MIP Timing Detector for CMS Phase-II Upgrade

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on behalf of the CMS collaboration

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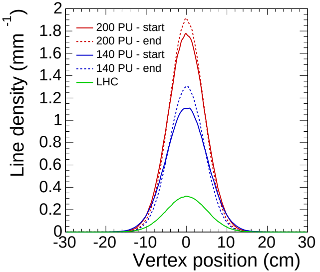
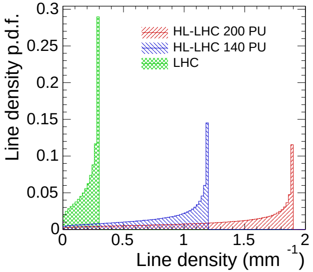
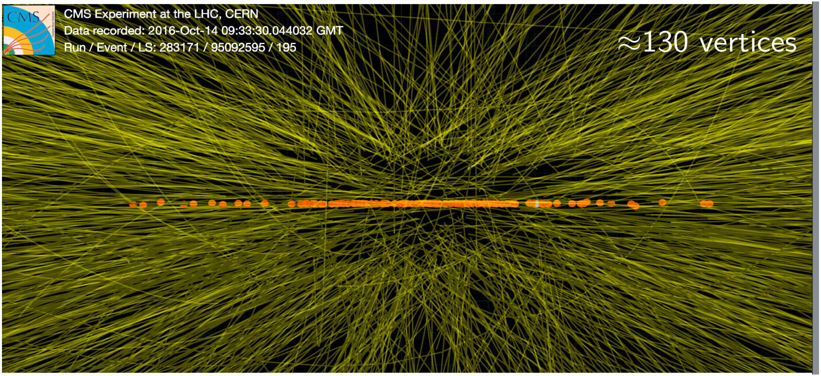
Introduction

- **HL-LHC:** Significant upgrade of LHC and injectors to increase beam intensity
  - Baseline: Peak $L_{\text{inst}} = 5.0 \times 10^{34}$ cm^{-1} s^{-1} (140 PU)
  - Ultimate: Peak $L_{\text{inst}} = 7.5 \times 10^{34}$ cm^{-1} s^{-1} (200 PU)
- Ultimate achievable integrated luminosity depends on choice of peak pileup/density for leveling, given expected detector performance





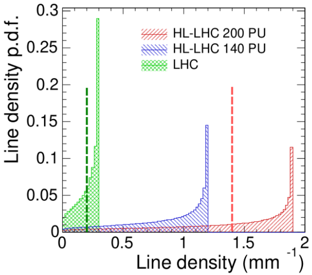
Proof of Concept, Proof of Challenge

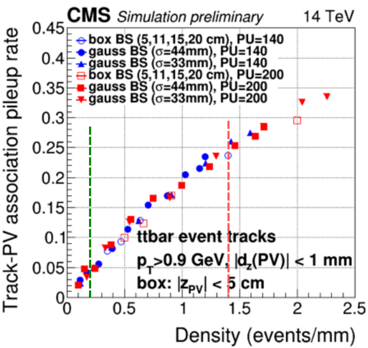


- Real-life event with HL-LHC-like pileup from special run in 2016 with individual high intensity bunches

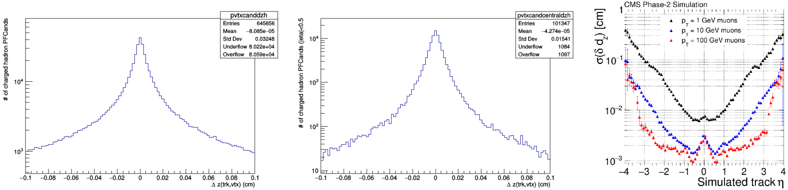
Impact of Pileup

- In current LHC conditions charged particles from pileup can be effectively excluded with geometric cuts
- Nominal $|\Delta z| < 1$ mm window for matching charged particles to the PV for phase 2 driven by the need to maintain very high efficiency in isolation sums, etc $\rightarrow$ tails are as important as core tracking resolution
- Contamination of charged particles from pileup scales with pileup density





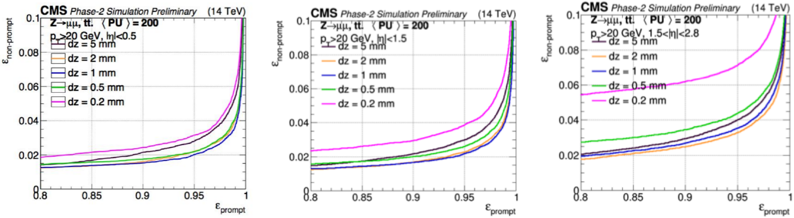
Optimization of Δz window



(a) $\Delta Z(trk, vtx)$ All Tracks (b) $\Delta Z(trk, vtx)$ $|\eta| < 0.5$ (c) Core Resolution

- Nominal $|\Delta z| < 1$ mm window for matching charged particles to the PV for phase 2 driven by the need to maintain very high efficiency in isolation sums, etc $\rightarrow$ tails are as important as core tracking resolution
- Tails driven by decays in flight, nuclear interactions, photon conversions, heavy flavor, etc

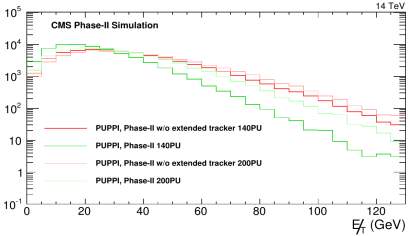
Optimization of Δz window

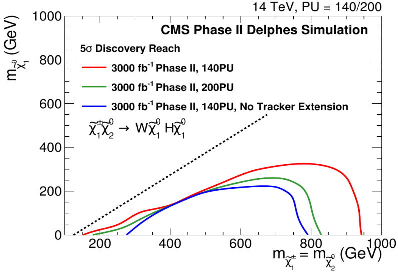


(a) $|\eta| < 0.5$ (b) Barrel (c) Endcap

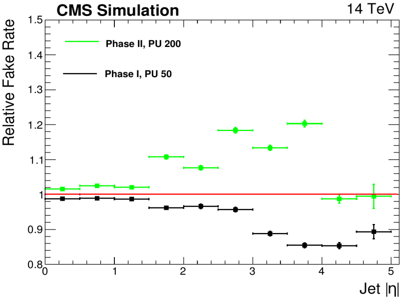
- Nominal $|\Delta z| < 1$ mm window for matching charged particles to the PV for phase 2 driven by the need to maintain very high efficiency in isolation sums, etc $\rightarrow$ tails are as important as core tracking resolution
- This window is $\sim$ optimal for all η regions

Physics Impact





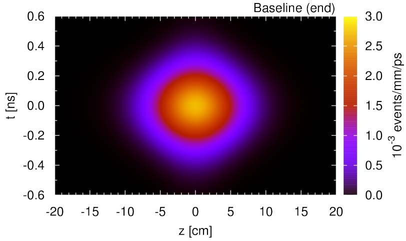
(a) $\not\!\!E_T$ Tails/EWK SUSY Search

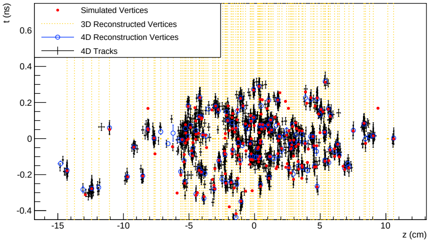


(b) Jets from PU

- Additional pileup has a significant impact on physics reach

Mitigation with Precision Timing

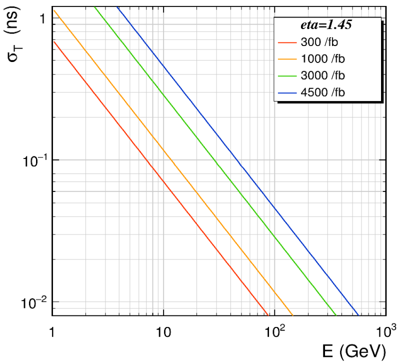




- Interactions are also spread in time, with a nominal RMS of 180ps, uncorrelated with z ($\sigma_z \sim 4.5$ cm)
- With sufficient time resolution and coverage for charged particles, traditional three-dimensional vertex fit can be upgraded to a four-dimensional fit and remaining charged particles from pileup can be effectively cleaned

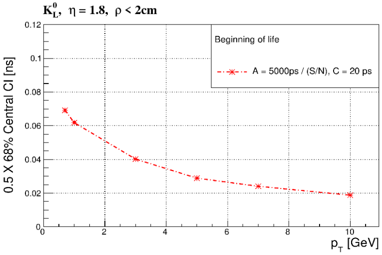
ECal Barrel Electronics/Cooling Upgrade:

- Additional cooling and upgraded front-end electronics will keep noise levels under control
- With proper attention to clock distribution, reduced shaping time, and high ADC sampling rates (160 MHz), can achieve $\sim$ 30 ps time resolution for 30 GeV photons at high integrated luminosity (limited by S/N of existing APD photo-detectors)

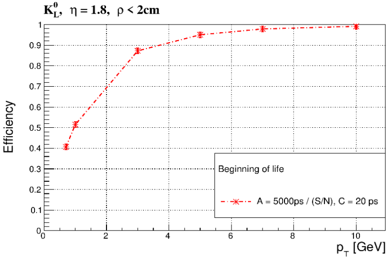


High Granularity Calorimeter:

- Excellent intrinsic timing performance of Si sensors for sufficiently large signals
- Electromagnetic showers have sufficient number of hits with large charge deposit down to a few GeV in energy
- Hadrons have sufficient large-deposit hits only at somewhat higher energy, depending on final thresholds, etc



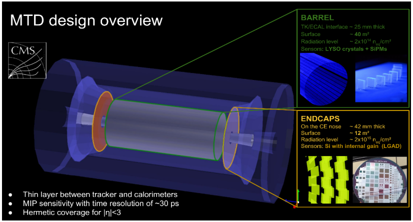
(a) Resolution



(b) Efficiency

Additional Timing Capabilities

- Calorimeter upgrades can already provide precision timing for high energy photons in the central region, moderate energy photons, and higher energy hadrons in the forward region
- **Additional capabilities: MIP timing to cover large fraction of charged particles in the event**
- **Targeting $\sigma_t = 30$ ps**
- **Extension to Phase-II Upgrade: MIP timing layer**
- Concept for central region: Thin **LYSO + SiPM** layer built into tracker barrel support tube (in between tracker and ECal Barrel) $\rightarrow$ precision timing for charged particles and converted photons



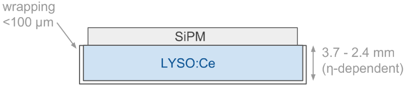
- Concept for forward region (more stringent radiation hardness requirements): **LGAD** (Silicon with Gain), single layer between tracker and HGCal (on HGCal nose)

Technology Choice Drivers

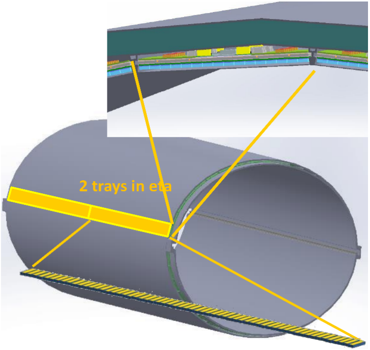
	Barrel LYSO+SiPM	Endcap LGAD
Coverage	$\lvert\eta\rvert < 1.5$	$1.5 < \lvert\eta\rvert < 3.0$
Surface Area	$\sim$ 40 m^2	$\sim$ 12 m^2
Power Budget	$\sim$0.5 kW/m^2	$\sim$1.8 kW/m^2
Radiation Dose	$\leq$ 2e14 neq/cm^2	$\leq$ 2e15 neq/cm^2
Installation Date	2022	2024

- Barrel (LYSO+SiPM):
  - LYSO is bright ($\sim$4500 p.e./MIP) and fast (60 ps rise time, 40 ns decay)
  - Larger surface area
  - Lower radiation dose
  - Earlier installation date
  - Mature technology (commercial availability for TOF-PET applications)
- Endcap (LGAD):
  - LGAD operated with gain of O(10) for sufficient S/N
  - Smaller surface area
  - Higher radiation dose
  - Later installation date (some additional time for R&D)

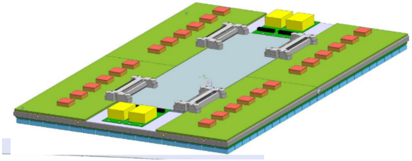
Barrel Layout

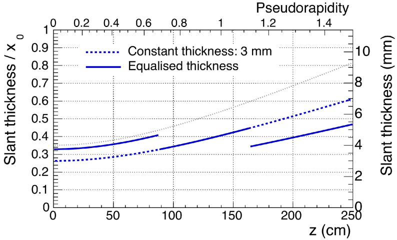


11x11 mm tile, 4x4 mm SiPM active area, $\sim$ 250k channels



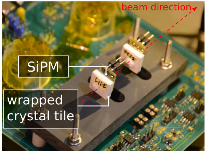
25 mm of available space within tracker support tube

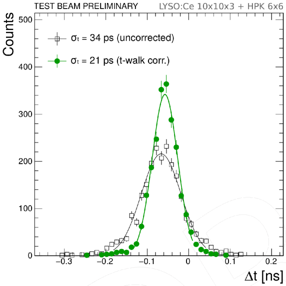


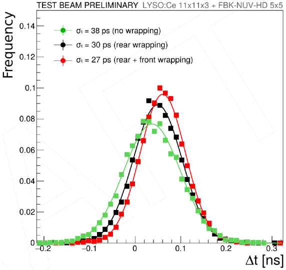


Variable thickness to maintain more uniform material budget and signal-to-noise

BTL Test Beam Results



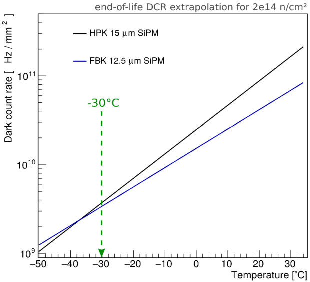




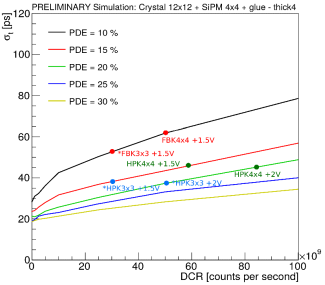
- Sufficient performance achieved at single sensor level with near-final aspect ratio
- Timestamp from constant threshold discriminator requires amplitude-dependent time-walk correction → need to read out pulse amplitude together with timestamp

BTL Radiation Hardness

- LYSO radiation hardness qualified up to 1e15 neq/cm^2 with minimal transparency loss
- Main effect for BTL is increased dark count rate in SiPMs due to radiation, mitigated by low operating temperature (-30C) and small cell pitch ($\leq 15\mu$m)
- Impact on time resolution estimated in simulation, extrapolating from DCR measurements of irradiated SiPMs with smaller area
- Further test beams with irradiated SiPMs planned

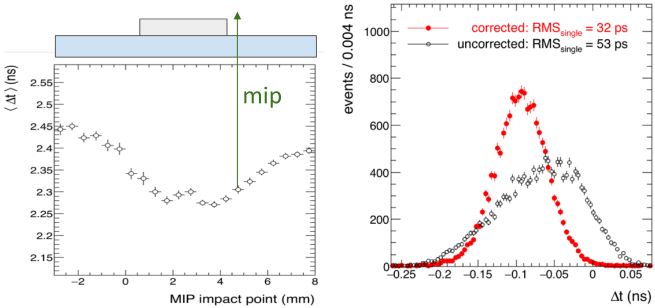


(a) DCR Temp. Dependence



(b) Time Resolution

BTL Impact-Point Dependence



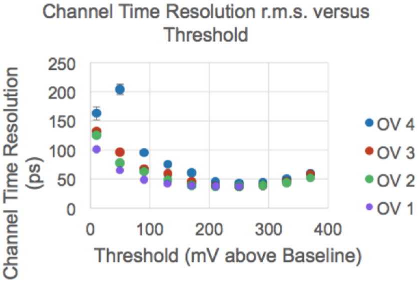
(a) Offset (b) Resolution

- 200 ps variation in average time as a function of impact point due to non-uniform coverage of SiPM, contributes $\sim$ 40 ps in quadrature to σ_t if uncorrected
- Offline correction possible with sufficient precision only for well-reconstructed tracks with $p_T > 2$ GeV (also excludes heavily displaced charged particles from e.g. photon conversions)

BTL Impact-Point Dependence

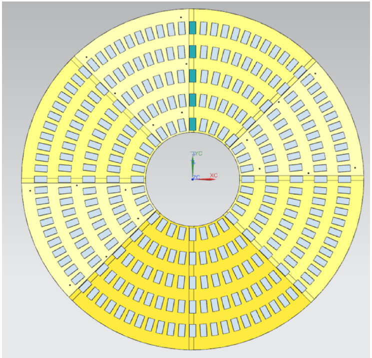
- Two options being explored to mitigate in hardware:
- **Large Area Sparse Cell SiPMs:**
  - Same number of active pixels spread over larger area to cover full tile
  - Dark current and power consumption kept constant with respect to 4x4 mm SiPM's
  - Samples from two different vendors expected in next few months, test beam at CERN in Sept.
- **Alternate Geometry: Elongated LYSO Bars with double-ended readout**
  - 3x3x50 mm bars with 3x3 mm SiPMs on each end
  - Offline combination of two timestamps to remove impact-point dependence
  - First tests in recently completed test beam at FNAL, further test beams planned at CERN in May and September

BTL Frontend Electronics



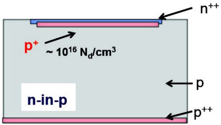
- Frontend electronics based on existing TOFPET2 chip
- 37 ps resolution achieved with existing TOFPET2 chip
- Design is being adapted (TOFHIR) for radiation hardness and with changes to amplifier and TDC configuration to further improve time resolution and accommodate needed rate

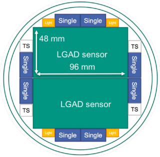
Endcap Timing Layer (ETL)

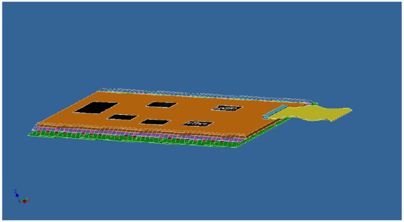


Overlapping disk structure for hermetic coverage with single LGAD layer

$\sim$ 95% coverage, limited by dead area between pixels

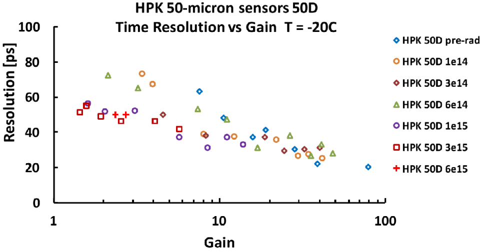






1x3 mm LGAD channels, read out in groups of 3 for $|\eta| < 2.1$ where occupancy allows, 1.8 M channels at readout level

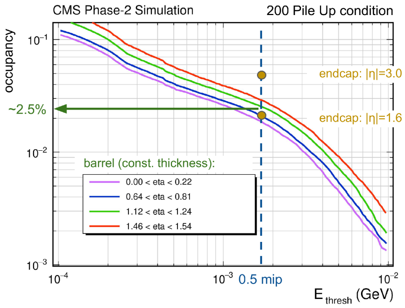
LGAD Test Beam Results



Region	η	R (cm)	z (cm)	Fluence (cm^{-2})	Dose (kGy)
barrel	0.0	117	0	1.7×10^{14}	16
barrel	1.15	117	170	1.9×10^{14}	21
barrel	1.45	117	240	2.0×10^{14}	25
endcap	1.6	127	304	1.1×10^{14}	25
endcap	2.0	84	304	2.4×10^{14}	75
endcap	2.5	50	304	6.6×10^{14}	260
endcap	3.0	30	304	1.7×10^{15}	690

- 30 ps resolution achievable with existing sensors up to 1e15 neq/cm^2
- <40 ps resolution across whole detector up to 2e15
- Ongoing R& D (doping, sensor thickness) to further improve radiation hardness and fill factor

Occupancy



- Occupancy is at the level of 2-5%
- Pulse shape simulation shows negligible impact from out-of-time pileup or additional low-energy deposits

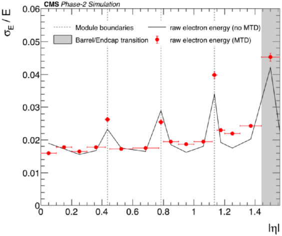
- Total data-rate: $\sim$ 4 Tb/s (read-out with zero suppression and nominally at L1 accept rate)
- Data volume prohibitive for 40 MHz readout without additional reduction

Clock Distribution

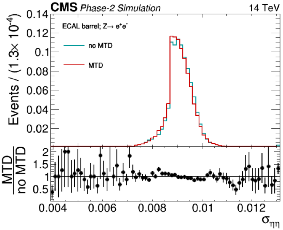
- Common R&D project for CMS phase 2 upgrades underway for high precision clock distribution targeting 10-15 ps time resolution
- Two options kept open for timing detector:
  - LHC clock to each module encoded in lpGBT control links (no additional fibres needed)
  - Dedicated clock fibres + fan-out chip in case desired precision cannot be otherwise achieved
- Slow drifts or other low-frequency instabilities can be monitored and calibrated out with minimum bias data in-situ

Impact On Calorimeters

- Additional material of ETL is negligible
- BTL adds $\sim 0.4\ X_0$ of material, but quite close to calorimeter $\rightarrow$ limited subsequent spread of any interaction products in magnetic field



(a) *e* Resolution



(b) *e* Shower Profile

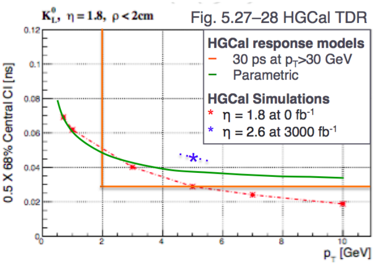
- Study overestimates effect since constant 4mm LYSO thickness was assumed in simulation
- Additional benefits possible using amplitude readout from BTL (4x better transverse segmentation than ECal Barrel)

Simulation and Reconstruction for Performance Studies

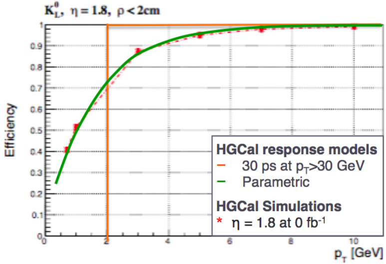
- Unless otherwise indicated, object-level performance studies are done using a fast simulation of the MIP Timing Detectors combined with a full simulation of the rest of the CMS Phase 2 detector
- Separate studies with full simulation of timing detectors to verify impact on other subdetectors and low-level effects not explicitly included in the fast simulation
  - Expected efficiency at $\sim 95\%$ level within acceptance
  - Additional contributions to timing resolution from backpropagation, overlapping signals, etc < 10 ps in quadrature
- **Fast simulation of MIP Timing Detectors:**
  - Sim-truth based assignment of timestamp to reconstructed tracks at the beamline smeared by the expected resolution (30 ps)
  - BTL Acceptance: $|\eta| < 1.5, p_T > 0.7$ GeV
  - ETL Acceptance: $1.5 < |\eta| < 3.0, p > 0.7$ GeV
- **Full implementation of higher-level offline reconstruction with timing starting from these tracks:**
  - 4D Primary Vertex Reconstruction
  - Integration into Particle Flow and Puppi for Jets/MET

Simulation and Reconstruction for Performance Studies: Treatment of HGCal

- HGCal timing where indicated is implemented in the endcap region re-using the same fast simulation machinery, two variations:
  - **Full parameterization** from HGCal TDR (taken at beginning of life, zero pileup, averaged over η)
  - **Simplified parameterization** assuming 30 ps resolution for charged particles with $p_T > 2$ GeV, no timing information otherwise

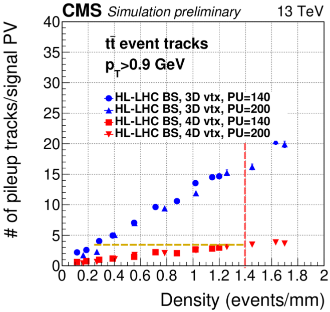


(a) Resolution

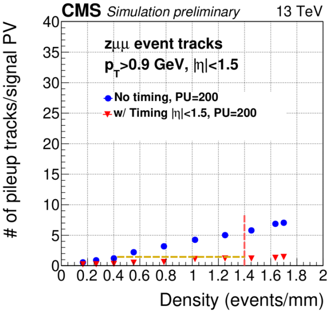


(b) Efficiency

Object-Level Performance Benefits: Track-Vertex Association



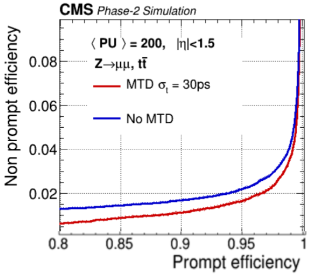
(a) Full Acceptance



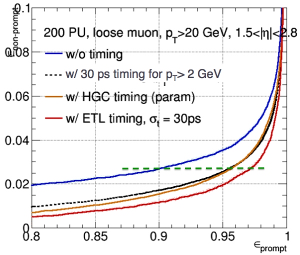
(b) Barrel Only

- **4-5x reduction in effective pileup in terms of charged multiplicity** across full η range with 3σ (90 ps) cut on timing
- Reduces pileup contamination for charged particles at 200 PU back to LHC Run 2 levels

Object-Level Performance: Muon Isolation



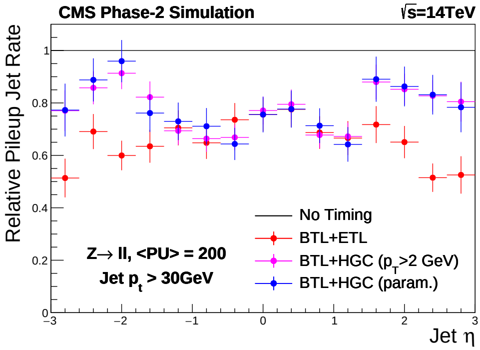
(a) Barrel



(b) Endcap

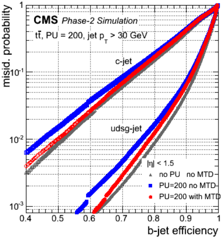
- Precision timing significantly improves charged lepton isolation in both barrel and endcap
- Full acceptance of ETL provides benefit on top of expected HGCal timing for charged particles (both HGCal parametrisations are equivalent for relevant working points)
- HGCal performance estimates assume that primary vertex time is known (HGCal cannot provide precision timing for muons)

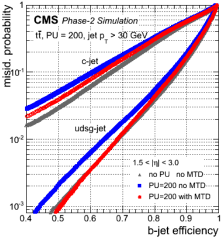
Object-Level Performance: Pileup Jet Suppression

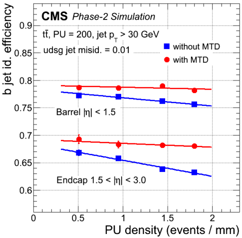


- 30-40% reduction in pileup jet rate from precision timing of charged particles
- Significant gain of full ETL acceptance on top of expected HGCal timing for charged particles (both HGCal parametrisations are equivalent)
- Additional complementary gains from neutral timing in HGCal to be studied for TDR

Object-Level Performance: b-tagging

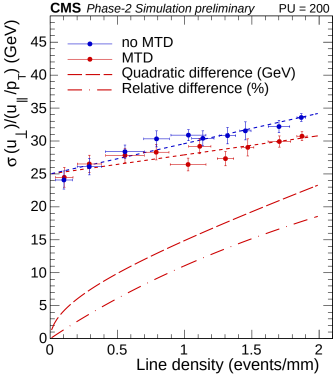




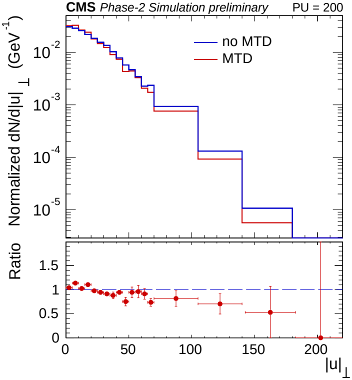


- b-tagging also improved in both barrel and endcap with additional cleaning of pileup tracks for secondary vertex reconstruction and discriminators

MET Performance



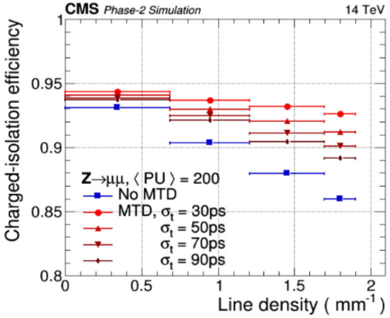
(a) MET Resolution



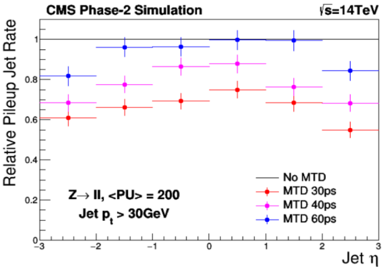
(b) MET Tails

- 15% improvement in MET resolution, $>30\%$ reduction in tails (reducible background for BSM searches)

Object Performance Dependence on Timing Resolution



(a) Muon Isolation

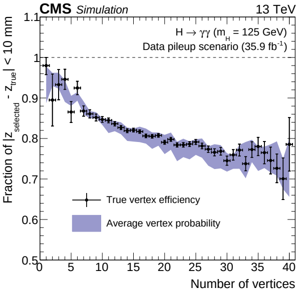


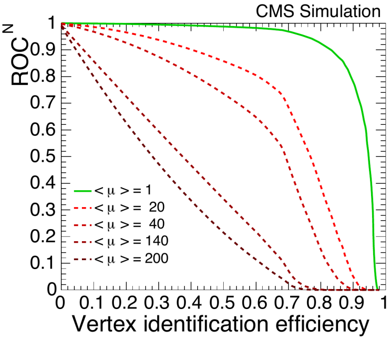
(b) PU Jets

- Smooth degradation of performance with degraded timing resolution

Primary vertex identification in $H \to \gamma\gamma$

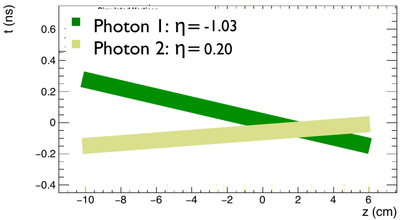
- No pointing information from ECal$\to$ CMS relies on hadronic recoil balancing and conversion pointing to locate primary vertex in $H \to \gamma\gamma$ events
- Becomes increasingly difficult to locate the primary vertex at very high pileup
- Vertex selection efficiency drops from $\sim$80% in current conditions to $\sim$30% at 200 PU

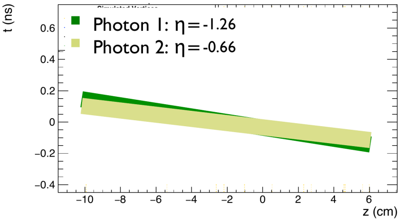




Precision timing for High Energy Photons - $H \to \gamma\gamma$

- Precision timing measurements for the high energy photons allows triangulation back to the primary vertex (30 ps resolution assumed here)
- Triangulation breaks down for small rapidity gap. In the absence of a known t_0 for the hard interaction, triangulation is ambiguous





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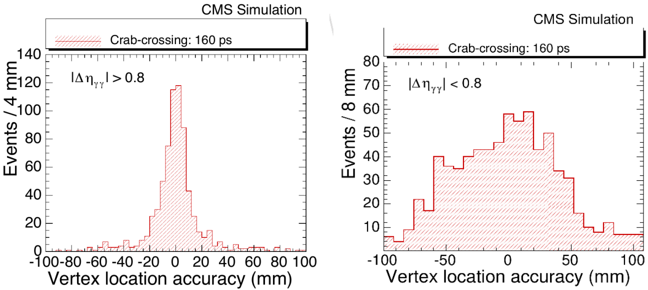
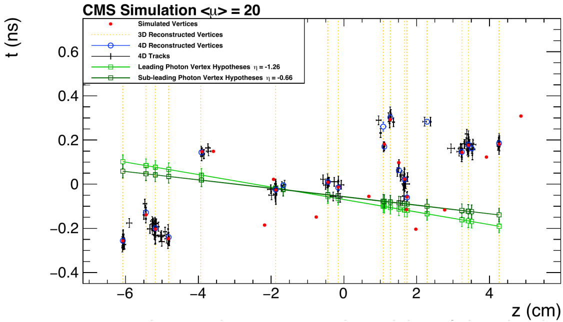


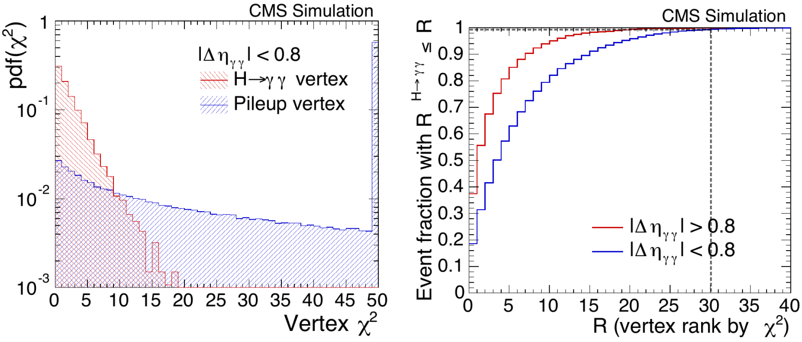
Precision timing for High Energy Photons - $H \rightarrow \gamma\gamma$

- Calorimeter timing-based triangulation can be matched to 4d reconstructed primary vertices to resolve the ambiguity and restore the performance

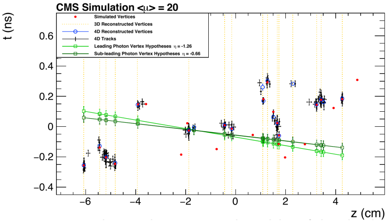


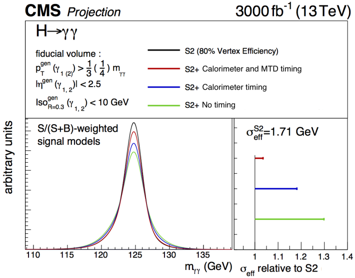
Precision timing for High Energy Photons - $H \rightarrow \gamma\gamma$

- Calorimeter timing-based triangulation can be matched to 4d reconstructed primary vertices to resolve the ambiguity and restore the performance
- Simple χ^2 matching provides a 5x reduction in the effective amount of pileup even for small rapidity gap events



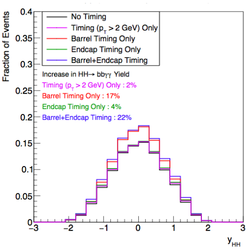
Primary Vertex Identification in $H \to \gamma\gamma$



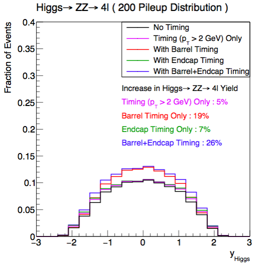


- Efficiently identifying the primary vertex for the full set of $H \to \gamma\gamma$ kinematic configurations requires timing for both the photons and the primary vertex
- Restores Run 2 vertex selection efficiency ($\sim 80\%$), corresponding to a 30% effect on diphoton mass resolution
- $\sim 30\%$ increase in effective integrated luminosity for stat. limited differential cross sections
- Additional potential gain from charged isolation of photons

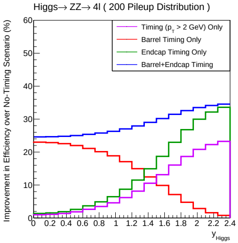
Physics Projections: Higgs and Di-Higgs Production



(a) $HH \to bb\gamma\gamma$

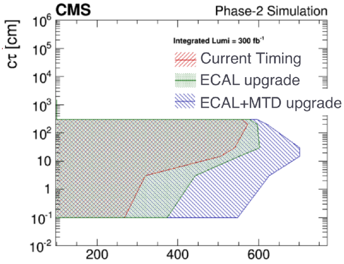


(b) $H \to ZZ \to 4\ell$

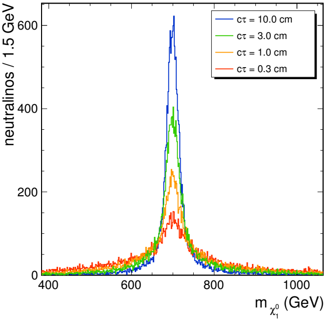


- Using Object-level gains for lepton (photon) isolation and b-tagging to project gains in Higgs/Di-Higgs selection efficiency at fixed background rejection (using working points in corresponding TDR analyses)
- Driven mainly by BTL given central nature of this signature
- **Corresponds to an 18-26% increase in effective integrated luminosity** (or corresponding decrease in needed operation time)

Long-Lived Particle Searches



(a) $\chi_1^0 \to G + \gamma$ Limits

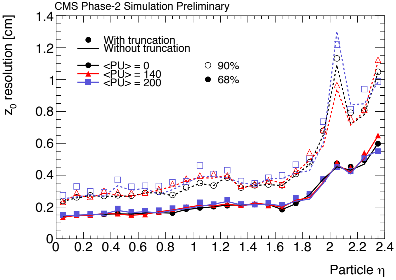


(b) $\chi_1^0 \to G + Z$ Peaking Variable

- Large increase in search reach for massive long-lived particles decaying to photons, combining calorimeter and MTD timing
- For a range of topologies, MTD allows reconstruction of a **peaking mass variable**, which introduces a **qualitatively new capability for long-lived-particle searches**
- BTL relatively more important for this case due to central signatures

Potential Trigger Benefits

- Full set of object-level performance gains from timing can be realized also in the High Level Trigger
- Additional opportunity to save CPU time with timing-based cleaning early in trigger sequences
- Possible integration of MTD into hardware trigger could allow, together with track trigger, determination of primary vertex time and use of timing for Particle Flow



Track Trigger z_0 resolution

Summary of Performance Benefits

Signal	Projected Physics Impact
$H \to \gamma\gamma$	25% improvement in statistical precision on xsecs $\to$ couplings
VBF $H \to \tau\tau$	20% improvement in statistical precision on xsecs $\to$ couplings
HH	20% increase in signal yield/decrease in running time $\to$ consolidate searches
EWK SUSY	40% reducible background reduction $\to$ +150 GeV mass reach
Long-Lived Particles	Peaking Mass Reconstruction $\to$ Unique sensitivity and discovery potential

- Substantial benefits across a wide range of objects and across the HL-LHC physics program leveraging gains across the full pseudo-rapidity coverage
- **20-30% increase in effective integrated luminosity**

Simulation and Reconstruction: Plans for MIP Timing TDR

- Performance studies with full simulation for TDR
- Integration of HGCal timing capabilities and precision timing for neutrals in Particle Flow
- Additional potential benefits:
  - **Electron and Photon Identification/Reconstruction** from BTL
  - **Particle ID** ($\pi/K/p$ seperation at low momentum)
  - **Object and computing performance in the trigger**
  - Complementary gains to isolation and Jets/MET performance with **neutral timing from HGCal** (maximally exploited with knowledge of primary vertex time from MTD)
  - Corresponding gains from **BTL timing of converted photons** (including late conversions without reconstructed tracks)
  - Matching of charged particle timing from ETL with shower timing from HGCal to **improve clustering and particle flow**

Conclusions

- HL-LHC conditions pose significant challenges for the experiments
- Precision timing can be used to significantly mitigate the effect of pileup and provide additional physics capabilities
- MIP Timing Detector for CMS ensures maximal coverage in η and p_T for charged particles, complementary with precision timing capabilities of upgraded calorimeters
- Following review of Technical Proposal, project approved to go ahead to TDR stage (submission to LHCC in late 2018)
- Precision timing capabilities will be essential for detectors at HE-LHC or future hadron colliders with O(1000) pileup and O(100μm) vertex separation

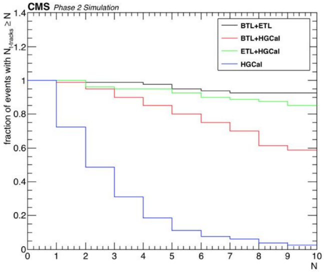
Backup

Summary of Performance Benefits

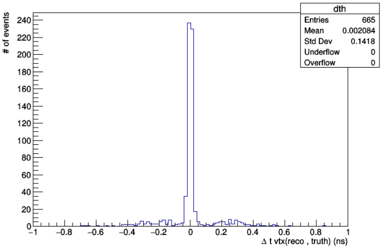
Signal	Detector requirement	Analysis impact	Physics impact
$H \to \gamma\gamma$	30 ps photon and track timing • barrel: central signal • endcap: improved time-zero and acceptance	$S/\sqrt{B}$: +20% - isolation efficiency +30% - diphoton vertex	+25% (statistical) precision on cross section
VBF+ $H\to\tau\tau$	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
$\chi^{\pm}\chi^{0} \to W^{\pm}H+p_T^{miss}$	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

- Substantial benefits across a wide range of objects and across the HL-LHC physics program

Impact of Partial Acceptance



(a) # of tracks for vtx timing



(b) Δt, No BTL, $Z \to \mu\mu$ in barrel

- For HGCal-only, < 3 tracks with good timing for $\sim 60\%$ of events
- In case cleanly-identified hard objects are in the barrel, endcap timing may not be able to unambiguously reconstruct vertex time
    - For $Z \to \mu\mu$ with both muons in barrel, ETL can only properly reconstruct PV time in 70% of events, due to additional vertices nearby in z combined with worse tracking resolution in endcap