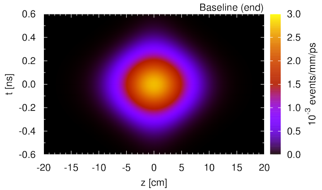
Precision Timing: CMS Plans and Performance Studies

Josh Bendavid (Caltech)
On behalf of the CMS collaboration

Oct. 6, 2016
ECFA High Luminosity LHC Experiments Workshop
Aix-Les-Bains, France

Introduction

- Basic motivation for fast timing is to improve suppression of pileup at HL-LHC
- Current CMS detector provides no meaningful angular resolution for calorimeter energy deposits → impossible to directly assign neutral particles to a primary vertex
- In HL-LHC with 140-200 pileup, primary vertices start to overlap in space within the tracking resolution
- Interactions are also distributed in time with a spread of 100-200 ps → a detector with 10's of ps timing resolution could meaningfully distinguish between interactions on the basis of timing



Precision timing for CMS Phase-II Calorimeter Upgrades

ECal Barrel Electronics 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

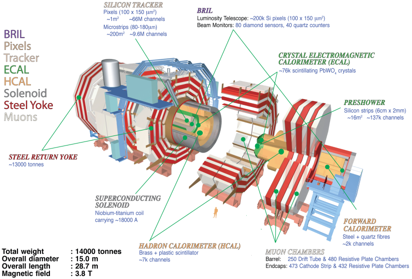
High Granularity Calorimeter:

- Excellent intrinsic timing performance of Si sensors for sufficiently large signals
- Baseline for electronics is hybrid readout: charge at lower energy + time-over-threshold at higher energy
- Time-over-threshold hits are accompanied by $\sim$50 ps timing resolution (multiple ToT hits can be combined within a shower)
- Electromagnetic showers have several ToT hits down to a few GeV in energy
- Hadrons have sufficient ToT hits only at somewhat higher energy, depending on final thresholds, etc

Potential Additional Timing Capabilities

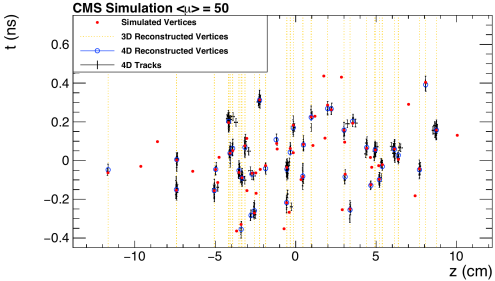
- Calorimeter upgrades can already provide precision timing for high energy photons in the central region, moderate energy photons, and higher energy hadrons in the forward region
- Additional potential capabilities: MIP timing to cover large fraction of charged particles in the event
- Possible extension to Phase-II Upgrade: MIP timing layer
- Possible concept for central region: Thin LYSO + SiPM layer attached to the outside of the tracker barrel support tube (in between tracker and ECal Barrel)

  $\rightarrow$ precision timing for charged particles and converted photons



Precision timing for charged particles

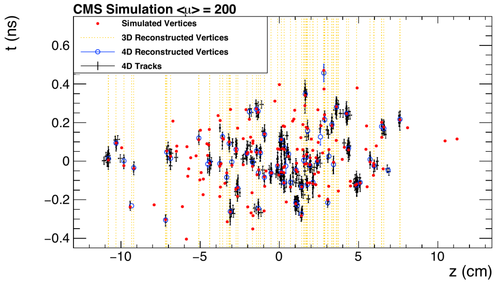
- Assuming sufficient timing performance for charged hadrons, e.g. from dedicated LYSO+SiPM layer in the central region, and from HGCAL or dedicated layer in the forward region
- Traditional three-dimensional vertex fit can be upgraded to a four-dimensional fit, with pileup vertices explicitly reconstructed in **position** along the beamline and **time** within the bunch crossing
- Further suppression of charged particles from pileup for jets/missing energy/lepton isolation/etc



20 ps resolution assumed for charged particles with $p_T > 1$ GeV

Precision timing for charged particles

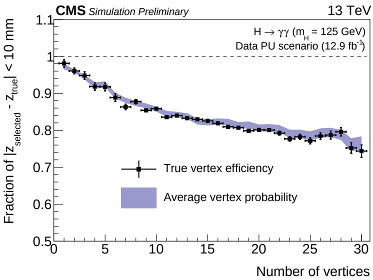
- Assuming sufficient timing performance for charged hadrons, e.g. from dedicated LYSO+SiPM layer in the central region, and from HGCAL or dedicated layer in the forward region
- Traditional three-dimensional vertex fit can be upgraded to a four-dimensional fit, with pileup vertices explicitly reconstructed in **position** along the beamline and **time** within the bunch crossing
- Further suppression of charged particles from pileup for jets/missing energy/lepton isolation/etc

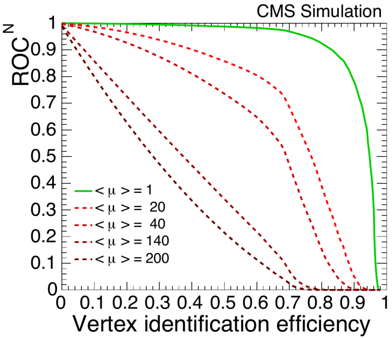


20 ps resolution assumed for charged particles with $p_T > 1$ GeV

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

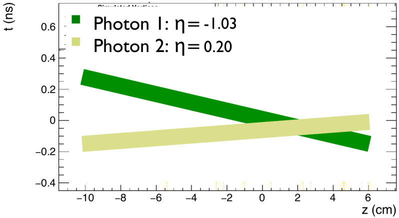
- No pointing information from ECal$\rightarrow$ CMS relies on hadronic recoil balancing and conversion pointing to locate primary vertex in $H \rightarrow \gamma\gamma$ events
- Becomes increasingly difficult to locate the primary vertex at very high pileup
- Vertex selection efficiency drops from $\sim$80%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

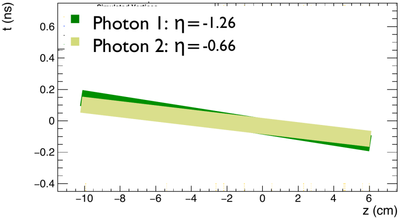




Precision timing for High Energy Photons - $H \rightarrow \gamma\gamma$

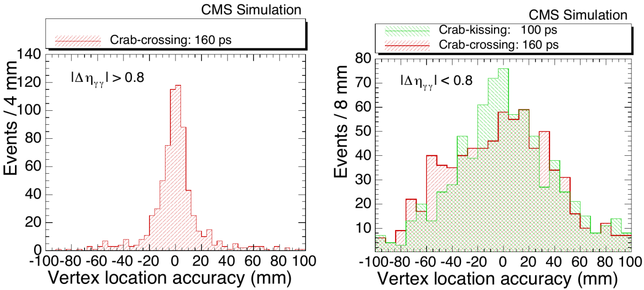
- Precision timing measurements for the high energy photons allows triangulation back to the primary vertex (30 ps resolution assumed here)
- Triangulation breaks down for small rapidity gap. In the absence of a known t_0 for the hard interaction, triangulation is ambiguous





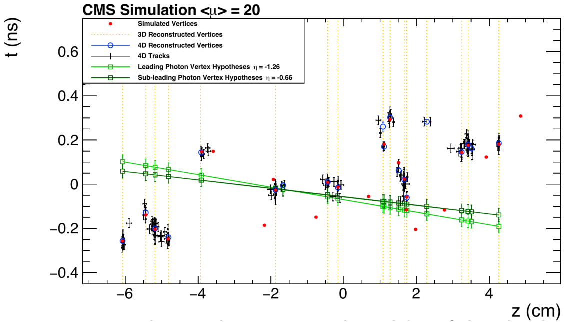
Precision timing for High Energy Photons - $H \rightarrow \gamma\gamma$

- 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



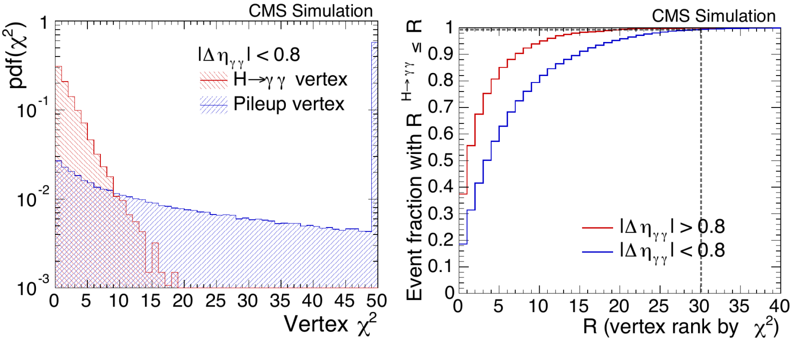
Precision timing for High Energy Photons - $H \rightarrow \gamma\gamma$

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



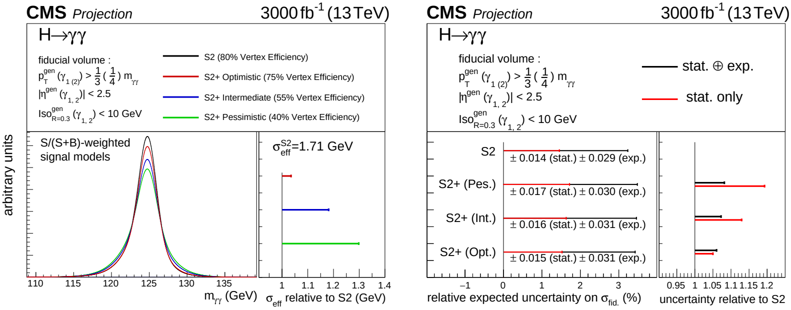
Precision timing for High Energy Photons - $H \to \gamma\gamma$

- 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



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

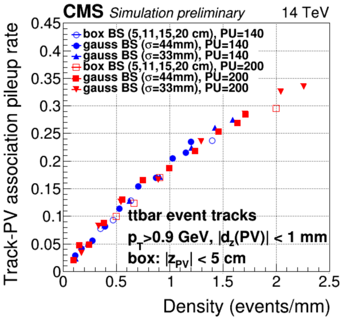
- Without precision timing, $H \rightarrow \gamma\gamma$ primary vertex selection efficiency is reduced from ∼80% in Run 2 conditions, to ∼40% at 140 PU
- Reduction in primary vertex selection efficiency has a dramatic (30%) effect on effective mass resolution when incorporated into projections
- Partially recovered by calorimeter timing alone, and almost fully recovered by calorimeter + MIP timing (∼ 30% improvement in effective integrated luminosity for stat. limited differential cross sections)



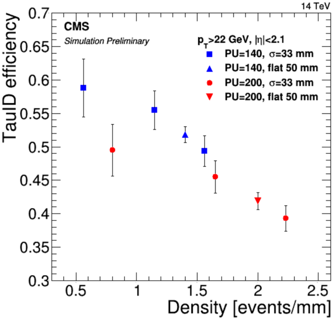
Precision Timing for Jets, Missing Energy and Isolation

- Major closely connected set of topics for physics impact of precision timing is lepton (or high energy photon) isolation, jet and missing E_t performance
- All of these depend strongly on the effectiveness of pileup rejection for relatively low p_T particles
- General rule of thumb for overall energy composition: 60/30/10 % charged hadron/photon (neutral mesons)/neutral hadron

Tracking Implications of High Pileup (without timing)



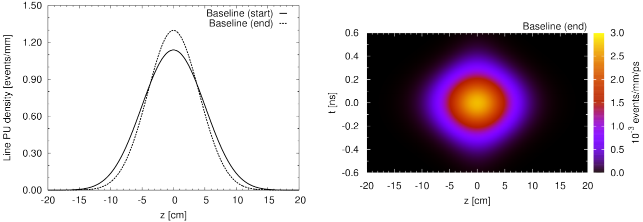
(a) PU Tracks attached to hard PV



(b) Tau Iso Efficiency

- As vertices start to overlap within effective tracking resolution, rate of pileup tracks associated to hard interaction vertex increases
- Corresponding degradation of charged isolation, b-tagging, Jet/MET performance

Effect of Precision Timing on Vertex-Track Association



G. Arduini, R. Tomas

- Integrating over 95% confidence interval with detector resolution σ_z, σ_t, for 1d and 2d pileup densities ρ_z, ρ_{zt}, the effective amount of pileup for track-vertex association scales as $\sim 4.9 \frac{\rho_{zt}}{\rho_z} \sigma_t$
- For a 2d Gaussian luminous region of width σ_z^{bs}, σ_t^{bs}, effective pileup scales as $\sim 1.9 \frac{\sigma_t}{\sigma_t^{bs}}$
- **For 20-30 ps time resolution, back of the envelope expectation is a 3-5x reduction in effective pileup density for track-primary vertex association**

Effect of Precision Timing on Vertex Performance

CMS Simulation

<μ>	4D Merged Vertex Fraction	3D Merged Vertex Fraction	Ratio of 3D/4D
50	0.5%	3.3%	6.6
200	1.5%	13.4%	8.9

- Rate of vertex merging closely related to the rate of pileup tracks contaminating charged isolation, charged component of Jets/MET, etc
- Impact of precision timing+4d-vertexing on vertex merging consistent with back of the envelope expectation (timing resolution for vertices better than for single tracks)
- **Optimistic Expectation:** Precision timing for MIPs combined with 4d vertex reconstruction can substantially mitigate impact of HL-LHC PU conditions for quantities sensitive to pileup tracks attached to hard PV
- Detailed simulation and studies under preparation to explicitly confirm this

Conclusions

- Greatly increased pileup is a fact of life at HL-LHC
- Precision timing capabilities can help further disentangle pileup and restore physics performance
- Precision timing capabilities being pursued for ECal Barrel with upgraded electronics, HGCal, possible dedicated timing layer for MIPs
- Use cases for physics:
  - Cleaning of pileup from jets, missing energy, lepton isolation
  - Primary vertex identification to maintain mass resolution for $H \to \gamma\gamma$
- Detailed simulation and performance studies in progress to better quantify the benefit of fast timing for pileup suppression of both charged and neutral particles in conjunction with 4d primary vertex reconstruction