Extending the physics reach of the HL-LHC with precision timing capabilities in CMS

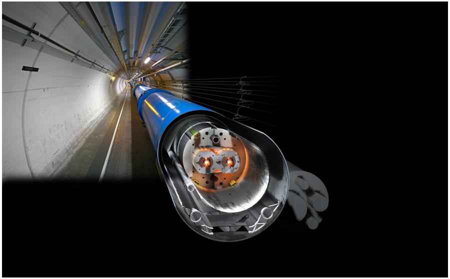
Josh Bendavid (Caltech/LPC DR)

May. 26, 2017
FNAL W&C

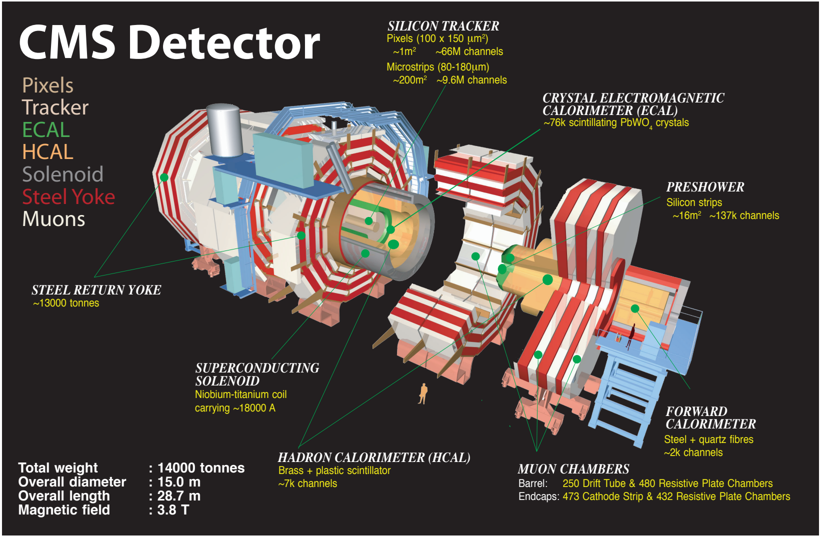
The Large Hadron Collider

- Proton-proton collider
  27 km in circumference, located at CERN in Geneva
- Design energy of 14 TeV

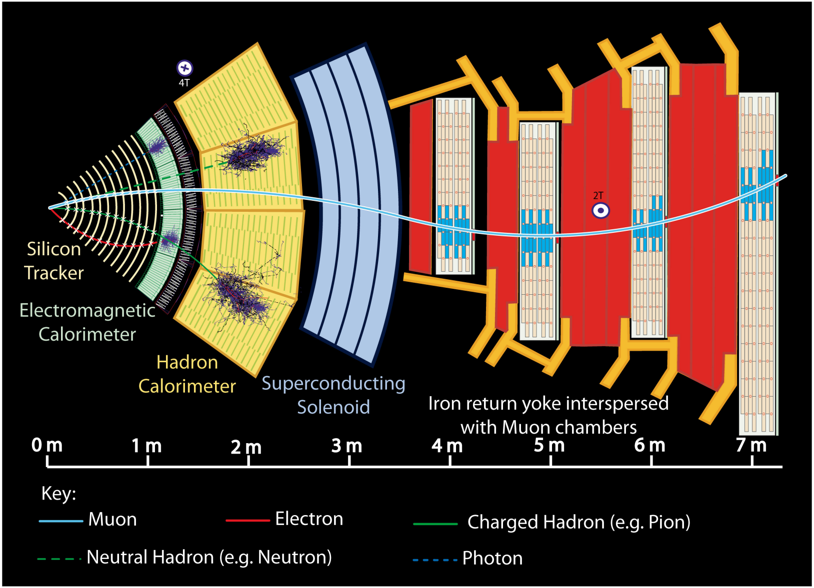
- Superconducting dipole magnets with a design field of 8.3 T, cooled to 1.9 K using superfluid helium



The CMS Detector



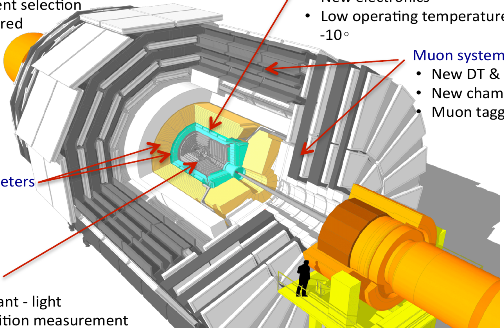
The CMS Detector



HL-LHC and Phase II Upgrades

- **HL-LHC:** Significant upgrade of LHC and injectors to increase beam intensity
  - $L_{\mathrm{inst}} > 5 \times 10^{34}\ \mathrm{cm}^{-1}\ \mathrm{s}^{-1}$, up to **140-200 pileup**
  - Ultimate integrated luminosity target of **3000 fb**$^{-1}$ (baseline)
- **Phase II Detector Upgrades:** Significant upgrades of ATLAS and CMS for HL-LHC conditions
  - Radiation hardness
  - Mitigate physics impact of high pileup
- Physics Goals/Opportunities:
  - Precision Higgs Measurements
  - Higgs Self Coupling
  - Extend BSM searches to smaller production cross sections
  - Precision measurements of rare B decays

CMS Phase II Upgrades



Trigger/HLT/DAQ
- Track information in hardware event selection
- 750 kHz hardware event selection
- 7.5 kHz events registered

Barrel EM calorimeter
- New electronics
- Low operating temperature ≈ -10°

Muon systems
- New DT & CSC electronics
- New chambers $1.6 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$

New Endcap Calorimeters
- Rad. Tolerant
- 5D measurement

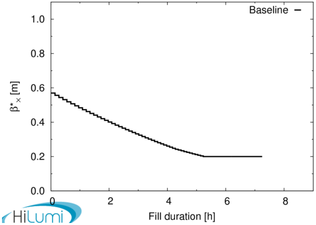
New Tracker
- Rad. Tolerant - light
- High Definition measurement
- 40 MHz selective readout for hardware trigger
- Extended Pixel coverage to $\eta \approx 3.8$

Beam radiation and luminosity
Common systems and infrastructure

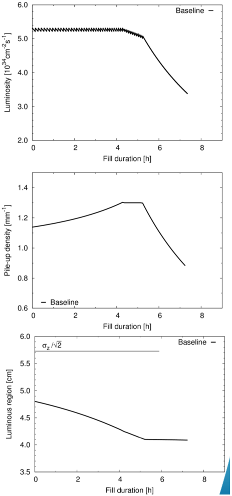
J. Butler, LHCP 2017

HL-LHC Luminosity Levelling: Baseline Scenario

- Leveling luminosity at $5.3\times10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ and 140 pileup
- Uniform luminosity and levelling with $\beta^* \to$ pileup **density** increases over the length of a fill



G. Arduini, R. Thomas, ECFA 2016

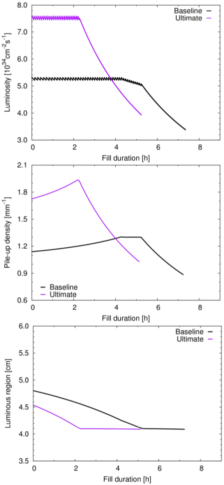


HL-LHC Luminosity Leveling: Ultimate Scenario

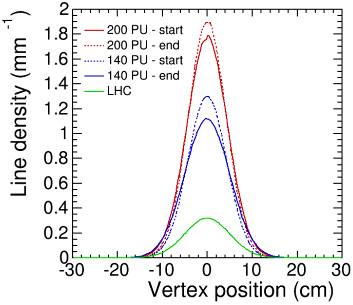
- Same beam parameters, different working point for lumi leveling
- 5.3×10^{34} cm^{-2}s^{-1} $\rightarrow$ 7.6×10^{34} cm^{-2}s^{-1}
- $\sim$3000 fb^{-1} $\rightarrow$ $\sim$4000 fb^{-1}

Scenario	Max. PU [events/xing]	Max. PU density [events /xing/mm]	Luminous Region long. r.m.s. size [cm]	$\Delta L_{int}/L_{nom}$ [%]	Additional HW [Y/N]
Nominal	140	1.3	<4.8	0	N
Ultimate	200	1.9	<4.5	+33	N
8b+4e	140	1.3	<5	-25	N
200 MHz	140	1.3	<4.8	-14	Y
Flat	140	1.1	<5.5	0	May be
Crab kissing	140	0.6-0.65	<7	-5	Y

G. Arduini, R. Thomas, ECFA 2016

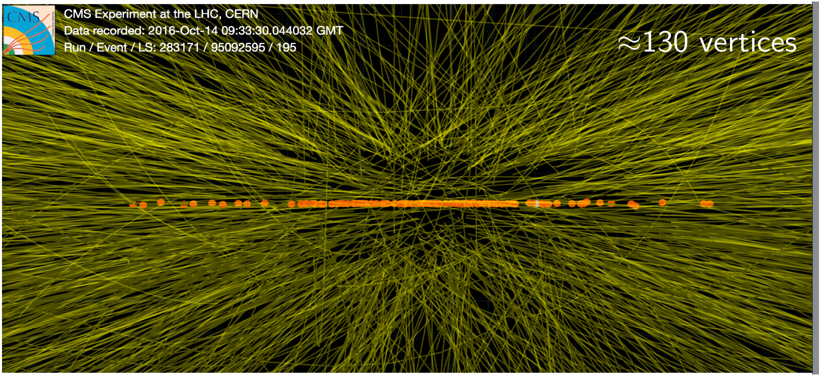


HL-LHC Luminous Region



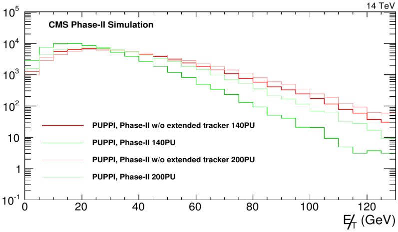
- Total amount of pileup and width of luminous region evolve over the course of a fill
- Linear **pileup density** further varies over the luminous region

Proof of Concept, Proof of Challenge

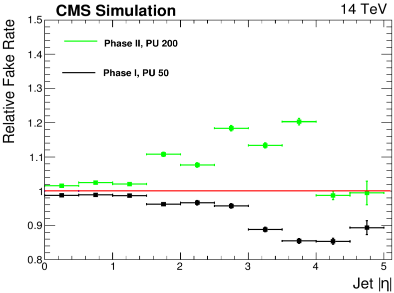


- Real-life event with HL-LHC-like pileup from special run in 2016 with individual high intensity bunches

Physics Impact



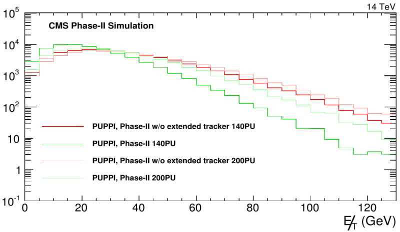
(a) $\not{E}_T$ Tails



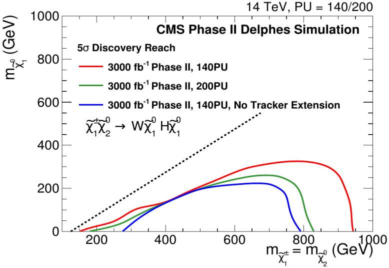
(b) Jets from PU

- Contamination of **neutrals** scales with overall PU to first order

Physics Impact



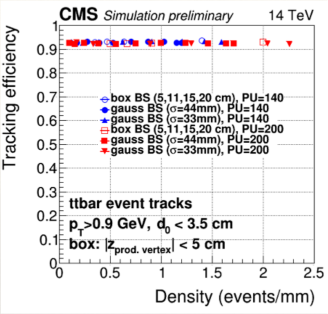
(a) $\not{E}_T$ Tails



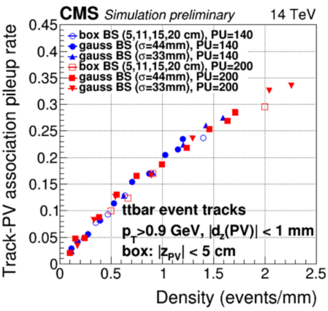
(b) EWK SUSY Search

- Significant impact on physics reach

Pileup Density Impact: Track-PV Association



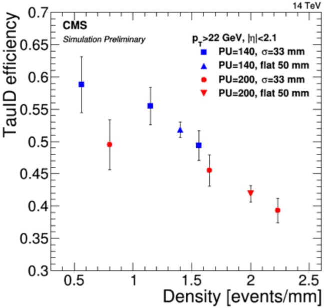
(a) Tracking Efficiency



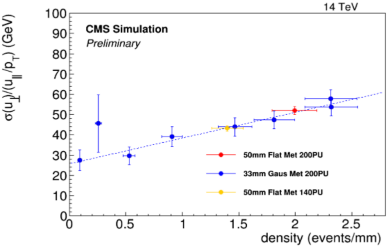
(b) Pileup Tracks in Hard PV

- Primary vertex and tracks from hard interaction can still be reconstructed efficiently, but pileup contamination increases rapidly as a function of pileup density (pure geometric effect, independent of total pileup)
- **Quantities based on charged particles are currently nearly free of pileup, will not be so at HL-LHC**

Pileup Density Impact: Leptons and MET



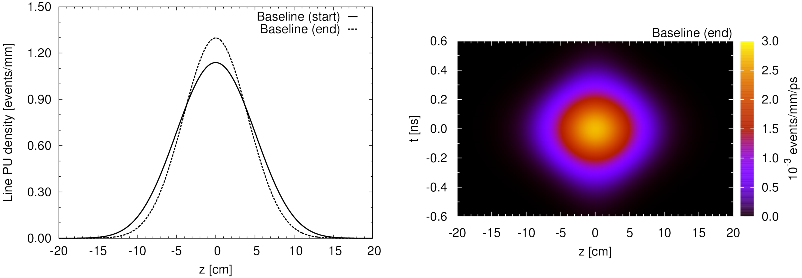
(a) Tau Isolation ϵ



(b) (Puppi) MET Resolution

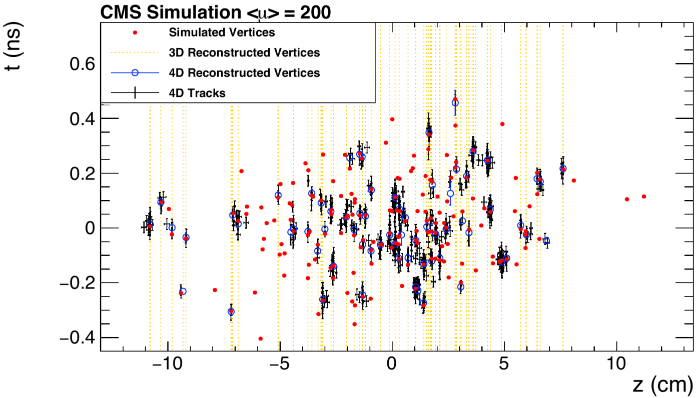
- Noticeable effect on charged isolation efficiency for leptons
- Puppi MET resolution scales with density since charged particles are used to aid in identification of relevant neutrals

Mitigation with Precision Timing



- Interactions are also distributed in time with a spread of 150-200 ps
- A detector with 10's of ps timing resolution could meaningfully distinguish between interactions on the basis of timing

Mitigation with Precision Timing



- With sufficient time resolution and coverage for charged particles, traditional three-dimensional vertex fit can be upgraded to a four-dimensional fit

Precision timing for CMS Phase-II Calorimeter Upgrades

ECal Barrel Electronics Upgrade:

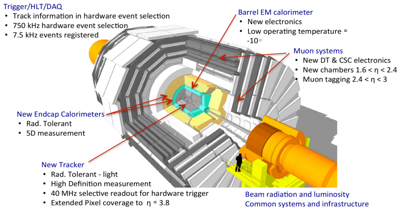
- Additional cooling and upgraded front-end electronics will keep noise levels under control
- With proper attention to clock distribution, reduced shaping time, and high ADC sampling rates (160 MHz), can achieve $\sim$ 30 ps time resolution for 30 GeV photons at high integrated luminosity (limited by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

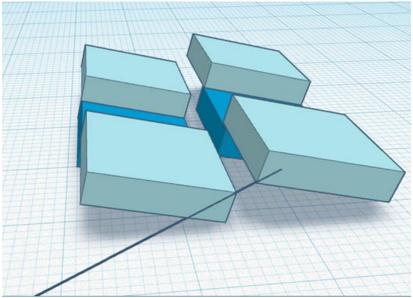
Additional Timing Capabilities

- 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



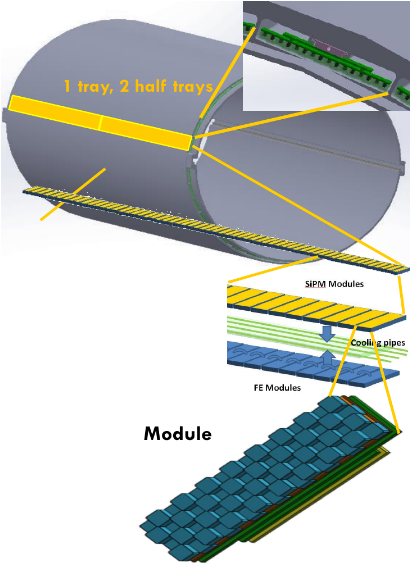
- Concept for forward region (more stringent radiation hardness requirements): **LGAD** (Silicon with Gain), with baseline location as additional final layer of strip tracker

BTL Example Mechanics

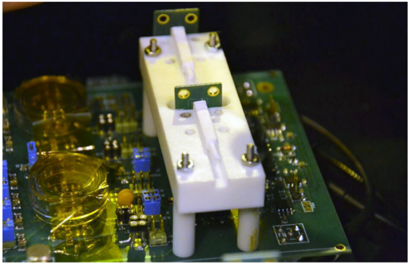


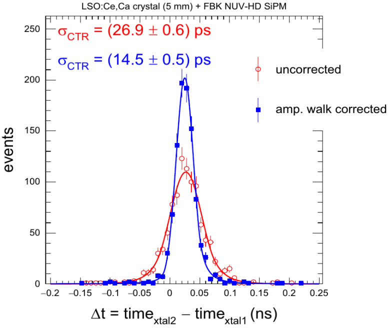
C. Tully

https://indico.cern.ch/event/633343/



LYSO+SiPM Timing Performance



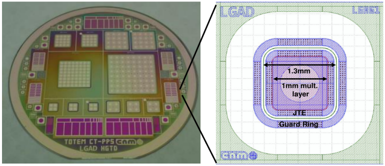


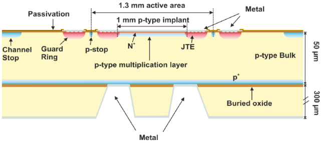
A. Benaglia et al,
https://doi.org/10.1016/j.nima.2016.05.030

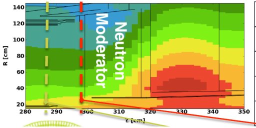
- LYSO good candidate for precision timing due to very high light yield
- Sufficient time resolution for MIPs already achieved in test beams for single channel thin LYSO+SiPM sensors

LGAD Timing Performance

D. Lange et al http://iopscience.iop.org/article/10.1088/1748-0221/12/05/P05003/meta



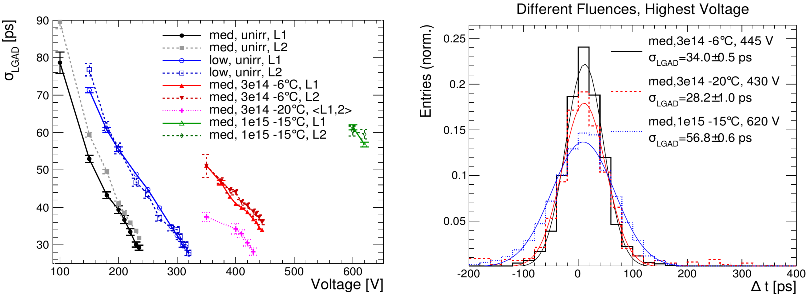




η	TK / HGCal nose
1.6	1.1 x 10^{14}
2.0	2.1 x 10^{14}
2.5	4.8 x 10^{14}
3.0	10.0 x 10^{14}

- Low Gain Avalanche Devices (LGAD): Silicon sensors with gain
- Typical operating points with gain in $\sim$10-30 range
- Key Challenge: Radiation dose up to 10^{15} n_{eq} cm^{-2} at $|\eta| = 3.0$ for 3000 fb^{-1}

LGAD Timing Performance



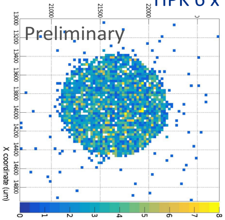
D. Lange et al `http://iopscience.iop.org/article/10.1088/1748-0221/12/05/P05003/meta`

- Promising results, 30 ps time resolution demonstrated up to 3×10^{14} n_{eq} cm^{-2}
- Sensor R&D continuing

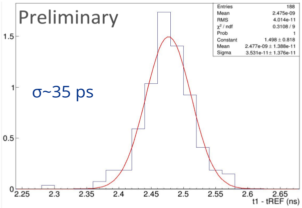
LGAD: Currently Ongoing Test Beam Campaign at FNAL

- Collaborative effort with CMS & ATLAS institutes:
  - Caltech, FNAL, Kansas, Torino, UC Santa Cruz
  - Close collaboration with Hamamatsu, CNM, FBK
- Characterization of newest LGAD sensors, both irradiated and unirradiated (work in progress)
- Promising results up to 6×10^{14} n_{eq} cm^{-2}

HPK 6 x 10^{14} n.eq/cm^2

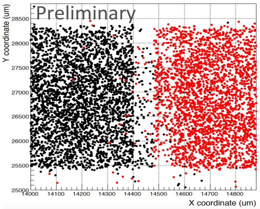


High uniformity of signal over irradiated sensor area



Excellent time resolution with irradiated devices

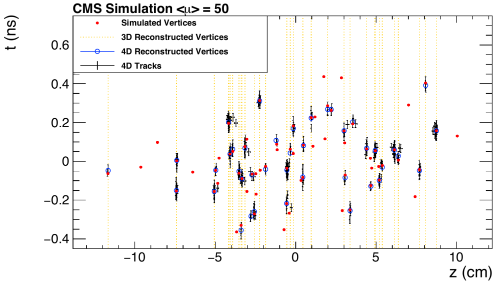
HPK unirradiated 2x2 array



Uniform, high efficiency over the surface of the detector.

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 LGAD 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



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

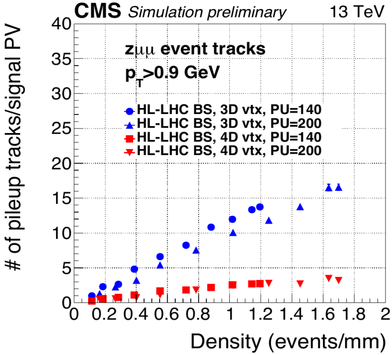
Effect of Precision Timing on Vertex Performance

CMS Simulation

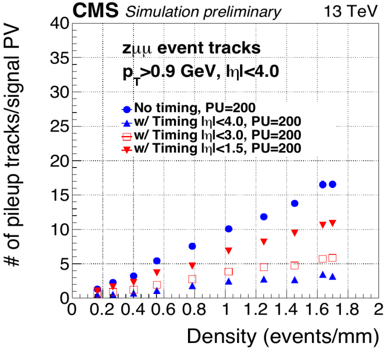
<μ>	4D Merged Vertex Fraction	3D Merged Vertex Fraction	Ratio of 3D/4D
50	0.5%	3.3%	6.6
200	1.5%	13.4%	8.9

- 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)

Effect of Precision Timing on Track-PV Association



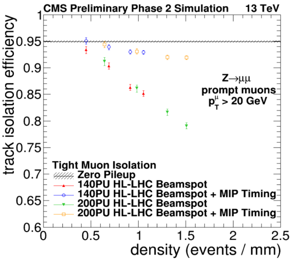
(a) Total # of tracks/hard PV



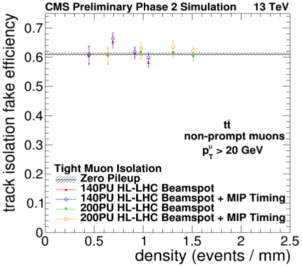
(b) η Coverage Variation

- **$\sim$ 5x reduction in effective pileup in terms of charge multiplicity**

Muon Charged Isolation



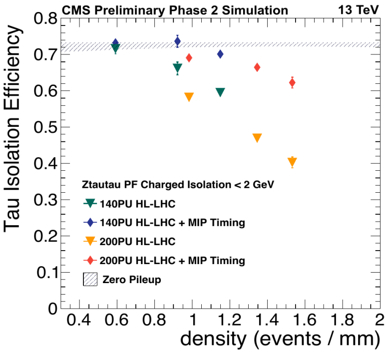
(a) Prompt μ Efficiency



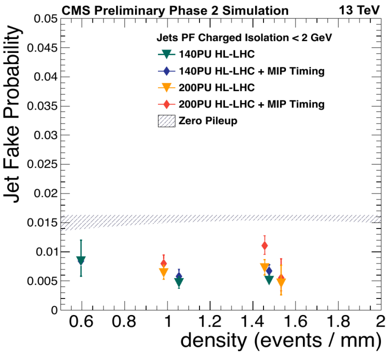
(b) Efficiency for fakes

- Muon charged isolation efficiency in $Z \to \mu\mu$ (prompt) and $t\bar{t}$ (fake) events
- Efficiencies plotted at fixed working point (but applying timing does not increase the number of fakes within present uncertainties)

Tau Charged Isolation



(a) Prompt τ Efficiency

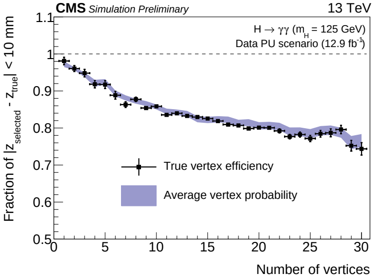


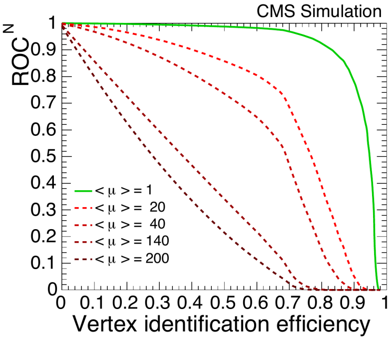
(b) Efficiency for fakes

- Large effect on Tau charged isolation efficiency in $Z \to \tau\tau$ at fixed working point

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

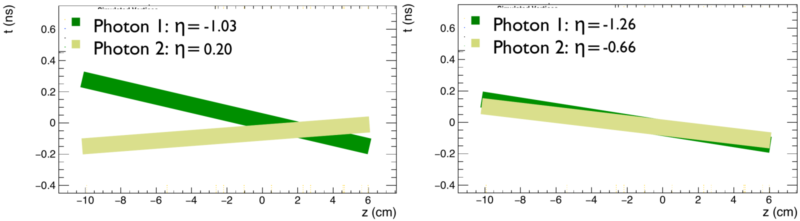
- No pointing information from ECal$\to$ CMS relies on hadronic recoil balancing and conversion pointing to locate primary vertex in $H \to \gamma\gamma$ events
- Becomes increasingly difficult to locate the primary vertex at very high pileup
- Vertex selection efficiency drops from ∼80% in current conditions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





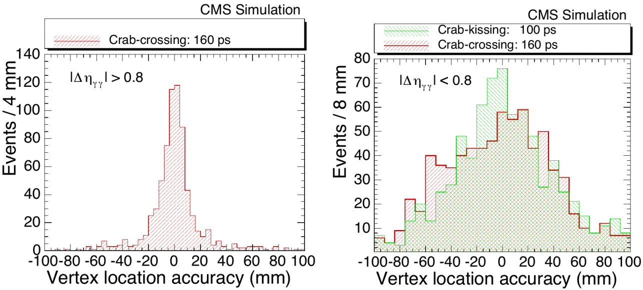
Precision timing for High Energy Photons - $H \to \gamma\gamma$

- 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



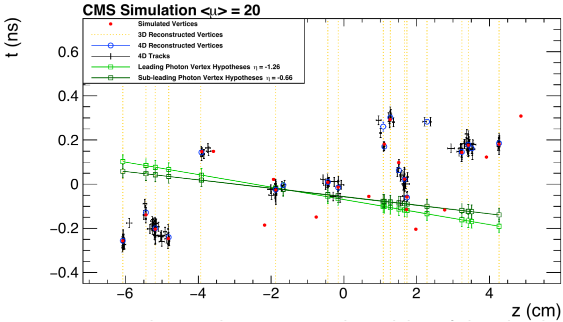
Precision timing for High Energy Photons - $H \to \gamma\gamma$

- 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



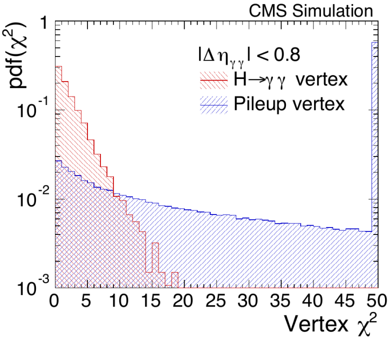
Precision timing for High Energy Photons - $H \rightarrow \gamma\gamma$

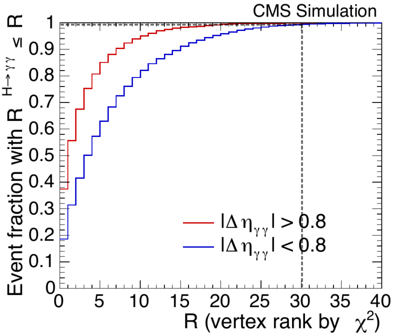
- Calorimeter timing-based triangulation can be matched to 4d reconstructed primary vertices to resolve the ambiguity and restore the performance



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

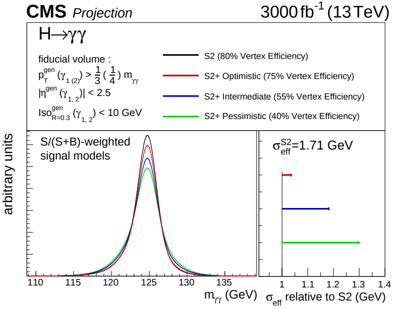
- Calorimeter timing-based triangulation can be matched to 4d reconstructed primary vertices to resolve the ambiguity and restore the performance
- Simple χ^2 matching provides a 5x reduction in the effective amount of pileup even for small rapidity gap events

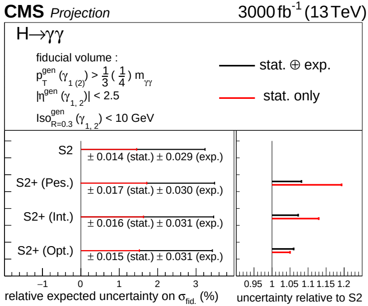




Precision timing for High Energy Photons - $H \to \gamma\gamma$

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

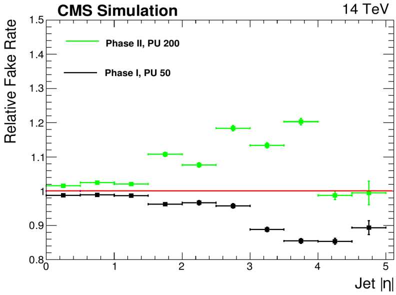




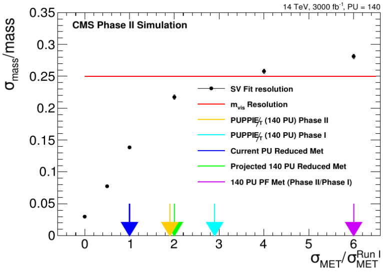
Precision Timing for Jets, Missing Energy and Isolation

- 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
- Studies underway extending the effect of precision timing for charged particles to missing energy resolution and pileup jet suppression
- Precision timing for neutrals begin incorporated as well, in particular for converted photons ($\sim$ 40%) in the barrel timing layer, and photon showers in the HGCal

Physics Prospects: $H \to \tau\tau$



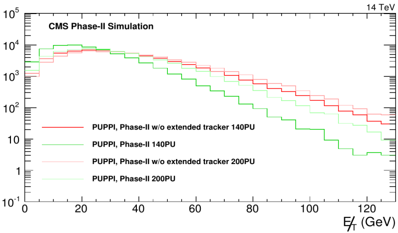
(a) PU Jet Suppression



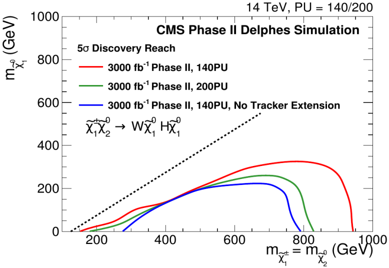
(b) $m_{\tau\tau}$ Resolution

- Benefits from precision timing for PU Jet suppression (for all VBF Higgs channels), τ isolation, missing energy resolution ($\tau\tau$ mass resolution)

Physics Prospects: Searches



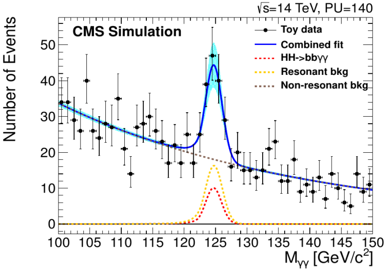
(a) $E\!\!\!/_T$ Tails



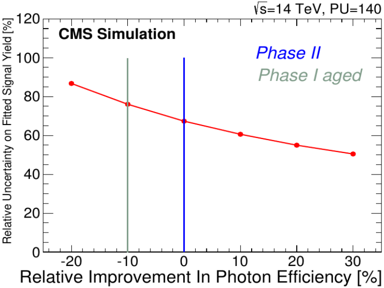
(b) EWK SUSY Search

- Improved missing energy resolution benefits all searches sensitive to missing energy tails of SM processes

Physics Prospects: Di-Higgs Production



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



(b) Effect of γ Efficiency

- Improvements in Photon isolation, maybe b-tagging will improve sensitivity

Conclusions

- Precision timing capabilities can help further disentangle greatly increased pileup at HL-LHC pileup and restore physics performance
- Precision timing capabilities being pursued for ECal Barrel with upgraded electronics, HGCal, dedicated timing layers for MIPs
- Scope for CMS Phase-II Upgrades being extended to include MIP precision timing detectors
- Use cases for physics:
  - Cleaning of pileup from jets, missing energy, lepton isolation $\rightarrow$ benefits for full range of HL-LHC physics program
  - Primary vertex identification to maintain mass resolution for $H \rightarrow \gamma\gamma$
- Initial simulation and performance studies demonstrate benefits of precision timing for pileup suppression of charged particles
- Additional and more detailed studies in progress, including quantitative projections to HL-LHC physics results
- Better pileup suppression capabilities from the experiments may enable physics exploitation of instantaneous and integrated luminosity scenarios for HL-LHC exceeding the current 3000 fb^{-1} baseline