate (amplifier configuration) and TDC contribution
  - Radiation hard design in parallel – TSMC 130nm
Endcap Timing Layer (ETL) Design

- **LGAD Sensors**: established technology available from at least three foundries

- **Overlapping disk structure**
  - Placed in independent cold volume for accessibility
  - Al wedges with embedded cooling pipes (CO2 cooling @ -30 C)

- **Sensors on both disk sides**
  - Single-hit hermetic coverage
  - Nominal geometry 4.8 x 9.6 cm$^2$ modules with 1x3 mm$^2$ pads
LGAD Performance and Radiation Tolerance

- Over most of ETL area present LGADs achieve 30ps resolution, the issue is only at the highest $\eta$
- Measured < 45 ps at $3 \times 10^{15}$ $n_{eq}/cm^2$ ($1.5 \times$ max fluence at highest $\eta$)

(studying together with ATLAS)

LGAD can deliver < 40 ps timing resolution for entirety of HL-LHC

- New optimization studies with latest LGADs indicate further improvements
Multi-pad Sensor Development

- Large arrays of LGADs are possible already with small pad sizes
  - Production of pixellated LGAD sensors show large viable pad yields
- Prototypes of multi-pad sensors with CMS pad size now available
  - 2x8 arrays now, 4x24 in early 2018 (1/16 of a full sensor)
  - Will study gain uniformity, viable pad yield, fill factor for large pads

CMS Pad Geometry

Multi-pad array (FBK)

Pixellated LGAD sensor hit-map

- Very recent beam test @ SPS-H8
- More than 99% of pads working
- Same voltage behavior as single pad: breakdown above 280 V
- More pads than in a full TE sensor

Very good news!
ETL Front-end ASIC

- Chip specs defined: 25 ps without sensor, 110 mW/cm²
- Use cascade of timing measurements to achieve distributed TDC over large-area ASIC
  - Well established technology, used already in PicoTDC
  - Layout being designed in 65 nm TSMC benefitting from experience and available common blocks in RD53
- Simulations ongoing to define layout

Last stage of measurements uses DLL + passive elements to achieve finest binning.

Most precise elements, resistors and capacitors, are radiation tolerant.
Concluding Remarks

• MTD will benefit the whole physics program
  - Preserves the performance of Particle Flow and PUPPI
  - Increases effective luminosity: +20% for di-higgs
  - Recovers search performance in MET tails

  ▷ Benefits equivalent to additional 2-3 years of luminosity
  ▷ New capabilities for long-lived particle searches
  ▷ Sensor technologies underlying detectors becoming mature

• Many institutions are contributing to the studies and R&D

• Further investigations:
  - A region-of-interest readout for level one trigger
  - Benefit for HLT performance and offline computing
  - Ways to extend coverage to $|\eta| < 4.0$
Backup / Extras
# MTD Institutions

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<td>INP-BY</td>
<td>Institute for Nuclear Problems of Belarus State University, Minsk, Belarus</td>
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<td>HIP-FI</td>
<td>Helsinki Institute of Physics, Helsinki, Finland</td>
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<td>IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France</td>
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<td>KIT-DE</td>
<td>Institut für Experimentelle Kernphysik, Karlsruhe, Germany</td>
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<td>LIP-PT</td>
<td>Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal</td>
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<td>UW-US</td>
<td>University of Wisconsin - Madison, Madison, WI, USA</td>
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MTD Impact on Other Subdetectors

- MTD has a minor impact on upstream sub detectors
- BTL yields minor degradation in energy resolution for photons
  - BTL information not yet included in corrections
  - Small reduction of outer tracker radius by 14mm, negligible impact on tracking performance
- ETL services require modification of first two layers of CE
  - Need to route services to neutron moderator front face
  - Affects two CE trigger towers
  - Possible to minimize impact with services routing optimization

Figure 2.11: Left: Impact of MTD on the electron ECAL energy resolution (left) and on a shower shape variable, $s_{hh}$, relevant for electron and photon identification (right). No information from the timing layer hit is included in the shower reconstruction.
MTD: TE Service Routing

45 No go zones for services

DRAFT

Timing Layer

Thermal screen
BH absorber
Fill Factor Investigations

- Mapping of HPK and CNM sensor geometries in test beams
  - Dead regions at pad boundaries:
    ‣ Distance between adjacent gain layers to prevent breakdown
    ‣ Shape of field lines
  - Both under optimization
    ‣ with ATLAS

- Target for CMS
  - Single layer detector
  - Dead regions < 40 μm
    ‣ Inefficiency < 10%
    ‣ Achievable through optimization of p-stop, junction termination extension
Optimal $|dz|$ cut for Isolation (no timing)

$|dz| < 1\text{ mm}$ cut outperforms significance-based in both barrel and endcap.
Optimal $|dz|$ cut for Isolation (no timing)

$|dz| < 1\text{mm}$ is uniformly the best choice as a function of eta, even in the most central barrel.
CMS Phase-2 Tracker $dz$ Resolution

dz resolution of low $p_T$ muons dominated by multiple scattering. 0.7 GeV tracks (most important for isolation) have $dz$ resolutions of 100s of microns in the barrel.
Lepton Isolation Performance

Figure 3.8: ROC curves calculated for a cut-off scan in relative isolation for muon candidates (left) and in raw isolation for tau candidates (right), comparing the no-timing and with-timing cases.

Figure 3.9: The efficiency for prompt and fake muons (left) and authentic tau candidates (right) as a function of the event density for a representative operating point selection.

Figure 3.10: Muon efficiency for relative isolation cut-off of 0.05 (left) and hadronic tau efficiency for absolute isolation cut-off of 2.5 GeV (right) for different timing resolution assumptions, as a function of event density.
Luminosity Scaling for Neutralino Limits

\[ \Lambda \text{ [TeV]} \times \sigma_{\tau} \text{ [ps]} \]

- \( \sigma_{\tau} = 300 \text{ [ps]} \) - Int. Lumi. = 300 fb\(^{-1} \)
- \( \sigma_{\tau} = 300 \text{ [ps]} \) - Int. Lumi. = 1000 fb\(^{-1} \)

\[ \text{ct} \text{ [cm]} \]

Integrated Lumi = 300 fb\(^{-1} \)
- \( \sigma_{\tau} = 300 \text{ [ps]} \)
- \( \sigma_{\tau} = 180 \text{ [ps]} \)
- \( \sigma_{\tau} = 30 \text{ [ps]} \)
Chi2 Vertex Sorting For Photons

Figure 3.12: Left: Distribution of the $\chi^2$ of $H \rightarrow \gamma \gamma$ (red histogram) and pileup vertices (blue histogram) for 30 ps resolution in the calorimeters, 20 ps resolution in vertex timing, and a $|\Delta \eta(\gamma \gamma)| < 0.8$ cut-off on the photon pair. Right: Fraction of events in which the diphoton vertex has a rank equal or lower than the rank in the horizontal axis, for events with about 100 reconstructed vertices. The graphs show, for 140 pileup events, the fraction of events in which the diphoton vertex ranks amongst the first 10 ($|\Delta \eta(\gamma \gamma)| > 0.8$) or 20 ($|\Delta \eta(\gamma \gamma)| < 0.8$) reconstructed vertices. Even in the least favourable case of diphotons with $|\Delta \eta(\gamma \gamma)| < 0.8$, this method provides a fivefold reduction of the effective multiplicity of collisions, for a marginal loss in the efficiency. The independent analysis of the vertex kinematic properties can thus be applied to a restricted list of vertices, comparable in size to (or lower than) at the present LHC, and is therefore expected to provide similar (or better) performance.

The effect on the $H \rightarrow \gamma \gamma$ fiducial cross section measurement at HL-LHC is estimated in the context of projections of the most recent Run 2 results [70]. The impact on the invariant mass resolution and on the signal-to-background ratio is estimated for different CMS upgrade scenarios. At 140 pileup without timing information, the primary vertex selection efficiency is reduced to 40% ("S2-no upgrades"). With precision timing available only for the photons from the calorimeters, the vertex is correctly identified for a fraction of the events via triangulation, corresponding to the sample with $|\Delta \eta(\gamma \gamma)| > 0.8$, and the total vertex selection efficiency is estimated to be about 55% ("S2+Calo"). With precision timing available both for the photons in the calorimeters as well as for the charged particles in the event, a fivefold reduction in the effective pileup is assumed for all of the events, and the total primary vertex selection efficiency is increased to 75% ("S2+MTD"), nearly fully recovering the present Run 2 performance ("S2"). The signal lineshapes for the four scenarios are shown in Fig. 3.13. The improvement from precision timing with the full upgrade scope corresponds to around 15% reduction in the statistical uncertainty of the fiducial cross section measurement. Although there are still significant systematic uncertainties on this measurement at 3000 fb$^{-1}$, the statistical-only uncertainty can serve as a proxy for finely binned differential cross sections and/or differential cross sections measured as a ratio to the fiducial cross section, for which most systematic uncertainties will cancel. For such statistically limited measurements, the improvements from precision timing correspond to an approximately 30% increase in equivalent integrated luminosity.

These projections do not include the acceptance gain from improved isolation with track timing.